More Plastics Growth, the Answer to Transportation in the 80's

National Technical Conference

Society of Plastics Engineers

NOVEMBER 6-8, 1979

Detroit Plaza Hotel
Renaissance Center
Detroit, MI

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A NEW 50,000 PSI MODULUS FLEXIBLE RIM FOR LIGHTWEIGHT FASCIA

Dr. H. A. Silverwood

Davidson Rubber Division
Ex-Cell-O Corporation
Dover, N.H. 03820

INTRODUCTION

Reaction Injection Molding (RIM)[1] is a relatively new polymer process for molding large, complex parts. Urethane has been the predominant polymer processed via the RIM technique. The major commercial application has occurred in the automotive market for the production of flexible bumper covers. The RIM process and automotive applications will now be described in more detail.

RIM is a process in which two reactive components (polyol and isocyanate, in the case of urethanes) are combined on demand in a mix chamber and injected into a mold cavity to react and cure. Intimate mix of the two components is accomplished by direct impingement of the two liquid streams in the correct ratio at high pressures (2000psi [13,800kPa], or greater). In-situ reaction begins immediately, and current commercial systems have been formulated to provide rapid cure and demold. Typically, cure can be as low as 30 seconds and overall molding cycles are in the range of 2-4 minutes.

The largest usage of flexible RIM elastomer to date has been in the automotive industry as front and rear bumper covers. The first commercial application in the U.S. of flexible RIM bumper fascia was the 1975 Model Year GM 2+2 sporty series Monza, Starfire and Skyhawk. As the RIM process and elastomeric urethane fascia performance gained experience and acceptance by automotive engineers, additional car bumper designs specified RIM urethanes. In model year 1980, approximately 25% of all cars to be produced in the U.S. will have RIM urethane fascia. Table I identifies these models. A penetration of over 60% usage on American car production is projected within the next 5 to 7 years.

This significant growth projection is based on two unique situations that has influenced the direction of the American automotive industry - each of which is directly influenced by U.S. Government mandates:

1. The government has mandated non-damageability requirements on all front and rear end safety and support components when subjected to a 5 mph test condition.
2. The government has mandated increasing fuel mileage requirements on car fleets (corporate average fuel economy - CAFE) each year until a corporate average of 27.5 mpg is reached in MY 1985.

COMMERCIAL RIM SYSTEMS

Two categories[2] of RIM urethane systems have emerged in recent years. The first and major type is a flexible elastomer used for flexible fascia. These materials have a room temperature flexural modulus of 25,000 psi (172,000kPa). The second category is that of rigid elastoplastics, which have a room temperature flexural modulus of greater than 100,000 psi (689,000kPa). The first high volume use of this type is the 1980 Chevrolet Caprice and Impala rear tail lamp panel. The use of fibrous reinforcements[3] can increase the flexural modulus range of rigid elastomers to 500,000 psi (3,500,000kPa) or greater. These materials combine the rigidity required for non-flexing applications with a relatively high elongation (30 to 70% or greater). The result is a very damage resistant product.

A third category, a stiff urethane elastomer, has been developed and is the subject of this paper. The combination of flexibility and high stiffness provide weight and cost reduction potential. The result is a high performance elastomeric RIM (HPE-RIM).

This elastomer has a room temperature flexural modulus value of 50,000 psi (344,000kPa) or greater, yet retains the impact performance of a conventional (25,000 psi - 172,000kPa) flexible elastomer.

Table II summarizes the key properties that differentiate the various categories of these RIM urethane systems. HPE-RIM falls midway between the flexible and rigid systems. Significant differences in properties and performance occur in each category and will be explained later.

APPLICATIONS

Flexible systems have found application in the automotive industry as bumper fascia covers, sight shields, valence panels, body side moldings, trim strips, and wheel opening flares. Rigid systems, unreinforced and reinforced, have been used or have been proposed for use as rear deck spoilers, tail lamp housing panels, fenders, door panels, hoods, valence panels and other exterior body panels. The new HPE-RIM system can be used in all flexible applications, but offers unique advantages when considered as a bumper fascia candidate. Before describing these advantages, let me describe the design and performance requirements for flexible fascia.

Flexible RIM fascia are uniquely qualified to aid automotive designers in meeting the government non-damageability and fuel mileage requirements because of specific performance characteristics of urethanes. The advantages gained by designing automotive front and rear bumper panels in RIM urethane include:

1. Non damageability - urethanes possess outstanding impact/damage resistance, and, being flexible, readily return to original shape after impact distortion. The materials perform satisfactorily over a wide temperature range (-20°F to 125°F) (-29°C to 52°C) and can withstand impact damage when painted with extensible coatings.
2. Low weight - with a nominal specific gravity of 1.0, urethane moldings will be lighter than metal alternatives by a factor of at least 2:1.
3. Complexity of design - the full advantage of the RIM process can be exploited by combining all front end components into one large fascia. The current Camaro front end (Figure 1) is an example of the aerodynamic styling and design benefits of a full front fascia.
4. Appearance - the surface finish of RIM urethanes closely resembles sheet metal and has aided in customer acceptance of plastic exterior body components.
5. Total corrosion elimination.

FASCIA DESIGN CONSIDERATIONS

The complexity of fascia design has evolved steadily over the past five years. The first design, the Chevrolet Monza, actually consisted of two separate fascia components for the front end and two components for the rear end. This was done to reduce the liability of attaining unacceptable components (appearance, fit considerations) from an untried manufacturing process (RIM).

The viability of RIM was established with the Monza series

as was the opportunity to design even larger and more complex fascia for RIM urethanes. Current usage of fascia can be grouped into three types that relate primarily to the size and complexity of the part:

1. Small - typically referred to as blade bumper covers and represented by most rear fascia applications. Figure 2 shows the current Mustang rear fascia which depicts a blade type fascia. Fascia of this size and style typically weigh 4-6 lbs. (1.8-2.7 kgms) and are molded in double cavity tools.
2. Intermediate - larger in size and weight than blade type fascia, the intermediate molding generally extends from the forward hood line to beneath the bumper and includes cut out areas for head lamps and grilles. An intermediate fascia will weigh 6-10 lbs. (2.7-4.5 kgms) typically and can be depicted by the Pontiac LeMans front (Figure 3).
3. Large - includes the most complex fascia design and incorporates integral grilles in the one piece molding. Large fascia typically weigh over 10 lbs. (4.5 kgms). The Camaro front (Figure 1) and Dodge Omni front (Figure 4) represent this class of fascia.

Although the trend to larger fascia provides weight advantages, and inherent cost advantages through integration of parts, their use does introduce more severe handling and appearance requirements. In designing full front fascia with aerodynamic considerations, large unsupported areas with overhang are common. With typical flexural modulus values of 25,000 psi (172,000kPa) these areas tend to sag under their own weight. Incorporation of supporting ribs or thickening of the area that tends to sag are techniques that might improve appearance, but can introduce molding and appearance problems. A more reliable alternative approach is the use of a higher modulus semi-flexible system that does not tend to sag while maintaining the other key properties of a flexible system. Additionally, large fascia molded in HPE-RIM elastomer can be more readily handled in both the molding plant and the assembly plant without distortion or damage; and the stiffer nature of the full fascia permits easier assembly to the vehicle. It was for these reasons, and the ability to further reduce part thickness yet maintain good appearance, that we undertook a program to develop a RIM system that possessed increased stiffness yet still retained the real-world performance characteristics of the current commercial flexible systems.

Thus, the important critical requirements for flexible fascias include:

1. In-plant handling performance
2. On-car impact performance
3. Aerodynamic design
4. Ease of assembly
5. Appearance

EVOLUTION OF FLEXIBLE SYSTEMS

An earlier paper[4] described the evolution of an improved flexible RIM urethane system for bumper fascia applications. It identified a new family of RIM urethane formulations that possessed outstanding cold-temperature flexibility, an absence of notch sensitivity at -20°F (-29°C), flexural moduli at -20°F (-29°C) equivalent to hydrocarbon rubbers, and greater resistance to sagging at high temperatures than that exhibited by earlier RIM formulations. Typical properties of two members of this family, identified as MC-1070 and MC-1071, are given in Table III. MC-1071 has been in continuous production at Davidson since 1977 on all the bumper fascia we supply to the automotive industry.

MC-1071 is characterized by its ability to withstand low temperature flexing and impact without cracking, even when painted with brittle paints. Brittle paints, such as PPG Industries' Durethane 100, are temperature-sensitive extensible polymer coatings used by the automotive industry to color-match elastomeric body moldings to painted metal components. The paints possess excellent gloss, weatherability and mar resistance properties; but will crack on flexing at low temperature. Their use has been limited to non-critical flexing applications, and to critical flexing applications where crack propagation through the substrate does not occur. Under dynamic impact conditions, the strain on the coating concentrated at a flexing point is sufficient to not only crack the coating film but also to propagate the crack through the urethane substrate by transfer of an instantaneous shock load to the already stressed substrate[5]. Many commercial RIM formulations, when coated with these brittle paints and flexed at -20°F (-29°C), exhibited a notch sensitivity that would result in partial or even complete crack propagation through the RIM material. The introduction of MC-1071 to the market place now allows fascia to be used with brittle paint and still meet all low temperature impact requirements.

ADVANTAGES OF THE HPE-RIM SYSTEM

HPE-RIM is the third system developed in the MC-1070 series, one that has twice the stiffness yet retains the real-world performance characteristics of the MC-1071 formulation. This system is identified as MC-1073, and typical properties are given in the last column of Table III.

In addition to a room temperature flexural modulus which is double that of MC-1071, most of the mechanical properties of MC-1073 are slightly improved over the flexible system. With the increased stiffness, full fascia as thin as 0.100 inches (2.5 mm) can be molded and still retain good appearance without sag.

Additionally, no loss of flexibility or cracking of substrate was experienced when the D-100 painted material was bent over a 1/2" (12.7 mm) mandrel at -20°F (-29°C).

MC-1073 has recently been introduced on two 1980 model year vehicles. This represents the first commercial fascia use of a HPE-RIM urethane system in the U.S. The newly designed Corvette rear fascia and the Monza rear lower fascia have been molded in this new HPE-RIM system since the start of model year production. In each case, the same processing characteristics as the former flexible system were obtained. With the experience now being gained at both the molding plant and the car assembly plants, future expansion to other fascia designs in succeeding model years is planned.

With the success of the semi-flexible program to date, the opportunity to take advantage of MC-1073's unique property and processing characteristics is available. Full fascia can be designed at nominal wall thickness of .100 inch (2.5 mm). Flat, unsupported areas will not require ribbing or thickening to provide good appearance. The reduced thickness means a reduction in part weight on the order of 20 to 33%, as current full fascia are designed to nominal thickness of 0.120 to .150 inches (3.1 to 3.8 mm). The lower weight reflects a lower cost part also. The system processes well in large parts and allows for uniform material flow. The ease of handling in the assembly plant has already been demonstrated with the Corvette rear part where the increased stiffness allows the worker to fit the part to the vehicle with less difficulty.

The ability to take advantage of the improved mechanical properties of the semi-flexible systems can be demonstrated by the Monza rear lower panel. With the advent of Department of Transportation's Part 581 Bumper Standard, a damageability requirement that went into effect on all MY 1980 vehicles, the carryover design on the flexible Monza rear fascia did not meet the new standard. The failure mode was a tearing of the fascia and was peculiar to the particular part design. In order to meet the standard with the flexible system, part thickness in the impact ridge area would had to have been increased to 0.500 inch (12.7 mm). This would have meant a retooling program, increased part weight and cost, and increased molding cycle. MC-1073, with a 25% increase in tear strength, provided a part that met the new impact standard without a part design change. The new program started up without any tool or process change from the MY 1980 program.

COMPETITIVE ADVANTAGES

The advantages seen for HPE-RIM elastomers are similar to flexible RIM elastomers when compared to other materials of construction, such as steel, aluminum, thermoplastic olefin (TPO), and reinforced EPDM. Here, such factors as specific gravity, impact performance, physical properties, paintability and appearance, processing characteristics, and production costs were considered. Specific comparisons are as follows:

- Steel components are heavier, corrode, cannot withstand minor impact without damage, and require multiplicity of parts to provide a complete front end assembly.
- Aluminum components are more costly, require more energy to manufacture, cannot withstand minor impact without damage, and also require multiplicity of parts to also provide a complete front end.
- TPO requires a larger capital investment to mold, is more sensitive to molding distortion, cannot withstand minor impact without some damage or distortion, and is more difficult to paint. Special surface treatments are required to insure good paint adhesion and appearance. Reinforced EPDM is similar to TPO, but it also has exhibited non-uniform shrinkage and tendency toward distortion.

Table IV summarizes the key comparison aspects of all candidate materials for automotive front and rear designs.

SUMMARY

In summary, we have now seen the evolution of another RIM urethane system that provides the opportunity to reduce further the weight and cost of fascia, improve the appearance on the vehicle and expand further the potential for this unique class of materials in the automotive industry. It is another example of the progress being made in the plastics industry to meet the transportation challenges of the 1980's.

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Table I

MY 1980 U.S. Cars With RIM Bumper Fascia

General Motors	Ford	Chrysler
Chevrolet Monza	Mustang	Omni 024
Chevrolet Corvette	Capri	Horizon TC-3
Chevrolet Monte Carlo	T'Bird	Dodge Mirada
Chevrolet Camaro	Cougar XR-7	Chrysler C-300
Pontiac Firebird		Chrysler New Yorker
Pontiac LeMans		
Pontiac Grand Am		
Pontiac Phoenix		
Buick Skyhawk		

Table II

Key Properties of Urethane RIM Materials

Properties	Flexible RIM	HPE-RIM	Rigid RIM	Reinforced Rigid RIM (RRIM)
Nominal Sp. Gravity	1.0	1.0	1.0	1.1-1.25
Molded Part Thickness, In.	0.125	0.100	0.100-0.125	0.100-0.125
(mm)	(3.)	(2.5)	(2.5-3.)	(2.5-3.)
Flexural Modulus, $X10^3$ psi	25	55	120	>200
($X10^4$ kPa)	(17.)	(38)	(83)	(>138)
Elongation, %	250-350	200-250	60-70	5-25

Table III

Typical Properties of Flexible and Semi-Flexible RIM Fascia Systems

	Flexible Systems (MC-1070)	(MC-1071)	Semi-Flexible System (MC-1073)
Specific Gravity	1.0	1.0	1.0
Tensile Strength, psi	2400	2700	3600
(kPa)	(16,500)	(18,800)	(24,600)
Elongation, %	250	220	220
Flexural Modulus, psi			
(kPa)			
@ 75°F (24°C)	18,000	26,000	65,000
	(124,000)	(182,000)	(446,000)
@ -20°F (-29°C)	60,000	67,000	140,000
	(413,000)	(460,000)	(965,000)
@ 158°F (70°C)	6,000	11,000	30,000
	(41,000)	(76,000)	(205,000)
Cantilever Heat Sag, Inches (mm)	0.5	0.5	0.3
(1 Hr. at 250°F, 0.150 in. thickness) (118°C, 3.81 mm)	(12.7)	(12.7)	(7.6)
Tear Strength, pli	350	420	550
(N/mm)	(61)	(73)	(96)
Cold Flexibility, D-100 White (-20°F, 0.5 in. mandrel)(-29°C, 12.7mm)	Pass	Pass	Pass

Table IV

Summary Comparison of Front and Rear End Materials of Construction

	Flexible RIM	HPE-RIM	Steel	Aluminum	TPO/EPDM
Weight Consideration*	1.2-1.5	1.0	>2.7	>1.3	1.0
Cost Consideration**	1.0-1.2	1.0	>1.2	>2.3	0.9
Design Consideration	1-Piece Construction	1-Piece Construction	Multiple-Piece Construction	Multiple-Piece Construction	1-Piece Construction
Resistance To Damageability (Minor Impact)	Excellent	Excellent	Poor	Poor	Fair
Appearance	Excellent	Excellent	Excellent	Excellent	Fair
Miscellaneous	Industry Standard	Improved Handling Capability	Corrodes	High Energy Usage To Manufacture	Difficult To Paint, Tendency Toward Molding Distortion

* Relative Weight Comparisons, With HPE-RIM Equal To 1.0

** Relative Costs Based On Raw Material Cost/Lb. Only; With HPE-RIM Equal To 1.0

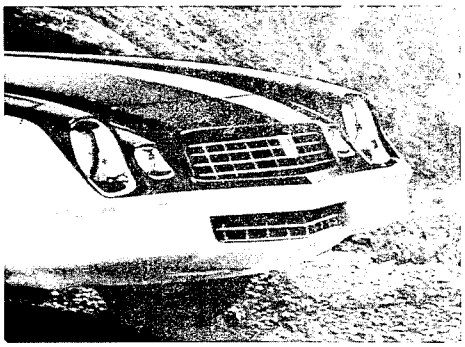

FIGURE 1: Camaro Front Fascia

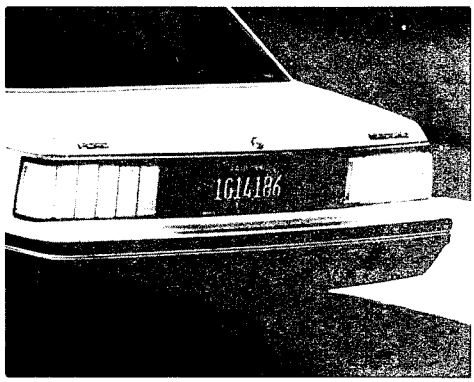

FIGURE 2: Mustang Rear Fascia

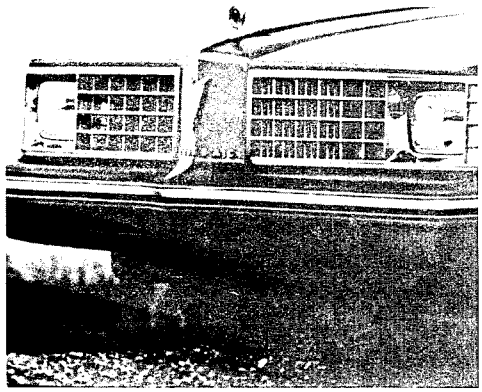

FIGURE 3: LeMans Front Fascia

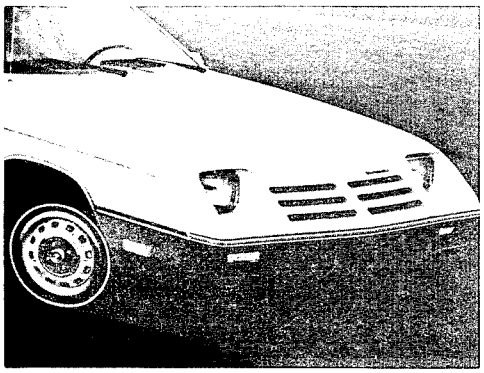

FIGURE 4: Omni 024 Front Fascia

HIGH MODULUS RIM SYSTEMS FOR AUTOMOTIVE BODY PANELS—AN UPDATE

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INTRODUCTION

Federal mileage requirements for automobiles in 1985 have stimulated the use of light weight materials for body components. Among the light weight materials under consideration, reinforced RIM (RRIM) polyurethane is a leading contender and is therefore under current evaluation for several automotive body components including fenders, door panels and rear quarter panels. In response to these new RIM application areas, the polyurethane raw material suppliers have launched intensive development efforts to ensure the automotive industry of the best possible materials to meet the necessary performance criteria. This paper discusses the performance requirements for reinforced urethane body panels, and extrapolates back to the characteristics of the unfilled base urethanes necessary to meet these requirements. The raw material supplier uses characteristics of the unfilled polyurethane as guidelines in formulation work. These guidelines must be well-defined to facilitate the development of even more effective urethanes for exterior automotive body components in the future.

PERFORMANCE REQUIREMENTS OF BODY PANELS

High modulus RIM urethanes are currently used for several automotive body components, including spoilers, air dams, quarter panel and fender extensions and similar "add-on" parts. These high modulus urethanes are in the 50,000 psi to 150,000 psi range of flexural modulus, and are used without filler. Physical property specifications are not as stringent as those for fascia applications. Parts are painted off-line with conventional elastomeric paint systems. Dimensional stability during use is not critical. In general, however, the resulting parts performed very well both from a cosmetic and functional standpoint.

In contrast to these applications, polyurethane body panels are being specified to meet very demanding performance requirements. These include stiffness, dimensional stability during use, resistance to 325°F bake oven temperatures, impact resistance and appearance. Although specifications of each of these requirements are presently incomplete, the general guidelines are being communicated to the raw material supplier. These requirements will now be discussed in detail.

STIFFNESS

A body panel should be stiff enough to resist the force of air currents at test conditons of 55-100 mph. The panel should also be stiff enough to resist excessive deformation when leaned upon by a person of average weight. The panel should "feel" stiff enough to the consumer.

The minimum room temperature flexural modulus is yet to be specified for body panel applications.

DIMENSIONAL STABILITY IN USE

The dimensional stability of a reinforced polyurethane body panel in use must be compatible with that of the sheet metal. Expansion and contraction of the body panel must be minimized to prevent interference with opening and closing of doors, and to ensure a consistently good appearance. Coefficient of linear thermal expansion (CLTE) values of urethanes filled with 20-30% by weight of milled glass fibers are in the 15-25 x 10^{-6}/°F range measured parallel to the flow direction. This means that a part five feet in length will expand or contract approximately .1 inches for a 100°F temperature change. Feedback to the raw material supplier thus far suggests that this amount of dimensional change is tolerable, at least for a polyurethane fender adjacent to a metal door. Further experimentation with combinations of fillers is ongoing to investigate more effective ways of reducing CLTE.

Resistance to change in shape during hot/cold cycles in the -40°F to 180°F range is the other important aspect of dimensional stability of the part in use. As of this writing, desert testing on prototype fenders is in progress. No lab test effectively simulates performance of the part when mounted on the car.

From tests conducted so far, it appears that reinforced urethanes have sufficient dimensional stability for body panel applications.

RESISTANCE TO DROOP DURING PAINT BAKING

As the use of reinforced RIM body panels expands to large volumes, there will be strong economic incentives for on-line painting with the rest of the car. This will likely necessitate bake temperatures as high as 325°F.

If painted off-line, the requirement to have a common body paint will still necessitate the high bake temperatures. In this case, the material must be such that the part holds its shape without elaborate support fixtures.

Preliminary tests indicate that laboratory sag values obtained for RRIM materials at 325°F for one half-hour are higher than the amount of distortion observed on prototype RRIM parts mounted on the vehicle. Resistance to distortion of actual parts when exposure times extend beyond one half-hour is yet to be determined.

Sag values as low as .05 inches for one half-hour at 325°F have been measured for urethanes filled with 20-30% by weight of glass fibers. Recalling that the fascia sag specification is .5 inches for one hour at 250°F, it appears that existing RRIM composites will remain distortion-free during oven baking for one half-hour at 325°F. Only further testing of parts mounted on test vehicles will provide the answer.

Sag measurements for one hour at 250°F on reinforced RIM parts are negligible (less than .05 inches). Therefore, it is likely that only minor fixturing will be required for traditional elastomeric paint systems.

IMPACT RESISTANCE

Unlike fascia applications, the use of polyurethanes for body panels is not mandated by federal damageability restrictions. However, consumer acceptance of vehicles with the first polyurethane body panels will be greatly affected by the ability of the body panels to withstand impact. The mode of failure of the part is also important, since it will determine the ease of repair.

Several types of impact resistance are desirable for polyurethane body panels. These include resistance to minor parking lot collisions, resistance to door opening dents and resistance to shatter at average impact speeds of 30 mph.

Pendulum impact testing of prototype parts is beginning. Without a government standard, an important observation is mode of failure as a function of test temperature, velocity and filler type and loading level.

To compare polyurethane candidates for these applications, several lab test methods are used, both for filled and unfilled samples.

These test methods include notched izod, modified Gardner, Dynatup, and Rheometrics. Of these tests, the latter two yield more quantitative information, including force vs. deflection curves and corresponding energy values.

Materials are also compared indirectly by using the ultimate elongation from a tensile test. The room temperature elongation values seem to correlate with room temperature impact strength and tendency toward non-brittle failure. However, extensive testing of fascia elastomers shows that room temperature elongation does not correlate with low temperature impact. Formulation chemistry to achieve a low glass transiton temperature is more essential for low temperature impact.

With no impact standard, the raw materials supplier screens candidates with all of the above tests, and submits the best candidates for prototyping programs. Impact testing of the prototype parts will provide valuable information.

APPEARANCE

The part must match the exterior sheet metal when painted. Trials with RRIM have shown that parts can be demolded and coated with traditional elastomeric paints without intermediate sanding and filling steps. A high gloss, non-porous finish results. As better quality prototype and production tools are built, the effects of level and type of fillers can be better specified. Work is in progress to determine compatibility of RRIM urethanes with common body paints.

REVIEW OF TRENDS OF IMPORTANT PHYSICAL PROPERTIES AS A FUNCTION OF MILLED GLASS FIBER CONTENT

To better define the characteristics of the base polyurethane system, it is helpful to review the general physical property trends as a function of filler content (references 1-7). From the polyurethane formulation chemist's standpoint, these base unfilled polyurethanes characteristics are the most important criteria in his development work.

Since most of the available data on RRIM urethanes involves 1/16" milled glass fibers, trends will be reviewed with this filler. It is understood that future technology improvements will likely involve combinations of other fillers as well.

Dimensional stability is the primary reason for using fillers in polyurethane exterior automotive body panels. Therefore, the effect of milled glass fibers on the value of the CLTE should be discussed first. In general, the value of CLTE decreases with milled glass fiber content. To what extent does this reduction of CLTE depend upon the base polyurethane system?

Figure 1 shows values of CLTE as a function of 1/16" milled glass fibers for several base urethane systems. All values are measured parallel to the flow direction corresponding to the direction of orientation of the glass fibers. The flexural modulus of the base polyurethane system ranges from 25,000 psi. to 150,000 psi. These data result from reinforced RIM evaluations at several locations and on several different types of RRIM machinery.

These data show that the ultimate CLTE values for all of the base polyurethane systems lie in the 15-25 x 10^{-6}/°F range at loadings of 20-30% by weight milled glass fibers. This ultimate value is independent of the value of the base polyurethane. Values of CLTE in this range are acceptable for fender applications through testing of prototype parts for dimensional stability. Therefore, sufficient dimensional stability can be achieved at 20-30% milled glass loadings regardless of the initial value of CLTE or the flexural modulus of the base polyurethane system. This means that flexural modulus of the base polyurethane system should not be a consideration in specifying materials to meet dimensional stability requirements. Making the base system stiffer does not make the filled system more dimensionally stable in the -40° to 180°F range. The filler appears to dominate the value of CLTE in the composite, at 20-30% loading levels of glass.

Flexural modulus, sag, and impact resistance of the composites do depend on the characteristics of the base polyurethane system.

Flexural modulus measured parallel to the flow direction at 25% milled glass fibers is two to three times the value of the base urethane.

Sag measured for one half-hour at 325°F for 25% glass filled urethanes is reduced to approximately one-third the value of the base system.

Impact resistance of filled urethanes as measured by notched izod, modified Gardner, Dynatup and Rheometrics tests is significantly lower than for the unfilled systems. Room temperature notched izod values for 25% filled composites are approximately one-fourth the value of the base polyurethane. More extensive full scale testing of glass filled fenders is beginning, but the direction is clear. To achieve the best impact performance of composites, the impact characteristics of the base polyurethane system are controlling.

These trends in physical properties as a function of milled glass fiber content suggest the following:

1. Sufficient dimensional stability for exterior automotive body components will require at least 20% by weight of milled glass fibers according to prototype testing. Dimensional stability of the reinforced part as measured by the CLTE is independent of flexural modulus of the base polyurethane in the 50,000-150,000 psi. range.

2. Flexural modulus, sag and impact resistance of the 25% glass filled urethanes are highly dependent upon the corresponding properties for the base unfilled urethane. Therefore, the best perfroming composite with respect to these criteria will depend upon the optimum combination of these properties for the base unfilled urethane.

To achieve this optimum combination of properties, the constraints must be well understood. For example, high flexural modulus and high impact resistance are generally mutually exclusive. From an impact standpoint, it makes sense to start with a more flexible base urethane, provided that the sag value is tolerable. How much stiffness is required? For better insight into these interactions, sag and impact resistance will be discussed in more detail.

SAG AT 325°F

To ensure minimal distortion of the part during on-line or off-line painting, the natural tendency is to choose the stiffest material available. It is assumed that the stiffer the material, the better its resistance to droop. However, this is a misconception with regard to RIM urethanes which can lead to over-specification of the minimum stiffness requirement for the exterior body panels.

Figure 2 illustrates that sag at 325°F bears no relationship to room temperature flexural modulus of the unfilled polyurethane system, for the flexural modulus range of 50,000 psi. to 175,000 psi. These data represent a wide variety of system chemistries. The graph has been sub-divided into ranges of flexural modulus of 25,000 psi. Within each range of flexural modulus, sag values are scattered between 0 and 2.5 inches. The overall randomness of the data is further illustrated in Figure 3, which shows that the sag values for the 56 data points are distributed about a mid-range value of 1 inch.

When sag at 325°F is plotted vs. flexural modulus at 325°F as in Figure 4, a more monotonic relationship is obtained. Samples from Figure 2 were chosen randomly for flexural modulus measurement at 325°F, attempting to select samples to span sag values over the range from 0 to 2.5 inches. As might be expected, a high flexural modulus at 325°F is much more important for droop resistance than a high flexural modulus at room temperature. Although not shown here, a similar relationship for sag at 325°F vs. Clashberg modulus at 325°F was obtained.

Therefore, choice of a material to resist droop at oven temperatures at 325°F should not be made on the basis of room temperature flexural modulus. The performance at 325°F is related to a material's ability to retain its modulus over a broad temperature range. This temperature insensitivity of RIM urethanes is highly dependent upon system chemistry.

The dependence of sag behavior on system chemistry is further shown in Table I. Included here are commercial and experimental high modulus systems ranging in flexural modulus from 50,000 psi. to 125,000 psi. Sag data is shown for unfilled and filled materials, when available. The most interesting comparison in Table I is between Bayflex 110-50 and Bayflex 130-125 which represent the extremes in flexural modulus shown in this table. B-110-50 sags only one-third the value of B-130-125, which has nearly triple the room temperature flexural modulus. The key here is the relatively temperature insensitive response characteristic of B-110 chemistry compared with conventional formulation technology.

Another interesting point is the large decrease in sag accomplished through isocyanate change for the experimental B-110 high modulus system. Mondur E-486 with functionality of about 2.4 yields lower sag than Mondur PF (functionality of about 2.0). Based upon our previous data, the addition of 25% milled glass fiber to this system with E-486 should reduce the sag to less than .1 inches. It is also worth noting that the product with E-486 has a lower room temperature flexural modulus than the product with PF.

IMPACT RESISTANCE

Although an impact standard is yet to be established for automotive body panels, materials have been selected for fender prototyping programs on the basis of preliminary Rheometrics impact testing of filled samples, and on the basis of room temperature elongation values of the unfilled polyurethanes.

Table II shows notched izod and Rheometrics test data for unfilled high modulus systmes ranging from 50,000 psi. to 125,000 psi. Also shown are corresponding elongation values.

First, it is interesting to compare the high modulus systems in the 100,000 psi. modulus range. The sequential development of B-130-125, B-110-105, and the B-110 experimental high modulus systems has produced progressively improved ductility and impact resistance. The Rheometrics data reflects the improved ductility, by measurement of the deflection or penetration distance before

break of the dart into the sample. Also, the 200% elongation value of the most recently developed experimental high modulus B-110 type is as high as some of the original fascia systems with only 25,000 psi. flexural modulus.

Another important comparison in Table II is between B-110-50 and the three higher modulus systems in 100,000 psi. range. The elongation and Rheometrics test data shows that B-110-50 has a much higher ductility than any of the 100,000 psi materials at room temperature. In fact, the ductility of B-110-50 at -20°F exceeds the room temperature value of both B-130-125 and B-110-105. Also, B-110-50 is capable of passing a -20°F fascia bumperette impact test with Durethane 300 white topcoat. This performance cannot be matched by any existing commercial system in the 100,000 psi. range. Therefore, from an impact standpoint, it makes sense to start with a 50,000 psi. material as a base polyurethane. With 25% milled glass fiber, this will represent an impact resistant composite, with a flexural modulus of 150,000 psi.

CONCLUSION

The data presented in this paper show that the performance of filled urethane body panels is a strong function of the characteristics of the base urethane. The selection of the optimum base urethane will require further testing of prototype parts. Sag and impact resistance are the most important characteristics which have yet to be specified. Sag resistance of the final composite is not dependent upon the flexural modulus of the base urethane, but is highly dependent upon formulation chemistry.

Conversely, impact resistance is dependent upon the flexural modulus of the base urethane. Base urethanes in the 50,000 range have significantly better impact resistance than urethanes in the 100,000-150,000 psi. range. For these reasons base urethanes in both the 50,000 psi. range and the 100,000 psi. range should be included in the prototyping programs. This will allow the materials engineer to select a material with the best combination of sag and impact resistance for body panels.

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   MacGregor, C. J., and R. A. Parker; SAE Congress and Exposition; 7912034, Detroit, MI, February 26 to March 1, 1979.
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   MacGregor and Parker; op. cit.
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   MacGregor and Parker; op. cit.

TABLE I

SAG AT 325°F 1/2 HOUR

HIGH MODULUS SYSTEMS

	Bayflex 110-50	Bayflex 130-125	Bayflex 110-105	Experimental B-110 with Mondur PF	B-110 with E-486
Sag (inches) ½ hour @ 325°F					
unfilled	.40	>2.00	.65	.80	.25
25% milled glass fibers	.12		.20	.25	
Flexural Modulus @ 77°F (psi)	50,000	125,000	105,000	100,000	85,000

TABLE II

Impact Test Comparison

50,000 psi vs. 100,000 psi Type Materials

	Bayflex 110-50	Bayflex 130-125	Bayflex 110-105	Bayflex 110 Experimental High Modulus
Room Temperature Flexural Modulus (psi.)	50,000	125,000	105,000	100,000
% Elongation	300%	75%	125%	200%
Notched Izod Impact Strength @ room temp. ft. lb./in.		2.5	5.0	10.0
Rheometrics Impact Data 5 mph. D (mils)* at 77°F	1027	488	695	857
at -20°F	706	200	417	

*D- deflection distance (penetration of probe into sample)

FIGURE 1 CLTE vs Wt % Glass Fibers
Several Polyurethane Substrates

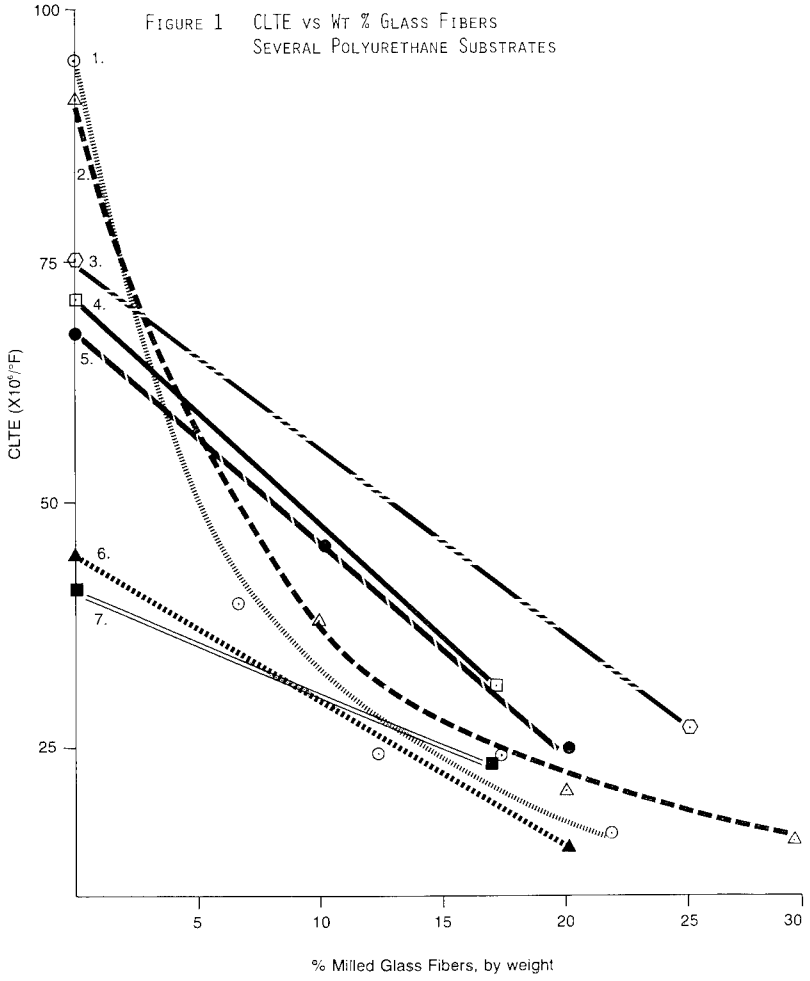


FIGURE 2 Sag at 325°F vs Room Temperature
Flexural Modulus

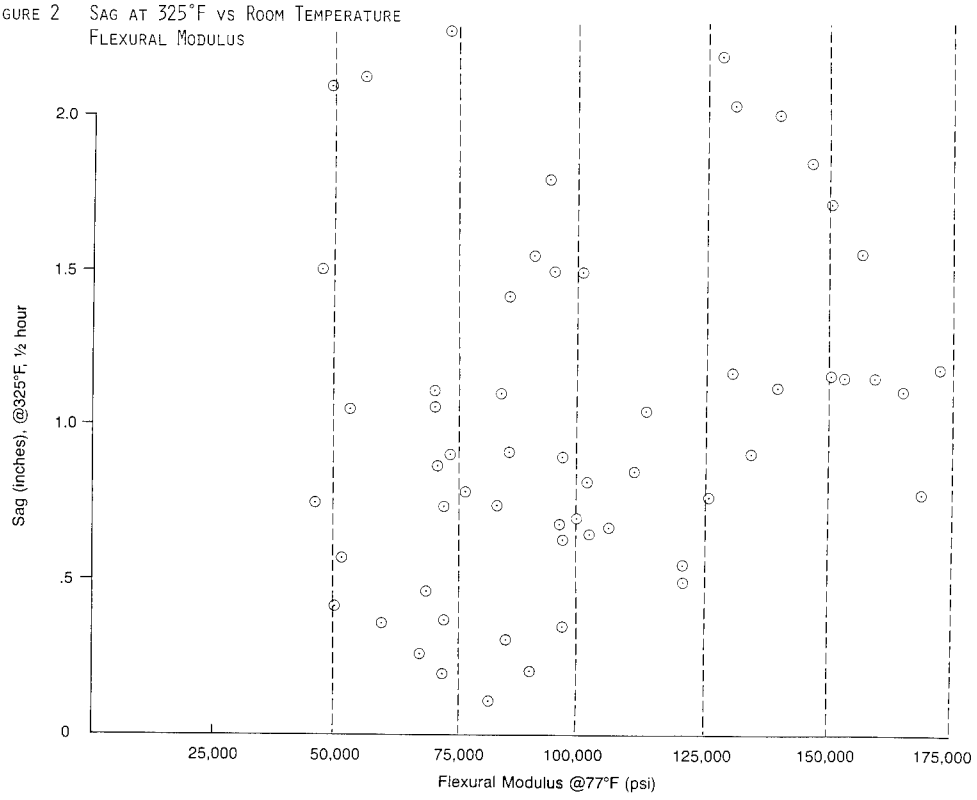


FIGURE 3 FREQUENCY DISTRIBUTION; SAG DATA FROM FIGURE 2

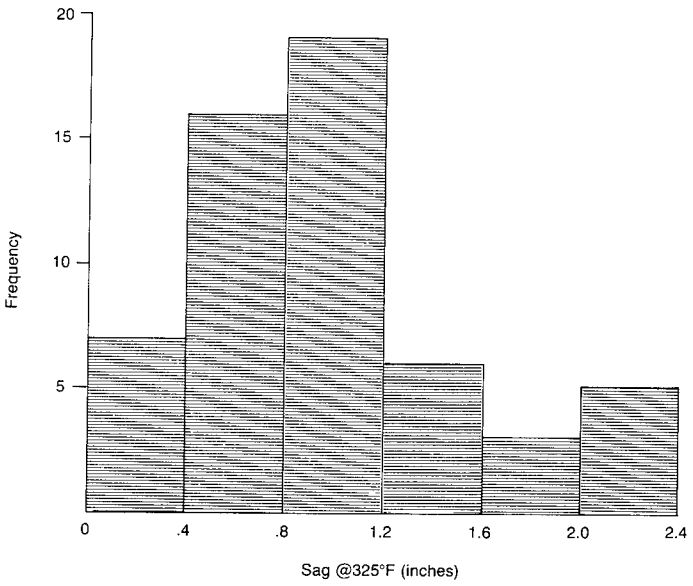
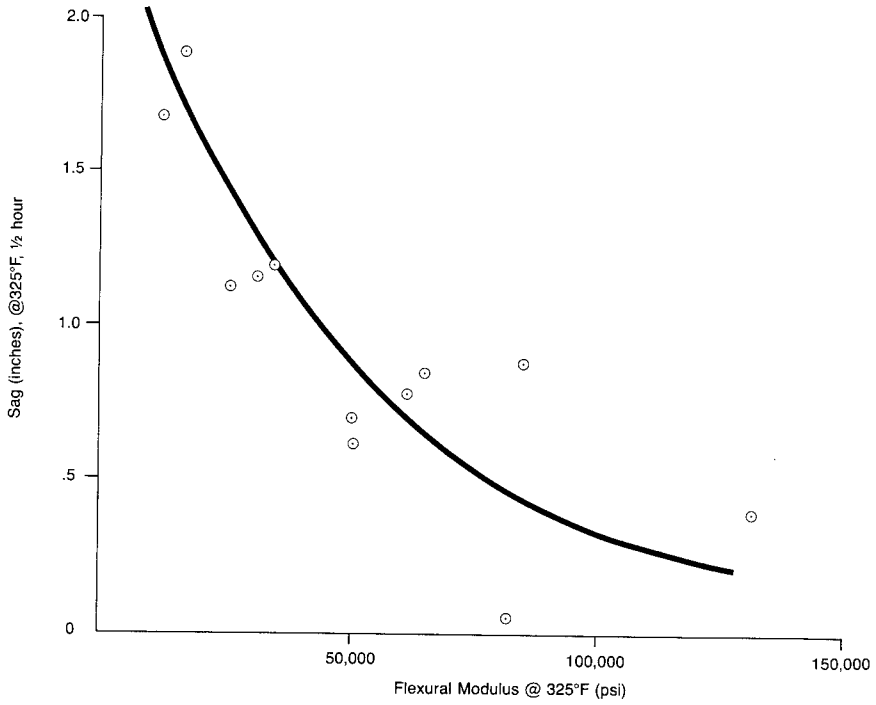


FIGURE 4 SAG AT 325°F VS FLEXURAL MODULUS AT 325°F



RIM ELASTOMERS HAVING SUPERIOR HIGH TEMPERATURE PERFORMANCE

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INTRODUCTION

The automobile industry has proven that the production of large, thin-walled polyurethane parts by the RIM (Reaction Injection Molding) process is commercially viable. An example of this fact is the current successful production of automobile fascia by the RIM process. New RIM applications which represent an even larger potential market than fascia are exterior body panels such as fenders, door panels, deck lids, etc. Major automobile companies and their suppliers are currently involved in extensive research to develop RIM materials suitable for these new applications.

Some of the properties which a material must possess to be suitable for exterior body panel applications, especially fenders, are[1,2]:

1) Coefficient of thermal expansion near that of steel.

2) A flexural modulus high enough so that the part is self supporting.

3) Good dimensional stability at elevated temperatures.

4) Good impact resistance over a wide temperature range.

The first two requirements can largely be met by including fibrous fillers in the RIM formulation. These additives lower the coefficient of thermal expansion and stiffen the part. Fibrous fillers also aid in increasing the high temperature dimensional stability of a part.

From a commercial standpoint, it is highly desirable that the material not distort at the paint bake temperatures used on steel parts. Changes in the assembly procedure are minimized when a part can be attached onto an automobile and painted in the same way as the steel part it is replacing. Otherwise, additional expense is incurred.

Under prior technology, RIM urethane formulations developed for exterior body panels did not meet the temperature requirements for on-line painting. We have recently made a discovery which dramatically improves the high temperature dimensional stability of RIM polyurethanes. We found that elastomers made from certain RIM polyurethane formulations respond to high temperature annealing in a manner similar to thermoplastic block copolymer polyurethanes. Differential Scanning Calorimetry (DSC) studies by Cooper[3,4,5] and Jacques[6] have shown that high temperature annealing causes complex ordering processes to occur in thermoplastic polyurethanes. Studies on our RIM polyurethane materials indicate that high temperature annealing causes similar ordering processes. We then discovered that these changes lead to better heat stability and other temperature-related properties.

There are probably three major types of ordering involved: 1) phase separation, i.e., a more complete separation of the hard segment phase (isocyanate-chain extender reaction product) and the soft segment phase (polyether polyol); 2) molecular alignment within the hard segment phase; and 3) crystallization. No doubt, high temperature annealing also results in more complete reaction and relaxes molded-in stresses.

This paper is limited to unfilled RIM polyurethanes; however, our work with the filled versions of these materials indicates that they follow the same trends.

FORMULATIONS

RIM polyurethane formulations are generally based on three major components: a low molecular weight diol chain extender, a liquid MDI or a polymeric isocyanate, and a high molecular weight polyol. In this study we will attempt to demonstrate the important role that chain extenders and isocyanates play in the ultimate properties of RIM polyurethanes. In addition, the importance of proper annealing will be demonstrated.

From our work we have chosen the following four basic formulations to demonstrate the effects mentioned above. These formulations yield flexural modulus values of about 140,000 psi at room temperature. In all cases a high molecular weight, high primary hydroxyl polyether polyol is employed.

Formula A: Polyol/ethylene glycol/Isonate 143L* liquid MDI
Formula B: Polyol/ethylene glycol/Isonate 191* MDI-enriched polymeric isocyanate
Formula C: Polyol/ethylene glycol/PAPI 901* polymeric isocyanate
Formula D: Polyol/1,4-butanediol/Isonate 143L liquid MDI

SAMPLE PREPARATION

The data presented in this paper were obtained from plaques molded from the above formulations on our Cincinnati Milacron LRM-II RIM machine. Fifteen minutes after release from the mold, the plaques were annealed in forced draft ovens for thirty minutes (unless otherwise noted) at temperatures ranging from 250°F to 350°F. Appropriate test samples were then cut from the plaques and allowed to equilibrate for one week at standard ASTM conditions before testing.

PROPERTIES

High Temperature Performance

One method of rating the relative thermal stability of materials is the heat sag test. In this test, one end of a sample of given dimensions is clamped onto a fixture. A specified length of the sample extends unsupported by the fixture in the horizontal plane. The vertical distance from the unsupported end of the sample to the base of the test fixture is measured before and after subjecting the sample to a specified temperature for a given time. Measurements on a one-inch wide,

*A product of the Upjohn Chemical Company

one-eighth inch thick sample having a six-inch unsupported overhang and heated at 325°F for 30 minutes gave consistent and discriminating results.

In Figure 1, the six-inch heat sags of Formulas A, B, C and D are given as a function of annealing temperature. The heat sag drops dramatically as the annealing temperature increases to about 300°F. Thereafter, the heat sag remains relatively constant. Comparing Formulas A, B and C, it is evident that polymeric isocyanate adversely affects the minimum obtainable heat sag. A tentative explanation is that the higher degree of cross-linking by the polymeric isocyanate reduces inter-phase and intra-phase polymer mobility, thereby decreasing the potential for morphological changes and ordering processes to occur.

The chain extender used also dramatically affects heat sag. This is shown by comparing Formula A which uses ethylene glycol as the chain extender with Formula D which uses 1,4-butanediol. DSC studies show that these two formulations differ in their thermal behavior. We think that these differences correlate with the softening points of the two hard segment phases. For the 1,4-butanediol/liquid MDI reaction product (Formula D), these softening points occur at lower temperatures than for the corresponding ethylene glycol/liquid MDI product (Formula A).

In Figure 2, the effect of annealing time on heat sag is presented at two different temperatures, 310°F and 350°F. As the annealing temperature increases, less time is required to achieve optimum heat sag. Annealing at 350°F for 15 minutes will produce about the same result as annealing for 40 minutes at 310°F. In addition, the higher annealing temperature results in lower heat sags.

Our work indicates that samples should be annealed within a few hours after preparation. If samples are left unannealed for greater periods of time, gross distortion can occur when annealing at elevated temperatures. We have determined that this is caused by absorption of water with consequent expansion on heating. This phenomenon does not appear to occur if a properly annealed sample is later subjected to high temperatures.

In Figure 3, the flexural modulus values measured at 325°F are plotted versus annealing temperature. The 325°F flexural modulus appears to depend on both polymer composition and annealing temperature. The introduction of polymeric isocyanate (Formulas A to B to C) generally lowers the 325°F flexural modulus. Polymeric isocyanate also inhibits the flexural modulus enhancement that higher annealing temperatures impart to Formula A. These factors contribute to the superior heat sag observed for Formula A.

In Figure 4, the six-inch heat sag at 325°F is plotted versus isocyanate index. All samples were previously annealed for 30 minutes at 325°F. These data show that the ethylene glycol/liquid MDI system (Formula A) is rather insensitive to isocyanate index. When 1,4-butanediol is substituted for ethylene glycol (Formula D) the sensitivity of heat sag to isocyanate index increases, especially at lower indices. In contrast, the heat sag values for Formulas B and C, which contain polymeric isocyanate, are very sensitive to isocyanate index.

Impact Resistance

A goal of the automobile industry is to produce the so-called "friendly fender," that is, an exterior body panel which shrugs off minor impacts. Although no absolute correlation can be drawn between simple laboratory impact tests and real world impact failure, the Izod impact is a generally accepted screening test for rating the impact resistance of materials.

In Figure 5, the effect of annealing temperature on Izod impact is presented for Formulas A, B, C and D. The liquid MDI isocyanate (Formulas A and D) imparts significantly better impact resistance than does the polymeric isocyanate (Formulas B and C). Further, although the ethylene glycol (Formula A) and 1,4-butanediol (Formula D) formulations have similar Izod impact when annealed at 250°F, it is clear that the ethylene glycol formulation is superior at the higher annealing temperatures. DSC studies indicate that the 1,4-butanediol system has a rather crystalline hard segment phase when it is annealed at higher temperatures (340°F). This may account for the loss in impact resistance observed for this formulation.

Figure 6 shows the effect of isocyanate index on Izod impact. The results indicate that the Izod impact resistance of systems based on liquid MDI (Formulas A and D) is highly dependent on isocyanate index; Izod impact decreases as the isocyanate index increases. On the other hand, the Izod impact resistance of compositions containing polymeric isocyanate (Formulas B and C) shows only a mild dependence on isocyanate index.

Other Properties

We studied the effects of mold temperature, release time, injection rate, and impingement pressure on overall properties. We found that lower mold temperatures, longer release times, higher injection rates and higher impingement pressures result in slightly better properties.

In Table 1 we have summarized the properties for one of our candidate "friendly fender" formulations. Clearly, strength properties are only nominally affected by higher annealing temperature whereas thermal properties are dramatically improved.

SUMMARY:

Our search for RIM polyurethanes with high impact resistance and good dimensional stability at high temperatures has led us to certain conclusions about RIM polyurethanes:

1) RIM polyurethanes made from high molecular weight polyols, chain extenders, and isocyanates are similar in behavior and structure to commercial thermoplastic polyurethane block copolymers.

2) High temperature annealing improves the high temperature properties of most RIM polyurethanes.

3) Changes in the ordering of the hard segment phase, phase separation, and polymer morphology probably account for the observed changes in temperature-related properties.

4) Formulations based on high molecular weight polyols, ethylene glycol, and liquid MDI exhibit the best overall properties of the systems which we have studied to date.

We anticipate that more work along these lines will lead us to further improvement in the heat properties of RIM polyurethane elastomers. This work is currently under way at Texaco with increased heat stability and impact resistance as our primary goals.

The authors wish to express appreciation for the assistance and cooperation of G. P. Speranza and R. F. Lloyd in the preparation and review of this manuscript, and to Jefferson Chemical Company and Texaco Incorporated for supporting this project.

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BIOGRAPHY

D. Marvin Rice

Marvin holds a M.S. in Chemistry from Ohio State University. He has been at the Austin Laboratories of Jefferson Chemical Company, Inc., a subsidiary of Texaco Inc., for the past 19 years. Marvin has worked in different polyurethane areas over these years. He has been involved in the product development of RIM and RRIM polyurethane elastomers for the past five years.

BIOGRAPHY

Richard J. G. Dominguez

Richard holds a Ph.D in Chemistry from Texas A&M University. He worked for Shell at the Westhollow Research Center for two years in the elastomers department. He then came to work for Jefferson Chemical Company, Inc., a subsidiary of Texaco Inc., at the Austin Research Laboratories. Richard is involved in research and development of RIM and RRIM polyurethane elastomers.

Table 1

Physical Properties of a High-Temperature-High-Impact RIM Polyurethane

Properties			
Annealed for 30 minutes at	250°F	300°F	325°F
Tensile, psi (ASTM D-412)	4710	4740	4660
Elongation, % (ASTM D-412)	190	200	175
Tear, pli (ASTM D-624)	580	575	545
Flexural modulus, x 1000 psi (ASTM D-790)			
75°F	89.8	89.5	89.2
-20°F	195	176	168
158°F	55.1	60.6	62.5
325°F	19.1	20.5	24.1
Flexural modulus ratio, -20°F/158°F	3.5	2.9	2.7
Heat sag, 30 min/325°F, 6" overhang	3.5	1.0	0.6
Heat sag, 30 min/250°F, 4" overhang	0.18	0.07	0.06
Izod impact, ft lb/in of notch (ASTM D-256)	11.0	11.0	10.8

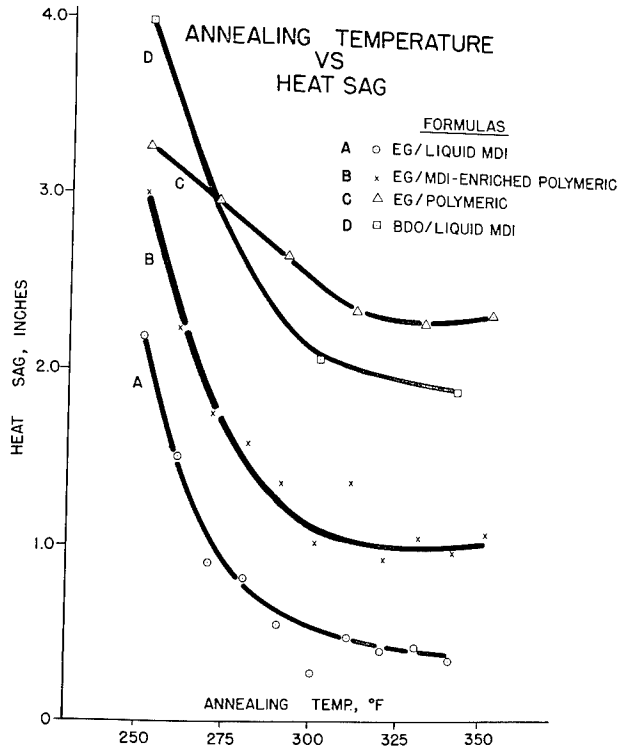
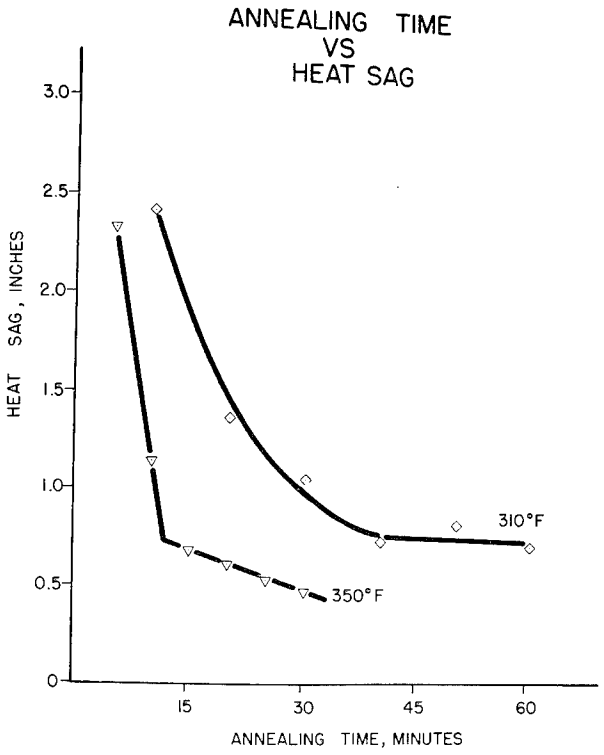


FIGURE 1



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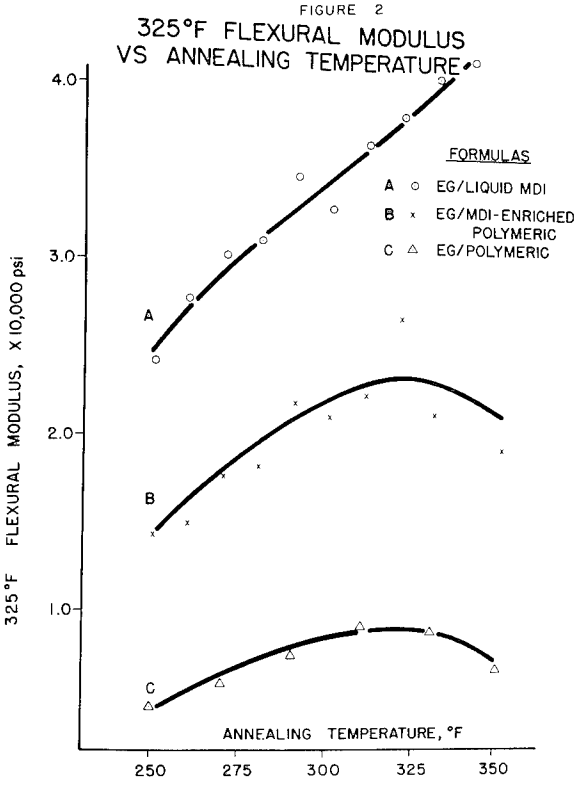

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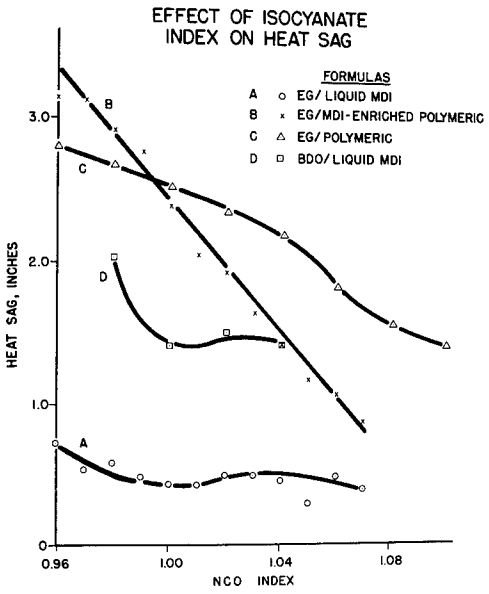

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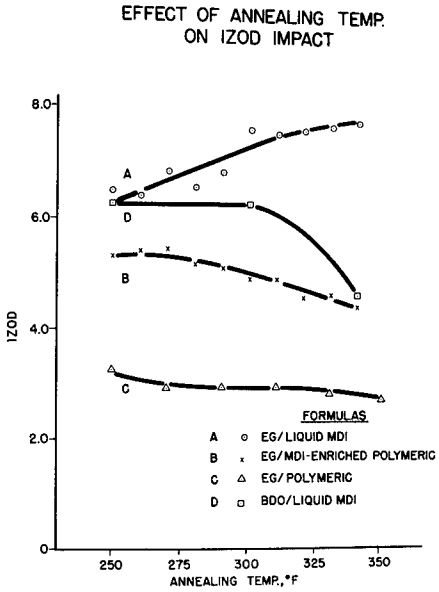
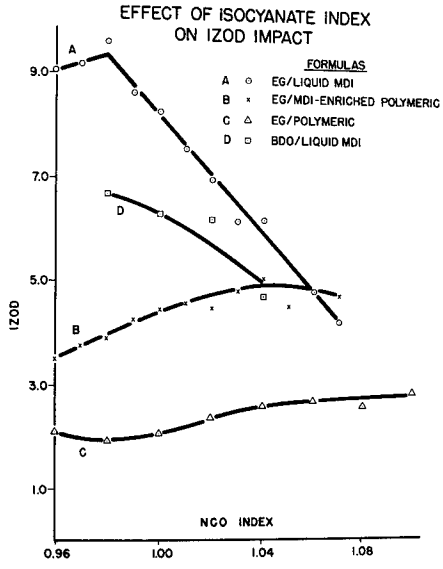


FIGURE 5



SELECTION OF REINFORCEMENTS FOR THE REACTION INJECTION MOLDING PROCESS

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INTRODUCTION

In the automotive industry, Reaction Injection Molded (RIM) urethanes are used primarily for soft bumper fascias. The advantages of these materials include good surface finish, paintability, and damage resistance, and a weight savings compared to conventional materials. The RIM process uses low molding pressures, has relatively low capital equipment costs, and provides flexibility of part design and parts consolidation.

The major limitations of RIM urethanes are high coefficient of thermal expansion, poor dimensional stability, and low stiffness. These limitations prevent the use of urethanes for other applications, such as fenders or door panels. The addition of a reinforcement improves these properties while maintaining the processability of the RIM material.

The use of reinforcements makes RIM urethanes viable candidates for these new applications. However, other factors, such as the structural and barrier impact requirements of a particular body panel, must be taken into account before that part can be manufactured from reinforced RIM urethane.

A development program involving the Reinforced Reaction Injection Molding (RRIM) process and materials is in progress at General Motors Manufacturing Development. The reinforced RIM material investigation involves both urethanes and reinforcements. A small scale mix-metering machine was used to mold test plaques with combinations of high modulus RIM urethanes and reinforcements. Plaques were molded with several different levels of each type and size of each reinforcement. Physical properties of all test plaques were measured.

The selection of suitable reinforcements for RIM urethanes requires the investigation of certain criteria. The purpose of this paper is to discuss these criteria and how they apply to several commercially available reinforcement materials. The paper is divided into the following sections:

RIM Process and Materials
Potential Reinforcements
Criteria for Evaluating Reinforcements
Conclusions

RIM PROCESS AND MATERIALS

The Reaction Injection Molding process involves the accurate metering of two fast reacting liquids, polyol and isocyanate, and mixing these liquids using high pressure impingement mixing. This mixture is injected into a mold and allowed to cure.

A schematic diagram of the RIM process is shown in figure 1.

The liquid chemicals are stored in separate tanks at a controlled temperature. Each chemical is protected from contamination by a dry air or nitrogen blanket. Each liquid chemical flows from the tank to a feed pump, which transfers it to the high pressure metering unit. This unit, which consists of either positive displacement pumps or metering cylinders, delivers the chemicals at a predetermined ratio and output to a high pressure impingement mixhead. At the mixhead, each chemical is forced through a small opening at high pressure (typically 1000 to 3000 PSI) into the mix chamber, where it impinges against the other chemical to ensure mixing. This mixed material flows through a static mixer and runner system into the mold.

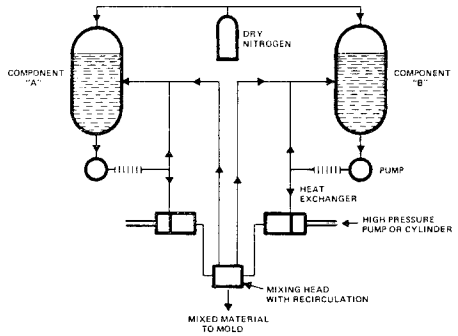

Figure 1 - Schematic RIM Process

Reinforcements can be added to one or both of the liquid components. The reinforcement material is pre-mixed with chemicals, and processed in a manner similar to that used for unfilled chemicals. For the molding of the reinforced RIM test plaques discussed in this paper, reinforcements were added to both liquid components to permit high loadings.

RIM urethanes are produced from two reactive liquid components, polyol and isocyanate. The polyol component consists of a polyether polyol, a chain extender, and one or more catalysts. A blowing agent is usually included in one of the two components.

RIM urethane formulations are available in a range of physical properties. This range is from low flexural modulus (<30,000) PSI), high elongation (>200%) materials, such as those used for soft bumper fascias, to high flexural modulus (up to 400,000 PSI), low elongation (<20%) materials. Generally, the higher the flexural modulus, the lower the elongation of the RIM urethane.

Table I shows the typical physical property range for the RIM urethanes being considered for fender applications. The values shown are for the unfilled materials.

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Table I - Typical Physical Properties (Unfilled) of RIM Urethane Candidates for Fender Applications

Flexural Modulus (psi) @ 72°F	90,000 to 130,000
Tensile Strength (psi)	4,000 to 5,000
Elongation (percent)	100 to 200
Heat Sag (inches, 1 hr. @ 250°F)	0.1 to 0.5
Coefficient of Thermal Expansion (in./in. x 10^{-6}/°F)	60 to 75

Table II shows the physical properties of a particular high modulus RIM urethane with a flexural modulus of 100,000 PSI.

Table II - Physical Properties (Unfilled) - 100,000 PSI Flexural Modulus RIM Urethane

Flexural Modulus (psi) @ 72°F	100,000
Tensile Strength (psi)	4,000
Elongation (percent)	170
Heat Sag (inches, 1 hr. @ 250°F)	0.5
Coefficient of Thermal Expansion (in./in. x 10^{-6}/°F)	72

The comparison of the reinforcements discussed in this paper is based primarily on test plaques molded with this RIM urethane.

POTENTIAL REINFORCEMENTS

There are numerous types of commercially available reinforcements which may be suitable for the RIM process. The scope of this paper is centered primarily on two reinforcements: milled glass fibers and wollastonite. A more limited evaluation is made of two other reinforcements, chopped glass fibers and carbon fibers.

Milled glass fibers are individual glass filaments, approximately 0.5 mils in diameter, available in several lengths (typically 1/32", 1/16", 1/8" and 1/4") which indicates the screen size through which the glass filaments are passed during a hammer-milling process. Milled glass fibers have a wide distribution of filament lengths, from fine particles up to the screen size. A chemical sizing is applied to the fibers prior to the hammer milling process. The type of sizing used on a fiber is chosen dependent upon the polymer to which the fiber is to be added. Several glass manufacturers have milled glass fibers with urethane compatible sizings. The advantages of this chemical sizing are:

1) to ensure chemical compatibility between the fiber surface and the urethane; and 2) to minimize the viscosity build-up of the fiber-filled chemicals prior to processing.

The average aspect ratio for one type of milled glass fiber ranges from 9 to 1 for the 1/32" length to 26 to 1 for the 1/4" length. The most common length used to date for reinforced RIM development is 1/16", which has an aspect ratio of 14 to 1.

Wollastonite is a naturally occurring fiber-like mineral, which is milled to a particular average length. The particular grade of wollastonite used in this evaluation had an average diameter of 0.4 mils, an aspect ratio of 15 to 1, and was treated with a urethane compatible sizing.

CRITERIA FOR EVALUATING REINFORCEMENTS

The reinforcements being considered for the RIM process were evaluated using the following criteria:

- Physical Property Enhancement vs. Loading
- Orientation of Fibers
- Processability: Viscosity Build-up vs. Loading
- Paintability
- Toxicological Effects
- Cost

Each criterion is discussed separately.

Physical Property Enhancement vs. Loading

The purposes for adding reinforcements to a high modulus RIM urethane are:

- reduce coefficient of thermal expansion (C.T.E.)
- increase flexural modulus (stiffness)
- increase temperature stability (reduce heat sag)
- maintain damage resistance (impact strength)

Other physical properties, such as tensile strength, elongation, and part shrinkage, are also affected by the addition of reinforcements.

Coefficient of Thermal Expansion

Figure 2 illustrates the reduction in the coefficient of thermal expansion (C.T.E.) of a 100,000 PSI flexural modulus RIM urethane, caused by the addition of increasing loadings of 1/4" and 1/16" milled glass fibers and wollastonite.

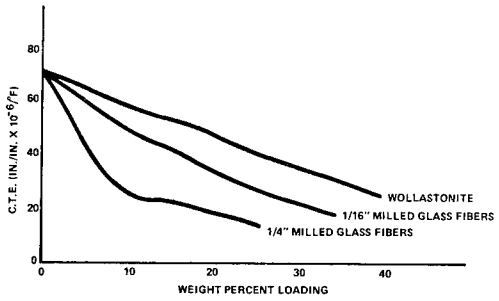

Figure 2 - Coefficient of Thermal Expansion - Reinforced RIM Urethane (measured parallel to flow)

The 1/4" milled glass fibers were more effective at reducing C.T.E. than the 1/16" milled glass fibers at comparable loadings. Wollastonite was less effective than either 1/4" or 1/16" milled glass fibers at reducing C.T.E. Wollastonite has a similar aspect ratio to 1/16" milled glass fibers, but a shorter average length. It appears that increased fiber length provides greater C.T.E. reduction at each loading.

Flexural Modulus

Figure 3 shows the relationship between the flexural modulus of a high modulus RIM urethane and increasing loadings of 1/4" and 1/16" milled glass fibers and wollastonite.

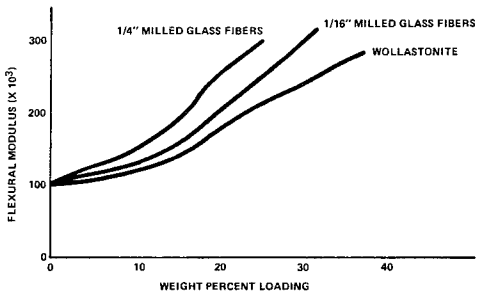

Figure 3 - Flexural Modulus - Reinforced RIM Urethane (measured parallel to flow)

Both the 1/4" and 1/16" milled glass fibers and wollastonite substantially increased the flexural modulus of the RIM urethane as the loading was increased. The longest fiber, the 1/4" milled glass fiber, provided the greatest flexural modulus improvement of each loading, while wollastonite, the shortest fiber, caused the least improvement.

Heat Sag

The heat sag test is a measure of the urethanes' ability to resist distortion at elevated temperatures. Figure 4 illustrates the effects that increasing loadings of 1/4" and 1/16" milled glass fibers and wollastonite had on the heat sag values of a 100,000 PSI flexural modulus RIM urethane.

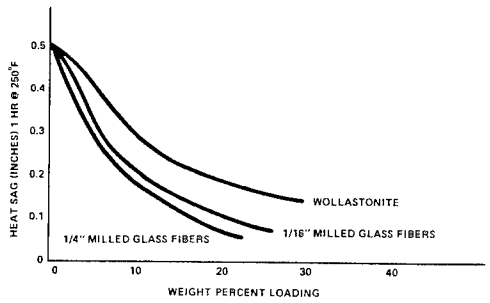

Figure 4 - Heat Sag - 1/4" and 1/16" Milled Glass Fibers vs. Wollastonite (measured parallel to flow)

The heat sag values for the RIM urethane were reduced substantially with increased loadings of 1/4" and 1/16" milled glass fibers and wollastonite. The 1/4" and 1/16" milled glass fibers were noticeably more effective than wollastonite, at the same loadings.

Impact Strength

A numerical measurement of the impact strength of reinforced RIM parts can be obtained with several conventional impact testing devices, such as the Notched Izod Impact Test. These impact values may not provide sufficient correlation to the actual damage resistance of a reinforced RIM part. For this reason, a program is underway at General Motors Manufacturing Development to investigate impact strength with an instrumented testing device. The parameters being investigated include: 1) rate of impact, 2) temperature, 3) part thickness, and 4) type of reinforcements. Preliminary work is being done with RIM test plaques reinforced with milled glass fibers only. Additional work is necessary before any comparison between the impact properties of milled glass and wollastonite can be made.

Other Properties

The tensile strength of the 100,000 PSI flexural modulus RIM urethane increased slightly as the loading of milled glass fibers or wollastonite was increased. The elongation and part shrinkage both decreased substantially as the loading of milled glass fibers or wollastonite was increased.

Orientation of Fibers

One characteristic of the reinforced RIM process is the orientation of fiber-shaped reinforcements in the direction of flow into the mold. This fiber orientation results in greater physical property enhancement parallel to flow than perpendicular to flow into the mold. Table III illustrates the orientation effects of 25% by weight loadings of 1/4" and 1/32" milled glass fibers on the flexural modulus of a 100,000 PSI flexural modulus RIM urethane.

Table III - Effects of 25% by weight loading of 1/4 and 1/32" milled glass fibers on the flexural modulus of a high modulus RIM urethane

	Unfilled (I) & (II)	25% 1/4" Milled Glass Fibers (I) / (II)	25% 1/32" Milled Glass Fibers (I) / (II)
Flexural Modulus (PSI)	100,000	140,000/296,000	145,000/180,000
Ratio (I/II)	1.0	.47	.80

The 1/4" milled glass fiber caused greater orientation effects of flexural modulus than 1/32" milled glass at the 25% by weight level, and a higher flexural modulus parallel to flow. Other properties, such as coefficient of thermal expansion, elongation, heat sag, and part shrinkage, exhibited similar orientation effects.

Wollastonite, a fiber shaped particle, also had orientation effects on the physical properties of the RIM urethane. Table IV shows a comparison of the effects of 25% loadings of wollastonite and 1/16" milled glass fibers on the flexural modulus of a 100,000 PSI flexural modulus RIM urethane.

Table IV - Effects of 25% by weight loading of wollastonite and 1/16" milled glass fibers on the physical properties of a high modulus RIM urethane

	Unfilled (I) & (II)	25% by weight Wollastonite (I) / (II)	25% by weight 1/16" Milled Glass Fibers (I) / (II)
Flexural Modulus (PSI)	100,000	142,000/195,000	160,000/240,000
Ratio (I/II)	1.0	.73	.67

Both wollastonite and 1/16" milled glass fibers caused comparable physical property orientation of the RIM urethane. This orientation has not been a problem with prototype parts made on a large scale RRIM machine.

Processability: Viscosity Build-up vs. Loading

As reinforcements are added to the urethane chemicals, polyol and isocyanate, the viscosity of each chemical slurry increases. This increased viscosity makes pumping and mixing of the urethane chemicals more difficult. An effective reinforcement for the RIM process should provide the desired physical property improvement with only a minimal increase in the viscosity of the urethane chemicals.

Figure 5 illustrates the effects of increasing weight percent loadings of 1/4" and 1/16" milled glass fibers and wollastonite on the viscosity of a liquid polyol. The method used to measure the viscosity was an extrusion rheometer.

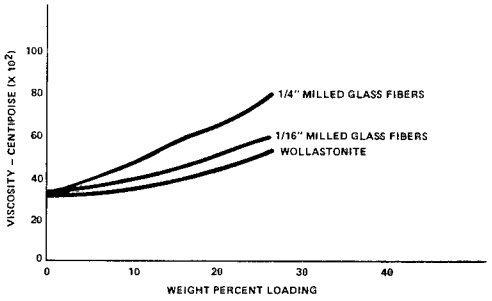

Figure 5 - Viscosity - Wollastonite vs. 1/4" and 1/16" Milled Glass Fibers in Polyol

The viscosity build-up of wollastonite and 1/16" milled glass fibers were comparable at each loading. Both wollastonite and 1/16" milled glass fibers had a moderate effect on the viscosity of the polyol. In actual molding trials, weight percent levels of 40% were attained with wollastonite and 1/16" milled glass fibers. The 1/4" milled glass fibers caused a greater viscosity build-up than 1/16" milled glass fibers or wollastanite. Weight percent levels higher than 25% of 1/4" milled glass fibers were difficult to process. Figure 6 shows the contrast in viscosity build-up between these three reinforcements and 1/8" chopped glass fibers.

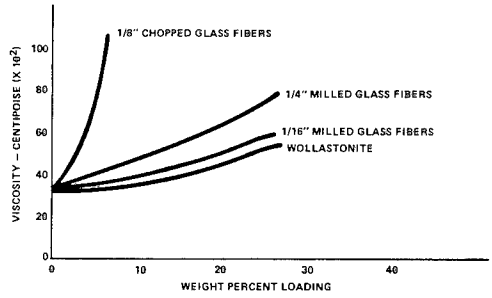

Figure 6 - Viscosity - Wollastonite vs. 1/4" and 1/16" Milled Glass Fibers vs. 1/8" Chopped Fibers in Polyol

These chopped glass fibers caused a much greater increase in the viscosity of the polyol than 1/4" and 1/16" milled glass fibers and wollastonite at each weight percent loading. In actual molding trials, levels of chopped glass greater than 5% by weight were very difficult to process.

Paintability

One of the primary advantages of RIM urethane is the excellent surface finish which can be attained, one that is suitable for

automobile fascias. The addition of a reinforcement should not adversely affect the surface finish or paintability of the RIM urethane.

Preliminary paint evaluations of reinforced RIM urethanes have been done with milled glass fiber reinforcement. At weight percent loadings over 20%, some loss of glass has occurred. A program to evaluate paintability of reinforced RIM urethanes with milled glass fibers and other reinforcements, such as wollastonite, is in progress.

Toxicological Effects

The reinforcements being considered for use in the RIM process are noncarcinogenic materials. The reinforcements currently being evaluated fall into two general classifications: 1) nuisance dust, and 2) inert mineral dust.

Both milled glass fibers and wollastonite are in the category of "nuisance dust." Safe handling of these reinforcements can be accomplished by mixing them with each urethane chemical in a closed mixing system. This method prevents air-borne particles from becoming a skin irritant to workers. Reinforcement-filled chemicals can be handled in the same manner as unfilled urethane chemicals, which includes proper ventilation for the isocyanate.

Cost

The final criterion for judging a reinforcement for the RIM process is the cost. For reinforcements with comparable physical property enhancement and processability, cost becomes an important factor. Figure 7 shows the effects of increasing loadings of three different reinforcements, wollastonite, milled glass fibers, and carbon fibers, on the cost per unit volume of the RRIM urethane.

The unfilled RIM urethane is assumed to have a relative cost of 1.00 per unit volume.

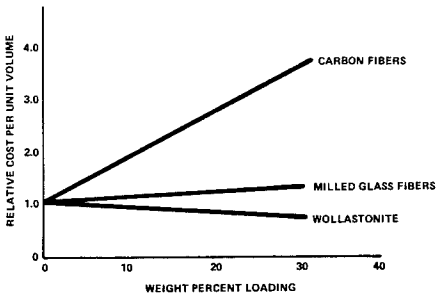

Figure 7 - Effects of increased weight percent loadings of Wollastonite, Milled Glass Fibers and Carbon Fibers on the relative cost per unit volume of an RRIM Urethane.

The wollastonite decreased the cost per unit volume of the reinforced RIM urethane slightly, while the milled glass fibers increased the cost per unit volume slightly. The carbon fibers increased the cost per unit volume of the RIM urethane dramatically, even at low loadings.

CONCLUSIONS

1. The addition of milled glass fibers or wollastonite to a RIM urethane resulted in decreased coefficient of thermal expansion, increased flexural modulus and decreased heat sag.

2. The 1/4" milled glass fibers provided more effective physical property improvement and greater orientation effect than the 1/16" milled glass fibers, but is more difficult to process.

3. Wollastonite was less effective than 1/4" or 1/16" milled glass fibers at improving the physical properties of a RIM urethane at each weight percent loading. Wollastonite does offer a cost reduction over milled glass, even if higher loadings are required to attain the same properties.

4. Both wollastonite and milled glass fibers can be processed at high loadings in a RRIM machine. Levels of 40% by weight of wollastonite and of 1/16" milled glass have been processed successfully.

5. Both milled glass fibers and wollastonite exhibit orientation effects of physical properties in the direction of flow into the mold. This orientation effect has not been a problem with prototype parts molded to date.

Future work in the reinforced RIM program falls in three general areas:

Paint Evaluation
Impact Testing
New Reinforcements and RIM Urethanes

Investigation of the paintability of reinforced RIM materials is an ongoing program at General Motors Manufacturing Development. Impact testing of various RIM urethanes and reinforcement combinations is also in progress.

The development of new reinforcements and RIM urethanes to improve physical properties, processability, and cost is of continued interest at General Motors.

ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance of Michael W. Liedtke and the members of the Low Pressure Molding Group of the Plastics Process Development Department in the preparation of this paper, and the members of the Plastics Materials Characterization Group for the physical property testing.

BIOGRAPHICAL SKETCH OF RAYMOND J. KOSTECKI

Raymond J. Kostecki is a Senior Project Engineer at General Motors Manufacturing Development. He is a Mechanical Engineering graduate from General Motors Institute. Since joining Manufacturing Development in July, 1977, he has been involved in the Reinforced Reaction Injection Molding development project. His primary responsibility is the investigation of urethanes and reinforcements for the Reinforced Reaction Injection Molding process.

ROBOTICS—THE ANSWER TO AUTOMATING PLASTICS MANUFACTURING FACILITIES

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This paper focuses on the field of Robotics as it relates to automating plastics manufacturing facilities including machine unloading, materials handling, post operations and packaging. Manufacturers of plastic products for the transportation industry must be fully knowledgeable about and apply all forms of automation available to remain competitive. This paper presents an overview of the state-of-the-art of Robotics familiarizing the plastics manufacturer with what a robot is, its structure, capabilities and principal application areas. The major emphasis is on the role of robots in plastics manufacturing facilities involving application analysis, cost justification, implementation considerations, safety, and the impact on labor and management.

Since the paper is presented via slides and movie film, which will be updated just prior to presentation, including a full text here is impractical. Therefore, the following outline of the subject matter to be discussed is presented for use as a guide in note taking.

I. Definition: What Is A Robot?
   A. General Characteristics
   B. Basic Components
      1. Manipulator: Mechanical unit that does the actual work of the robot (skeleton, muscles, nerves).
      2. Controller: Directs the movement of the manipulator (brains).
      3. Power Supply: Provides and regulates energy for the manipulator's actuators.

II. Familiarization: Commercially Available Robots.
   A. Mechanical Configurations
      1. Cylinderical Coordinate Robots.
      2. Spherical Coordinate Robots.
      3. Jointed-Spherical (Jointed Arm) Coordinate Robots.
   B. Degrees of Freedom
   C. Classification
      1. Non-servo robots (point-to-point).
      2. Servo-controlled robots (point-to-point).
      3. Servo-controlled robots (continuous path).
   D. Interfacing with the "Outside World"

III. Justification
   A. Increased Productivity
   B. Better Quality
   C. Elimination of Undesirable Tasks
      1. Poor working conditions.
      2. Fatiguing jobs.
      3. Monotonous, repetitive jobs.
   D. Safety
   E. Flexibility
   F. Economic Factors
      1. Cost avoidance.
      2. Cost savings.
      3. Costs.
      4. Measuring economics.

IV. Applications Development
   A. Become familiar with basic capabilities and limitations of available robots
   B. Make initial survey of potential applications
   C. Initial survey yields list of potential applications: make more detailed study
   D. Choose first application
      1. Suggestion: for first application, pick simplest job on list.
      2. Study the job; make sure you know everything the man has to do.
      3. Consider any alternatives other than robot.
      4. Look at possible advantages of mounting robot in other than usual feet-on-the-floor attitude.
      5. Consider reversing the usual bring-the-tool-to-the-work approach by having the robot carry the work to the tool.
      6. Try to anticipate all the things that could go wrong with anything associated with the job.
      7. Consider backups for the robot.
      8. Consider the environment.
      9. Consider equipment relocation and revisions.
      10. Consider space requirements.
      11. Consider future requirements.

V. Applications Engineering
   A. Select robot with sufficient reach, speed, memory, program capacity and load capacity to do the job. Provide some extra capacity if possible
   B. Consider protection of robot from contamination from environment (dust, paint overspray, metal particles, excessive heat, etc.) Intrinsic safety or explosion proofing may be required
   C. Make layout of installation: determine location, possible interferences, facilities changes required
   D. Determine interfaces required between robot and other equipment
   E. Determine changes required to other equipment
   F. Make provision for utilities (electric power, compressed air, cooling water, etc.)
   G. IMPORTANT: Provide adequate interlocks and guards to protect personnel in the area (also, protects robot from material handling equipment or other possible damage)
   H. Provide end-of-arm tooling: look at various alternative ways of picking up part
   I. If line tracking is required, provide for installation and inter-connection of suitable feedback device
   J. Provide for backup equipment or plan to protect production when robot is down
   K. Provide for spare parts and test equipment for maintenance
   L. Review application thoroughly with robot manufacturer

VI. Implementation Procedures
   A. Do as much preparatory work for installation as possible ahead of time
   B. Installation and start-up
   C. Monitor the operation
   D. Maintenance & service

ENERGY USAGE IN INJECTION MOLDING MACHINES

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The advent of expensive electrical power is causing great concern among users of injection molding equipment. Molders must now re-evaluate whether the increased cost of energy is inducing a significant change in part manufacturing costs and consequentially machine selection. Since much of the energy used during a cycle is actually the minimum amount required to perform a molding function, savings will not be dramatic. Most savings incurred will be quite subtle, making it difficult to relate with what changes the most energy is saved. Therefore, molders need the ability to quantitize their projected savings for each design change before investing in new equipment. It will be found that energy efficient machines cannot be built by selecting a special group of options and is greatly limited by inherent hydraulic design.

MOTORS

Much interest of late has been directed towards the new high efficiency motors now offered by several manufacturers. Increasing motor efficiency gives direct and immediate energy savings independent of machine design. However, the efficiency of motors normally associated with injection molding equipment doesn't lend itself to large improvement, minimizing greatly the potential for "high efficiency" motors. Motors above 20 horsepower are considered quite efficient. Presently the high horsepower motors have efficiencies bridging 90% or better, making the task of optimizing motor design difficult. However, energy savings of the smaller motors where initial efficiencies are closer to 80% (or lower), can be quite substantial. A relative comparison of present high efficiency motors and standard motors through a complete range of horsepower is shown in Figure 1. The efficiency of both motor types beyond 25 horsepower are comparable within 1%, but below 25 horsepower, the differential increases to 5% or greater. Where large numbers of small motors are found in industrial applications, high efficiency motors exhibit considerable savings over standard motors. But in sizes generally incorporated with molding machines, savings are not large and hence the rate of return is not within generally accepted levels. Very recent developments in high efficiency technology are obtaining efficiencies greater than 95% with large motors, and are worthy of investigation. It is skeptical however, that the overall efficiency of motors dedicated to injection molding service will be consistent with that 95% figure. During a typical molding cycle, the motor load of an injection press greatly changes. This fluctuation is contrary to most industrial applications where loads are generally constant. The efficiency of a motor is greatest at full rated load, and poorest under no load. Since the operating efficiency of each particular size of motor varies with each change of load, there ixists an optimized range of loads for each individual motor size, and injection molding loads are typically not within this optimum operating range. Therefore, the efficiency must be improved not only at full load (where efficiency percentages are quoted), but at no load operating regions as well.

One of the more widespread and prevalent misconceptions dealing with machine efficiency concerns proper sizing of the electrical motors to the required pumping system. Reducing rated horsepower of a machine without reducing appropriate pump sizes will not significantly reduce the overall power consumption of a molding press. As a dramatic comparison, Figure 2, illustrates graphically the kilowatts consumed by a 100 horsepower motor and a 50 horsepower motor for equal loads (listed in terms of horsepower required). It can usually be seen that:

1. There is little difference in energy consumption within the working range of a 50 horsepower motor and a 100 horsepower motor subject to equal loading.
2. The 100 horsepower motor only draws 2 kilowatts more at no load, compared with the 50 horsepower motor.
3. The 100 horsepower motor is actually more efficient in high peak load situations.
4. At no point in the available working range of a 50 horsepower motor, is there greater than 3 kilowatts difference despite doubling the horsepower!

The 50 horsepower curve has been extended to 100 horsepower. For typical molding machine motors, designed with 250% stall out torque, loads at any instantaneous moment may approach 200% of the full rated load without jeopardizing motor performance. The 50 horsepower motor is therefore expected, and frequently encounters 100 horsepower peaks. A 100 horsepower motor similarly is expected to handle 200 horsepower peaks. To properly size a motor, however, the average horsepower of the cycle must be maintained at or below the nameplate horsepower of a motor. Exceeding the nameplate figure for long periods of time will overheat internal components of the motor, which has necessitated the installation of overload heaters (usually of a lead alloy type) designed to interrupt machine operation when levels of high current or amperage are excessive. If heaters trip, interrupting the motor circuit, the load must be decreased or the motor size increased.

Using the above guidelines, two 50 GPM hydraulic pumps operating alternately at 1600 PSI are to be operated. Each pump requires 48 input horsepower. Neglecting idle requirements of the pumps, either pump may run continuous on a 50 horsepower motor. Both pumps may operate simultaneously at 96 horsepower for short non-continuous duty (on motors designed for 250% stall out torque). A 100 horsepower motor can run both pumps simultaneously for indefinite periods, or each individually. From an efficiency standpoint, the 100 horsepower is also favorable in this particular case. At the 48 input horsepower required, the 50 horsepower motor and the 100 horsepower motor both draw 43 kilowatts. At 98 horsepower, the 50 horsepower motor draws 87 kilowatts, and the 100 horsepower motor draws only 84 kilowatts, despite being twice as large. Based on the test results between these two particular motors, there would be no performance benefits obtained by under-sizing motors to anticipated jobs. Nameplate horsepower is not a true indication of energy consumption - it is only the potential for a motor to do work.

When a motor is operated at low load levels, a poor power factor relationship will be observed. Power factor is a phase relationship between current flow and voltage of alternating current systems. Maximum efficiency is obtained when the current and voltage phases directly coincide. Power factor of an electric motor is most destructive to efficiency at low or no

load. Power factor may be substantially corrected with power factor corrective capacitors - an option available from most machine manufacturers. Although the capacitors are capable of superficially reducing the supply line power factor (what the power company measures), the actual power factor and efficiency characteristics of the motor does not change. The overall difference is quite small, but the point being made is the addition of capacitors only changes supply line characteristics - not operating characteristics of the motor.

Hydraulics

To determine an approximate projection for the load actually created by an injection molding machine, the molding cycle should be broken down into each individual step or function. At each change of function, the individual pumps of the hydraulic system should be listed with their corresponding pressures. Using the pump manufacturers specification sheets for each respective pump, the load during any instantaneous point of the cycle can be computed by summing the cumulative load of all pumps, including those pumps at idle. The two parameters that directly effect the horsepower consumed by a pump are the rate of flow delivered (usually listed in gallons per minute or GPM) and the delivery pressure (usually pounds per square inch or PSI). Both factors are directly proportional to the resultant horsepower. From this, the equation

$$HP = GPM \times P \times K$$

HP = horsepower input required by the pump
GPM = hydraulic rate of delivery
P = hydraulic pressure at pump outlet
K = constant (.00062 HP/PSI·GPM)

may be synthesized and used for close approximation of input horsepower required of the pumps. At this point, it becomes significant to realize that a hydraulic pump at idle, one that is pumping full rated gallons at minimum pressure, requires a certain minimum horsepower merely to rotate the impeller and vanes submersed in oil. Nothing short of ceasing motor rotation will decrease this minimum. Therefore, the above equation for determining horsepower is limited to medium and high pressures only (500 PSI and greater).

From the input horsepower, the actual kilowatts necessary to operate the machine are then calculated. The kilowatts required are dependent upon the input horsepower, and the efficiency of the devise supplying the mechanical energy to the pump. Therefore, the equation

$$KW = HP \times K \div EFF$$

where

KW = kilowatts
K = constant (.745 kilowatts per horsepower)
HP = input horsepower
EFF = motor efficiency

will project quite accurately the kilowatts required to do a specific load or amount of work when the input horsepower required is supplied.

Using the above listed equations, molders may estimate energy requirements for machines that are presently running in production. When all clamp and injection unit functions are totaled and integrated by time, accuracy within 5% is usually obtained. For truely accurate measurements, a watt recording instrument should be incorporated.

Questions often arise when purchasing new equipment, concerning the operating cost of adding increased injection rates to a standard press. This requires an accurate projection of the increased restrictive pressure encountered when filling a mold at higher rates. Because the viscosity of polymers change at different flow rates, empirical data for each mold system should be used to verify projected parameters.

On a 250 ton 20 ounce molding machine utilizing a bleed-off system for rate control, the restrictive gates of a test mold imposed 900 PSI (hydraulic oil pressure) with a melt injection rate of 16.5 cubic inches per second. The polymer used was ABS, and total volume is 25 cubic inches. By reducing the injection rate and recording respective pressures, the following linear relationship evolved for rates between 6.0 cubic inches per second and 16.5 cubic inches per second.

$$\frac{(\text{Pressure 1})^{1.6}}{(\text{Pressure 2})^{1.6}} = \frac{\text{Rate 1}}{\text{Rate 2}}$$

(This equation is the relationship for the given molding system only, and may not be indicative of other ABS systems!) Using this individualized equation, an extrapolation will be made for increasing the injection rate to 23.6 cubic inches per second with the addition of an 18 GPM hydraulic pump. Solving the equation, the pressure at the increased rate is expected to be 1125 PSI. Actual pressure was found to be a nominal 1100 PSI.

Determining this pressure without emperical testing would be difficult if not impossible.

To determine the total effect of the increased oil, the pressures and rates ofthe total pumping system must be recalculated, and again integrated by time. The summation will yield a slightly higher energy figure, but cycle time (productively) will favorably improve. The net energy increase is due to larger idle requirements of additional pumps at no load conditions and the additional effects of a high pressure application, such as injection high volume. In the previous example, the high volume injection high oil required approximately 2.3 kilowatt hours per hour more, and idle requirements increased by 1.7 kilowatts. This increases energy requirements by 4.0 kilowatt hours per hour of operation. Utilizing this additional oil for the extruder motor would also increase power consumption but can also increase productivity.

OVERALL

Energy consumption must not be confused with efficiency. Decreasing machine potential not only decreases energy consumption, but versatility as well. The greatest inefficiency occurs when excess oil capacity is at idle, and no useful work is performed. For each part, there will be a limit to excess oil beyond which energy costs can overshadow part profit margins. Decreasing motor size has little effect on power consumption, but nameplate horsepower gives some indication of the overall potential and versatility of the machine.

Efforts are always made by machine manufacturers to gain more performance for the same input energy, and have previously been limited by the increases of initial cost, and the inability for molders to return prospective increases. As energy costs continue to escalate however, machine buyers may be forced to evaluate individual parts for determining optimum pump sizes and greatest profitability. Increased energy costs will force the evolution of more efficient machines, but the changes will be slow and subtle.

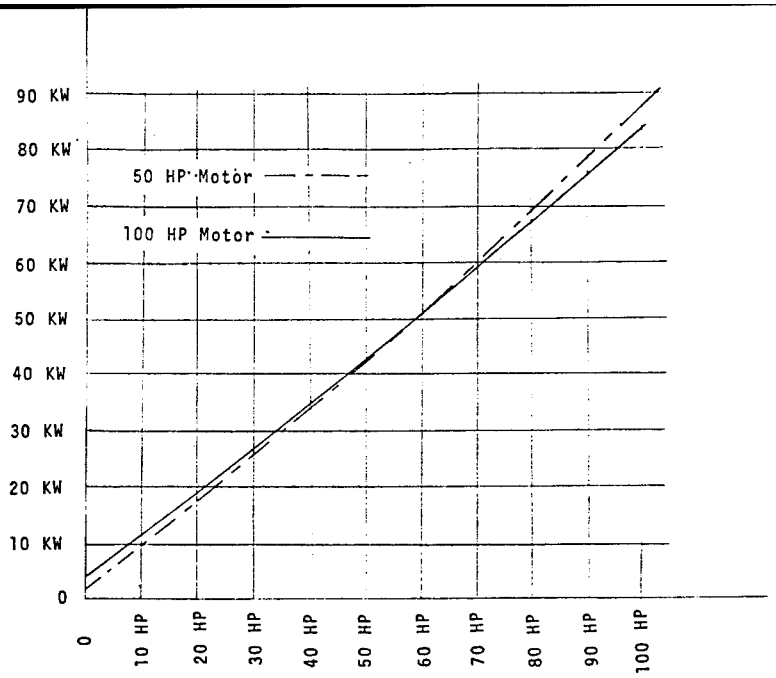

Figure 1

A relative comparison of a 50 HP motor and a 100 HP motor at equal load levels.

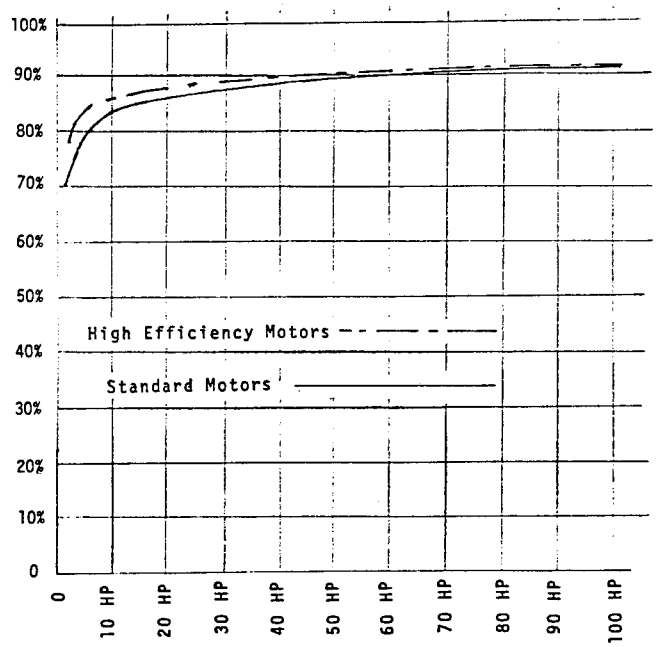

Figure 2

A relative comparison of standard motors and a present line of high efficiency motors at various horsepowers.[1]

1. Westinghouse May 22, 1979

THE NO COMPROMISE RUNNERLESS MOLD

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INTRODUCTION:

As the plastics industry moves toward the energy challenge of the 1980's, it is obvious that compromises in efficiency that have been tolerated in the past will no longer be acceptable.

While these challenges will represent some adjustment and, in certain cases, even hardships for certain facits of industry, I believe that it is fair to say that as is usually the case, those companies and industries who accept these challenges willingly and are innovative in their approach to these problems, will not only survive, but prosper.

I can think of no industry more challenged by the 1980's than the automotive industry. This means, of course, that the automotive industry is, in turn, challenging its suppliers and vendors to keep pace. The plastics industry has done a good job in the development and engineering of new materials to meet the challenges of the auto makers. The number of components used for structural and performance purposes, rather than purely decorative applications, testifies to this fact. However, more work must be done in the planning and implimentation of molding machinery and molds designed for these applications, if we are to be truly efficient and take full advantage of these materials.

THE NO COMPROMISE MOLD:

It is obvious that every applicable method known to the molding industry should be utilized when designing and building molds, which will manufacture the products of the 1980's. Unnecessary waste is inexcusable. New molds should be designed to run in the smallest and most energy conserving molding machines possible. Runnerless molds should be used wherever feasibility allows. It is most important to plan all new molds with specific production and quality objectives in mind. The 1980's will not allow molders the luxury of designing molds with convenience being the only chief motivating factor. In the 1980's, molders must find extremely large molds with high cavity counts as impractical as the very small mold, from a productivity standpoint.

The molds which are likely to be built by the aggressive new leaders of the 1980's are, what I shall call, "the no compromise molds".
The no compromise mold will be designed with the specific purpose of providing the intended part in the quantities desired, using the smallest possible combination of material and energy. Such a mold is likely to have no inherent scrap waste, will run the smallest possible molding machine, and be capable of extended automatic operation. These molds will be designed with the greatest possible flexibility in all aspects, including programable cooling circuits, interchangeable cavities and cores, and runner systems capable of a wide variety of materials.

In many cases, mold design by computer will aid in the planning of such molds, solving complex flow and heat exchange problems. Stack molds will become extremely important in the quest of molding with the greatest possible economy. New techniques make stack molding extremely viable, even with engineering grade materials. In many cases, stack molding will double the output of the molding machine, with no appreciable increase in operating costs.

One of the most important aspects in planning a modern injection mold, is the design of the runner system. Consideration must be given to the type of part to be made, the material to be used, the number of cavities, the size of the mold and the size press to be used. The runner system used in these molds will ultimately decide the success or failure of the mold. Improper construction, or the use of incorrect melt conveying equipment in the mold, will have a disastrous effect on the reliability of the mold.

There are many types of hot runner systems currently on the market. These systems offer valve gating, pin gating, internal heat and external heat with insulated, semi-insulated and hot manifolds. It is important to understand how these systems work and where one system may be preferred over another.

While there are many considerations to be given to the runner system design, as a general rule, the main consideration should be:

(1) Usable temperature range of the material.
(2) Material flowability.
(3) Physical size and location of each cavity.
(4) Fill requirements of each cavity.
(5) Part specifications and tolerance.

While each mold has its own parameters, generally speaking, a runner system which conveys melt evenly with no hot spots and no material stagnation is more reliable and, therefore, preferred over runner systems with poor melt conveying characteristics. However, in the "no compromise" mold, conveying melt is not enough. The melt must be distributed evenly to each cavity and then metered to the specific fill requirements of that cavity. By doing so, less injection pressure will be needed and part quality will be uniform from cavity to cavity.

The process by which material is metered to the cavity for even flow is called gate balancing. Recent breakthoughs in runnerless molding now allows reliable and consistent flow control, resulting in effective gate balancing. The ability to balance flow is an often overlooked but extremely important aspect of any multiple cavity mold. Molds which are used to manufacture parts with large surface areas or parts in high numbers require greater gate balancing ability than smaller molds with low cavity counts and easily filled parts. The important thing is to plan the mold anticipating flow problems and then select a runnerless molding system which will allow the molder to control flow, so it can be used to his advantage.

Probably the most common problem experienced in runnerless molding today, is gate malfunction. Obviously, if the separation of the part at the gate is not handled properly, rejects will be high and down time, frequent. Since no runnerless molding system is suitable for every type of material (abrasive materials pose different problems than non-abrasives, etc.), it is important for the molder to understand the theory of operation behind each system. A misunderstanding here can prove disasterous.

There are generally two methods used to gate a hot runner mold, mechanical shut-off and thermal separation.

The mechanically gated mold offers the most positive method of stopping the flow of material and separating the part from the runner. These systems also offer the best potential cosmetics. However, great care should be taken in selecting a mechanical shut-off, as malfunctions in the mechanical apparatus, due to wear, corrosion, fatigue or contaminants in the material, may cause unnecessary down-time. Also, increases in stack height due to the actuating apparatus should be watched closely. If the mechanism necessitates using a larger molding press due to increased mold size, you are defeating the purpose of the "no compromise mold".

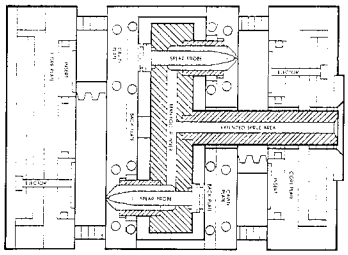
Thermally gated systems are considerably less complicated in design but, in most cases, do not offer the precise shut-off of material attributed to the mechanical shut-off. Most systems, using a thermal gate, depend on a slug of semi-solidified material in the gate area to hold back the reservoir of molten material while the part separates from the slug at the gate and is extracted from the mold. Should the slug of material in the gate area become too soft, it is likely to be extracted with the part and the reservoir of molten material behind the slug will run out of the gate. This condition is known as stringing or drooling.

One exception to this gating method is the Spear System. This runner system uses a dual element probe which places a secondary heating element, located at the tip of the probe, into the gate area. This tip heater element is cycled "on" and "off" during the molding process, which allows the gate to "freeze off" and then remelt for the next injection cycle. This process eliminates the need for the slug of semi-molten material in the gate area.

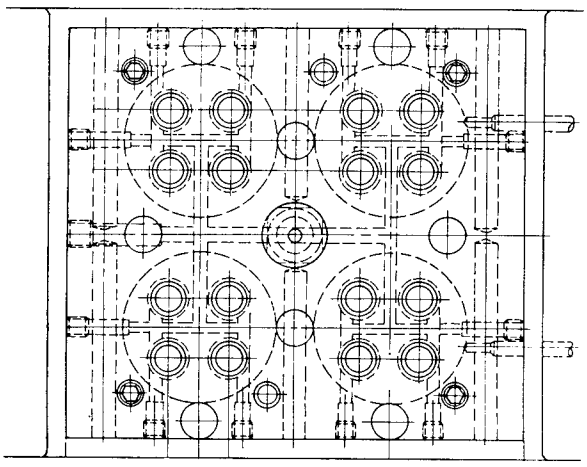
Reliability is the key to an economical mold. If stringing or drooling is likely to be a problem in a particular mold or if a perfect cosmetic mark is required, then the method of gating should be chosen accordingly. However, regardless of the method chosen, look for a system that will give sufficient control for your molding application.

Since the "no compromise" mold is based on eliminating waste in both a monetary, as well as an energy sense, it is important to note that there is also less margin for error. Therefore, proper design and selection of equipment is of paramount importance. The key to the greatest savings in your molding operation is in the hands of your mold designer. Extra work and study at this stage of the moldmaking cycle will yield incalculable savings during the life of the mold.

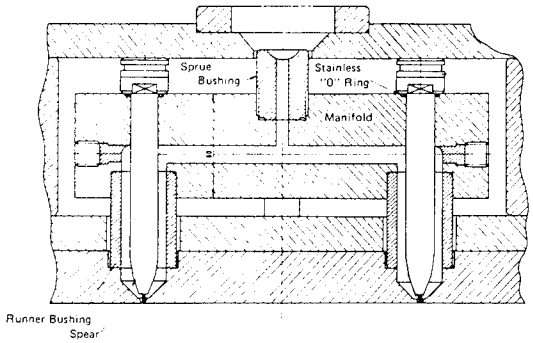
The successful molders of the 1980's will have a "no compromise" attitude that will carry through design, engineering and manufacturing. They and their customers will be the winners of the 1980's.

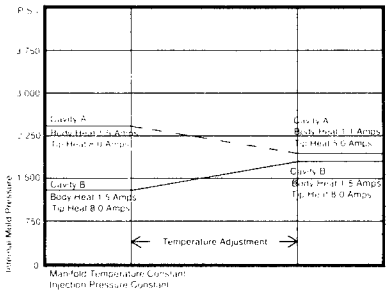


Stack molding offers tremendous increases in productivity. New breakthroughs in this area allow use with engineering grade materials with extreme reliability. Stacking cavities does not require tonnage increases. A much smaller press may be used to obtain the same production levels as standard molds.



Runner configuration is important to the overall success of the mold. By varying the size and configuration of the runner channels, a more even flow may be achieved to all cavities. This is an especially important factor in designing family molds or molds which must have unequal length runners.





Gate balancing is an often overlooked aspect of runnerless molding. Molds featuring dual element probes may use the body heater of the probe to vary the viscosity of the material. This variance allows greater flow at higher temperatures and reduced flow at lower temperatures. The tip heating element maintains the gate area even at reduced body heat settings. Experience has proven this to be a reliable method of gate balancing.

The above graph shows how gate balancing may be effected by varying the heat intensity of dual element probes. By decreasing the intensity of heat in the high pressure runner drop, flow is restricted and, therefore, pressure increases on the low pressure side of the mold. Pressure variances between the two cavities have been equalized without temperature or pressure increases.

VALVE GATE SHUT OFF SYSTEM FOR OPTIMUM FILLING OF INDIVIDUAL CAVITIES

BY
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The Incoe Valve Gate shut-off system for injection molds provides the molder with positive control filling of each mold cavity. There are many runnerless molding systems today, that have some form of shut-off that seals the mold gate after injection pressure is released, preventing drool and degradation of heat-sensitive materials at the gate. With these systems, whether they are air or spring actuated, cavity gate closing is basically a function of injection pressure. This new system is a significant improvement because it does not rely on injection pressure to actuate the valving, but has the ability to open and close each cavity gate independently of injection pressure. Opening and closing of each cavity gate independently of injection pressure permits optimum production control of cavities of a family mold. Even with widely varying part weights and shapes, fill time of individual cavities can be optimized, and each part molded uniformly.

Problems of incomplete cavity fill or overpack are eliminated, along with many associated problems of imbalanced mold geometry. The key to the system's operation is the method employed to open and close each mold gate. In operation, each gate is opened or closed independently and positively by a hydraulic cylinder. The closing force developed can seal gates against theoretical injection pressures of 70,000 p.s.i. - enough to handle any existing injection pressure setting.

It avoids the traditional use of injection pressure to activate the gate which causes the material to explode into the mold cavity, producing extra shear and its attendant heat. Gates are timed to open as soon as injection forward is initiated; there is no wait to develop full injection pressure. Each cavity is open for only the time it takes to reach optimum fill. When the last cavity is sealed, the screw immediately begins recovery.

Each positive gate shut-off consists of a hollow bushing and adjustable shut-off pin, a hydraulic cylinder and a timer. In a multi-gated mold (regardless of single or multi-cavity), each gate contains the first two elements mounted in manifolds and controlled by timers mounted in a control cabinet. The basic elements of the shut-off system for runnerless molding are shown in Fig. I. The heated bushings, mounted in a manifold, contain a 1/8 in. diameter pin running through the resin channel. The pin is connected at the back end to the hydraulic cylinder. The opposite end mates with a taper (gate) in the channel to seal off the flow of resin. Linear movement of the cylinder opens or closes the channel gate. The shut-off pin is threaded into the cylinder so that its projection into the bushing can be adjusted, and the adjustment made without pulling the mold and manifold out of the machine.

Misalignment of any element in the runner system will not cause pin actuation problems nor cause the pin to bend. The pin is secured at the back of the runner system and pivots at that point.

The pin rides free within the bushing, contacting the bushing only when it seals against the taper at the gate to shut-off the flow. Thus, the pin will pivot and compensate for misalignment.

In molding, all pins automatically open when the mold closes so that resin can flow into the cavities under normal machine injection pressure. Each timer also is actuated. (Timers are set during set-up for the precise amount of time necessary to fill each cavity.) When one cavity is filled, the timer signals the hydraulic cylinder to close the gate. Injection continues in the remaining cylinders, each one timing out individually and then closing.

Cycle time is reduced because the mold fills faster. There is no waiting to develop high injection pressure. Also, holding time can be eliminated because the pins perform that function. Conversion of a conventional runnerless two cavity polycarbonate mold to a valve gate system produced a cycle reduction from 42 seconds to 28 seconds.

The gates can be opened or closed at a predetermined time regardless of the injection pressure. This enables the molder to eliminate the problem of overpacking some cavities while continued injection fills out other cavities. This is important when filling a large, single cavity mold from multiple gates. In this case, gates feeding sections of the cavity that fill easily can be shut-down while injection continues into more difficult to fill sections.

Another area where this new system can offer advantages is in molding dissimilar parts. Independent cavity filling can balance out a mold with both large and small parts.

Alternate mold cavity filling is another technique possible with the positive shut-off system. A four cavity tool with two sets of dissimilar size parts can be run by injecting in one set on the first cycle and the second set on the alternate cycles. This approach would utilize about half the injection machine tonnage. A wide range of heated bushings can be adapted to the system to increase gate size - up to 1/4-in. opening. A 3/8-in. ID bushing with a 0.1-in. gate opening is standard equipment.

To permit close-center multiple cavity mold design, hydraulic cylinders are rear-mounted on a fluid manifold separated from the mold by air space. Hoses for each cylinder are attached to the outside of the manifold. Hydraulics are supplied by either of two options: a stand alone pump unit that is capable of supplying two systems, or a flow-control valve unit that takes off from existing machine hydraulics.

Alternate manual control of gate, actuation with an on-off-auto mode switch enables cavities to be purged individually to reduce material waste. Gate of the cavity to be purged is opened (indicator lights show the position of each gate pin) and the remaining pins closed before the injection cycle is begun.

For inventory control purposes, a cycle counter is connected to each timer and can be used to override it when a predetermined number of parts are produced from each separate cavity. At the same time it closes the gate pin, the counter can open the heating circuit to the bushing to prevent material degradation at the inactive gate.

Continuing developmental work will result in a more sophisticated version in which cavity pressure sensors coupled with microprocessor logic will control gate operation. Then cavity fill can be programmed, monitored, and adjusted - cycle after cycle - to achieve the optimum in molded part characteristics and properties.

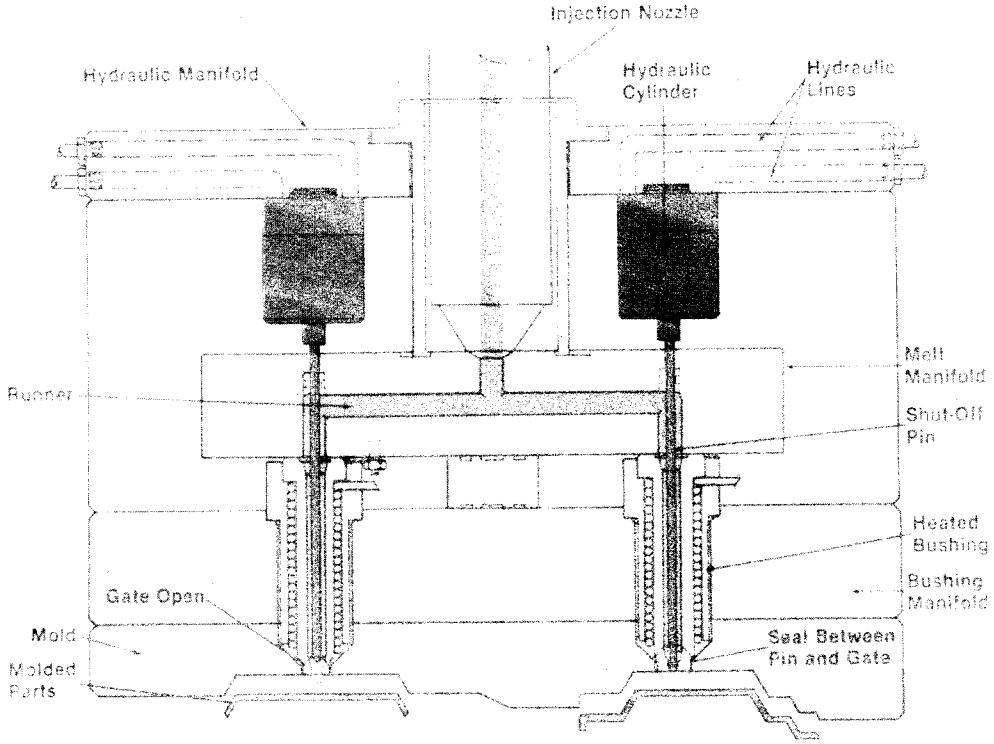
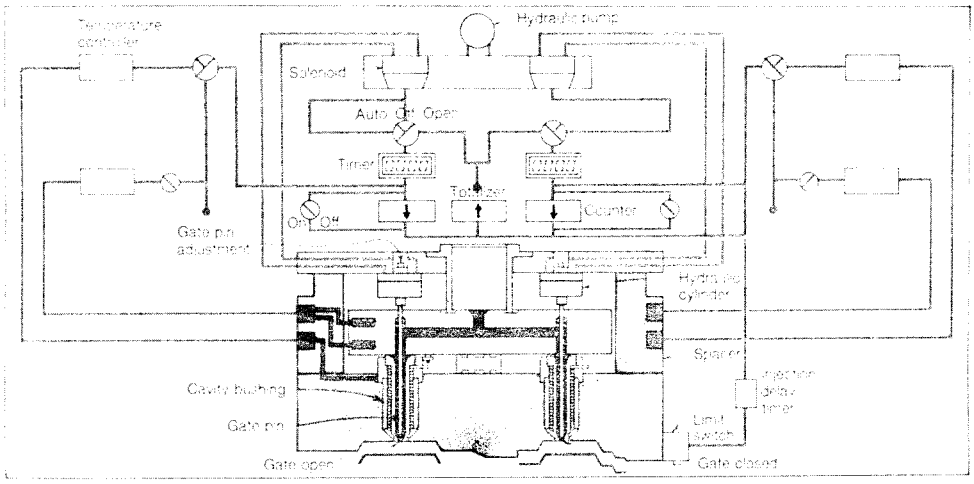


Diagram of positive gate shut-off system. Heated bushings house shut-off pin which is connected to a hydraulic cylinder. The cylinder is timer controlled. (Timer is mounted on the control panel and not shown in this diagram.) When the mold closes for injection, the gate pins open, permitting flow of resin into cavity. Gate pin closes off resin channel after predetermined amount of time has elapsed.



NEW ENGINEERING PLASTICS RESINS BASED ON POLYETHYLENE TEREPHTHALATE

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INTRODUCTION

Moldable, glass-reinforced polyethylene terephthalate (PET) was introduced in the U.S. as Rynite® thermoplastic polyester resin in October, 1978, and in Europe a half year later. It contains glass fibers uniformly dispersed in a polymer matrix, modified to provide rapid crystallization during injection molding. As compared with polybutylene terephthalate (PBT), the PET chain segment is shorter, stiffer and melts at a higher temperature. The invention of a way to get the stiff PET chains to crystallize rapidly permits conventional molding of tough, high performance parts with attractive appearance--without sticking and without large dimensional changes when subsequently heated. These new resins also offer an unusually good combination of high flow and impact strength.

- Rynite® 530 (30% glass) offers outstanding strength, stiffness, toughness and appearance as a molded part.
- Rynite® 545 (45% glass) is stiffer, more dimensionally stable and even faster cycling.

This paper highlights key laboratory and field performance data supporting Rynite's® claim to uniqueness among engineering plastics. Further product modifications will be reviewed, including a special grade formulated to provide extremely low warpage and an experimental flame-retardant composition.

Stiffness, Strength, and Toughness (Figure 1)- PET can be reinforced to provide stiffness which is unusually high for a modestly priced material. Rynite® 530 has a room temperature flexural modulus of 1.3×10^6 psi (9×10^3 MPa). Rynite® 545, 50% stiffer, was introduced as the most rigid commercially available glass-reinforced thermoplastic--with modulus in the range of experimental resins containing carbon fiber. Versus PBT, Rynite® has slightly higher Izod impact strength at the same 30% glass level; 45% glass provides additional toughness. In tensile strength, Rynite® 530 has a 30% advantage and Rynite® 545 is 60% higher.

Temperature Resistance - In Rynite® 530, tensile strength is maintained greater than 10,000 psi (69 MPa) up to 390°F (200°C); PBT with 30% glass drops to the same strength level at 355°F (180°C). Flexural modulus similarly shows about a 35°F (20°C) advantage for the PET system. These advantages result directly from molecular chain stiffness and melting point, and are reflected in other high temperature properties such as shear strength and creep.

FIELD PERFORMANCE INFORMATION

Field experience is summarized as follows. Polyester's typical low molding powder moisture requirement has been acceptable to molders. They are impressed with processability and especially flow. Excellent surface appearance continues to be a pleasant surprise to those familiar with earlier glass reinforced PET resins. An accumulating variety of field evaluation information confirms earlier laboratory data on physical properties.

Moisture - Hydrolysis of the ester linkage must be avoided whether polyester is being converted to fibers, films, or moldings. Elongation is reduced 15% if molding cube moisture is 0.04%, versus the recommended maximum of 0.02%. Our kinetic data are supported by field experience on the use of hopper driers. These commercially available units allow routine, trouble-free production of highest quality parts and are both more effective and dependable than oven driers. A 5 ft^3 (0.14 m^3) hopper drier with a 2-hour holdup at 275°F (135°C) can be used at a one-pound per minute (0.01 kg/s) processing rate (Figure 2). It is important to know that while surface appearance signals the molder when nylon's moisture level is too high, moldings of wet polyester change in performance but not in appearance.

Flow - Molders with background in glass-reinforced polyester and other engineering plastics have been impressed by flow and related molding characteristics of Rynite®. Snake-flow is 30-60% better than typical glass-reinforced PBT (Figure 3). This processing advantage has been dramatically confirmed in field molding of certain complex and thin-walled parts. In some cases as a mold heated up to equilibrium temperature, it was helpful to gradually reduce pressure settings; flow is so good that otherwise part, runner and sprue could overpack and hinder ejection. Excellent flow is especially helpful in highly reinforced or filled systems.

Cycle Time - Field experience to date indicates that Rynite® 530 cycles fast, and about the same as 30% glass reinforced PBT and nylon. With its higher levels of high temperature strength and stiffness, Rynite® 545 is an extremely fast cycling resin.

Rework - Melt stability is good and with proper control, rework is handled normally. With rework at the 25% level, one obtains tensile strength and impact resistance which are 97% and 95% of values for virgin resin.

Surface Appearance - Surfaces are glossy, uniform in appearance, and generally pleasing. Highest gloss is obtained, depending on mold design, at mold temperatures in the 176-212°F (80-100°C) range. At these temperatures, Rynite® 530 will replicate the mold surface finish.

Electrical and High Temperature Data (Figure 4) - Room temperature electrical data indicate performance adequate for those markets where PBT already has proven its value. Based on in-house temperature indexing, Rynite® should receive from UL in late 1979 about the same mechanical and electrical index values as glass-reinforced PBT.

Warpage - As noted in laboratory test (Figure 5), warpage is one-third less than PBT, both at 30% glass. Field experience to date on a variety of parts shows the same effect.

Resistance to Solvents, Chemicals, Automotive Fluids - A one-year test program is underway. Preliminary data shows behavior similar to that of PBT controls.

FURTHER PRODUCT MODIFICATION

A New Resin Exhibiting Very Low Warpage (Figure 5) - Increasingly, resin suppliers have heard the call from the marketplace for a very low warp, semicrystalline plastic. Solvent and temperature resistance properties of semicrystalline plastics are appreciated, but two factors led to sometimes marginal dimensional stability. First, parts could warp in paint ovens as annealing and stress relief occurred. Anisotropy introduced by glass was a primary contributor to this effect. If made of nylon, parts additionally could warp in service as moisture pickup caused additional dimensional change.

An experimental resin with substantially lower warpage than Rynite® 530 or 545 now has reached field development status. Part of the glass fiber has been replaced with mica which decreases warpage due to differential shrinkage. Two development products, Rynite® RE-5060 and 5061 have an excellent combination of stiffness, toughness and flatness. In most molds examined to date, they offer flatness of a mineral-reinforced nylon, but with superior stiffness, shiny surface, and with dimensional stability due to inherently very low moisture pickup. As suggested earlier, excellent flow characteristics of PET contribute to ready moldability of this highly reinforced system. In one field test, RE-5060 was the only resin tested which completely filled both cavities of a mold producing five foot long (1.5 m) panels.

A New Flame Retardant Resin (Figure 6) - Many electrical and appliance parts require flame retardant properties. Rynite® is a version which is UL-94 V-0 at 1/32" (0.8 mm) has reached field evaluation status. The technical challenge was to develop a composition which could be processed without excessive degradation; the higher melting point of PET normally required processing at melt temperatures about 40°C higher than PBT. The first step was to define a flame-retardant system which gives relatively good thermal stability. Composition then was adjusted to maintain outstanding flow at the 45°F (24°C) lower temperature recommended for molding the FR resin.

Since the preferred melt temperature of flame retardant Rynite® is still 27°F (15°C) higher than used to mold flame retardant PBT, it is necessary to control temperature with care and to size equipment so that holdup times are not excessive. Once this is done, key performance advantages of stiffness, temperature resistance and toughness hold equally well for the FR material. Cycle times are fast. Limiting oxygen index is 36% and performance in the hot wire ignition test is excellent. Behavior in preliminary high-temperature aging tests is superior to FR glass-reinforced PBT.

Research Directions - An experimental resin already field tested contains 55% glass. It molds without difficulty and features a flexural modulus of 2.7 million psi (18 x 10^3 MPa). Improved PET based resins are possible based on today's toughening technology. We anticipate early 1980 trials of a tougher 530-type resin to test market needs. Next is a more diffficult target: a tougher resin still offering the high stiffness and low warpage of RE-5060. We are convinced that this, too, is attainable.

Beyond these resins, one can visualize still faster cycling compositions, products with lower glass levels and those with mixed reinforcing agents as exemplified by mineral/glass nylons. As we said in October, 1978, "looking to the future we are enthusiastic over the potential for additional products... polyester, we believe, is nylon-like in its ability to satisfy diverse performance needs".

SUMMARY

1. Rynite® thermoplastic polyester resin provides parts with an outstanding combination of high flexural modulus, strength and toughness, dimensional stability, and surface appearance.
2. Melt flow and general processability, even in thin sections is excellent and cycle is fast.
3. Electrical and physical properties are acceptable after heat-aging.
4. A mica/glass reinforced resin provides near zero warpage.
5. A UL-94 V-0 composition has unusually good flow for a flame retardant resin.
6. Experimental resins include one with extraordinary stiffness for a glass reinforced resin, another featuring increased toughness.

ACKNOWLEDGEMENT

Product development is led by Mr. Edward J. Deyrup and Dr. James L. Hecht. Data and perspective on field performance are provided by Dr. M. Lana Sheer and are especially appreciated.

Figure 1. STIFFNESS, STRENGTH, TOUGHNESS OF RYNITE® AT 73°F (23°C)

Stiffness - Flexural Modulus	Kpsi	MPa
Rynite®		
530	1,300	9,000
545	2,000	13,800

Strength - Tensile Strength	Kpsi	MPa
Rynite®		
530	23	160
545	28	190

Toughness - Izod Impact	Ft-Lb/In	J/m
Rynite®		
530	1.9	100
545	2.4	130

Methods	
Flexural Modulus	D-790
Tensile Strength	D-638
Izod Impact	D-256

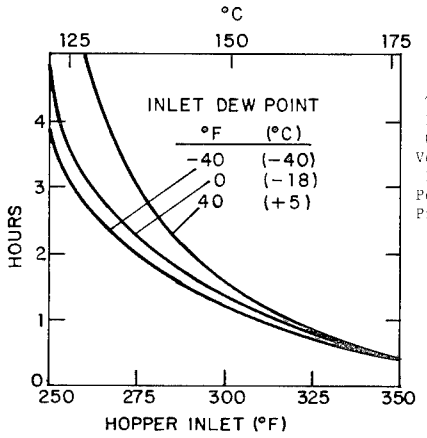

Figure 2

Time To Dry Resin From 0.25% H_2O To 0.013% H_2O; Air Velocity 0.7 Cubic Feet Per Minute, Per Pound Polymer Processed Per Hour.

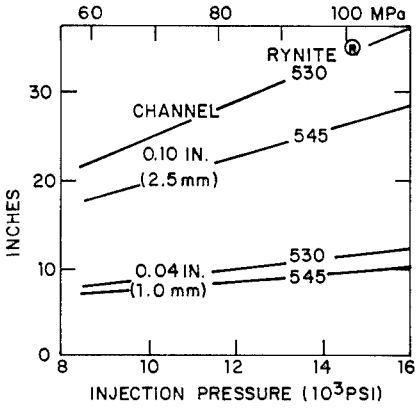

Figure 3

Snake Flow at 200°F (93°C) Mold Temperature, and 575°F (302°C) Melt Temperature

Figure 4A.

Temperature Indexing Data (D-638)

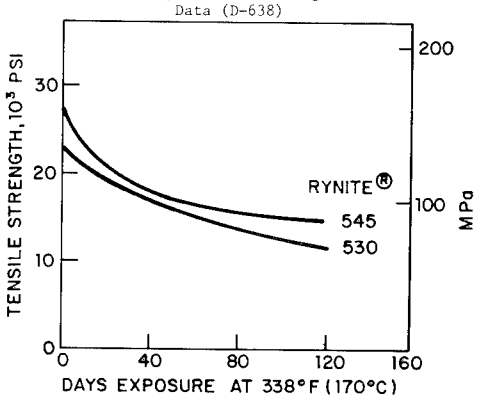

Figure 4B. DIELECTRIC STRENGTH (D-149), VOLTS PER MIL

- Effect of Sample Thickness at 73°F (23°C):

	Rynite® 530	Rynite® 545
0.031 in (0.8 mm)	1000	1000
0.062 in (1.6 mm)	750	730
0.125 in (3.2 mm)	550	540

- Effect of Temperature at 0.062 Inch Sample Thickness:

	Rynite® 530	Rynite® 545
73°F (23°C)	550	540
200°F (93°C)	590	570
300°F (149°C)	590	550

Figure 5. RE-5060, A LOW WARPAGE RYNITE®*

- Relative Warpage. Du Pont Method, Annealed Disc 4 x 0.125 in (100 x 3 mm)

Glass Reinforced Polyester		Reinforced Nylon	
Rynite® 530	110	Minlon® 10B	5
Rynite® 545	125	Minlon® 11C	5
RE-5060	5	FE-6130	35
PBT (30% Glass)	160	FE-6089	90

- Flexural Modulus D-790 1.54×10^6 psi (10,600 MPa)
  Tensile Strength D-638 15×10^3 psi (104 MPa)
  Izod Impact D-256 1.4 ft-lb/in (75 J/m)

- Snake Flow 30 in (760 mm)
  Conditions:

  0.1 x 0.5 in (2.5 x 12 mm) Channel, 18×10^3 psi (126 MPa) Pressure, 200°F (93°C) Mold, 565°F (296°C) Melt.

*Preliminary Data.

Figure 6. RE-9003, RYNITE® WITH UL-94 V-0 BEHAVIOR

- Flexural Modulus D-790 1.6×10^6 psi (11×10^3 MPa)
  Tensile Strength D-638 20×10^3 psi (140 MPa)
  Izod Impact D-256 1.8 ft-lb/in (98 J/m)

- Snake Flow: 26 in (0.66 m)
  Channel: 0.197 x 0.122 in; 19 kpsi
  230°F mold, 536°F melt

- Limiting Oxygen Index (D-2863): 36%
  Hot Wire Ignition (UL 746-A): >250 sec

- Dielectric Strength (D-149): 455 volts per mil (1/8")
  Comparative Tracking Index (UL-746): 190 volts

ROPET™ ENGINEERING THERMOPLASTICS: NEW CRYSTALLINE, LOW WARP, GLASS-REINFORCED POLYESTER-ACRYLIC ALLOYS

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INTRODUCTION:

Polyethylene terephthalate (PET) and polybutylene terephthalate (PBT) are two semi-crystalline, thermoplastic polyesters which have widespread commercial use. PET displays a high modulus, high tensile strength, high heat deflection temperature, and good chemical resistance; yet it is only just beginning to be accepted as an injection moldable engineering resin. The principal reasons for non-use have been poor processability, a tendency to warp when glass fiber reinforced, and poor impact resistance. PBT, on the other hand, processes well and may offer a higher impact resistance than PET; however, it also warps when glass reinforced and its modulus and heat deflection temperatures are lower than those of PET.

ROPET engineering thermoplastics are a new family of low warp, dimensionally stable, tough, glass-reinforced, polyester-acrylic alloys. Because they are alloys, they may be tailored to meet the processing/performance requirements of specific applications. The low warpage displayed by the glass-reinforced ROPET alloys permits their use in applications traditionally closed to glass-reinforced thermoplastics. This paper describes ROPET 400 and ROPET 500 and demonstrates their utility as injection moldable engineering thermoplastics.

AVAILABLE GRADES

Two grades are available today: ROPET 400, a general purpose, injection molding grade, and ROPET 500, an analogous flame retarded grade. Both grades contain 30% glass fiber reinforcement. Both are supplied as extruded pellets. Each grade offers the stiffness and heat distortion temperatures of fully crystallized, glass reinforced PET with the processability of PBT. Future grades will include unreinforced resins, mineral filled compounds, and specialty grades.

PROPERTIES OF ROPET RESINS

One difficulty encountered with glass reinforced, semi-crystalline polymers is to discover ways to mold them which will consistently give fully crystallized parts with a good balance of properties, good surface appearance and dimensional stability. Figure 1 shows the relationship between surface appearance and the crystallinity index, Xc, an experimental quantity defined by Equation 1, for a number of similar glass-fiber reinforced polyester alloys molded under identical conditions.

$$Xc = \frac{\%\ \text{Crystallized As Molded}}{\%\ \text{Crystallized After Annealing (150°C; 1 hour)}} \qquad (1)$$

The degrees of crystallinity used in Equation 1 were determined experimentally from the heat of melting of the polyester alloy. Figure 1 shows a clear correlation between surface gloss and Xc. This indicates that relatively small changes in crystallinity are easily discerned by viewing the surface appearance of molded parts.

1. Surface Quality

Table I is a comparison of the surface appearance of ROPET 400 and 500 with other 30% glass-reinforced polyesters molded under identical conditions. Note the consistent, high gloss achievable with ROPET 400 and ROPET 500. The data show that ROPET resins can be molded with good surface quality when the mold temperature is as low as 185°F (85°C).

2. Warpage

All glass-fiber reinforced thermoplastics share a problem in that they tend to warp. In crystalline glass-reinforced thermoplastics, the problem is particularly difficult to solve because there are two sources of shrinkage around the fibers: thermal and crystallization shrinkage. To solve the warpage problem, resin manufacturers have added mixed fillers and alloys into the glass reinforced compound. However, in general, the resulting resin suffers from the loss of one or more mechanical properties.

Warping is difficult to eliminate because glass fibers tend to align themselves along the direction of polymer flow during mold fill. As a result, the resin can shrink to a greater extent across the polymer flow than along the flow. The shrinkage difference in the two directions results in warping, especially in thin sections. Although, by varying molding conditions and mold design, it is possible to minimize the amount of warp in a part, heretofore it has been virtually impossible to eliminate the problem.

ROPET resins have a low tendency to warp. Figure 2 shows that ROPET 450 warps less in typical 4" x 6" x 1/16" plaques than comparable 30% glass reinforced PBT or PET compounds.

The dimensional stability of a glass-fiber reinforced thermoplastic material once it is removed from the mold is also of interest. Change in dimension during use at high temperatures could have adverse consequences on the ultimate utility of the injection molded part. As shown in Table 2, both ROPET 400 and ROPET 500 show a greatly reduced tendency to undergo additional shrinkage during heat treatment.

3. Mechanical Properties

Typical short-term mechanical properties for ROPET 400 are summarized in Table 3. Properties for ROPET 500 are summarized in Table 4. Of particular note are the impact strength values for both ROPET resins. The notched Izod impact of the ROPET resins is about double that of similar grades of glass-reinforced PET, and the tensile impact displays more than a two-fold improvement over PET. Similarly, the impact values are higher than 30% glass-reinforced PBT. Furthermore, the improvement in toughness has been obtained while achieving the high heat deflection temperatures at 66 psi and 264 psi characteristic of crystalline, glass-reinforced PET.

4. Flammability

The flammability characteristics of polymeric materials have become of great concern to design engineers. Flame retarded ROPET 500 passes the 94 V-0 test at 0.040" thickness when tested according to the Underwriters Laboratories Standard 94.* The Oxygen Indices for ROPET 400 and ROPET 500 are 19.9% and 29.1% O_2, respectively.

*This rating is not intended to reflect hazards presented by this or any other material under actual fire conditions.

5. Electrical Properties

ROPET resins exhibit excellent electrical properties and can be expected to maintain these properties over a wide range of temperature and humidity conditions. The electrical

properties of ROPET 400 are summarized in Table 5 and those of ROPET 500 are to be found in Table 6. Note the high Comparative Tracking Index (CTI) of both the general purpose and flame retarded grades. As developed by the IEC, CTI is intended to measure the relative behavior of solid insulating materials to their susceptibility to surface tracking when exposed to water and other contaminants in the environment. In practice, the voltage at which a material begins to track under aggressive conditions of high surface moisture and electrolyte concentration is used as a measure of the susceptibility of the material to track. The CTI of ROPET 500 is considerably higher than comparative grades of flame retarded PBT resins.

PROCESSING ROPET RESINS

ROPET molding resins can be molded in conventional equipment and do not pose any unusual processing problems. Reciprocating screw machines are preferred for processing ROPET due to their ability to produce uniform melt temperatures and minimum part stress. Since all grades of ROPET flow well, the molding press should have a well fitting check ring to minimize leakage and maintain injection pressure.

1. Drying

The moisture level should be kept below 0.05% during molding to prevent the hydrolytic degradation that occurs with all polyesters. Generally 2-3 hours at 250-275°F will be sufficient to dry ROPET compounds to be acceptable for molding. To maintain this moisture level, use of dehumidifying type hopper driers is recommended.

2. Screw Speed

Since both ROPET 400 and ROPET 500 are glass reinforced, some care must be taken to minimize fiber breakage which could result in a reduction in physical properties. Screw speeds should be held to 30-60 rpm and minimum back pressure should be used.

3. Mold Temperature

For optimum properties and surface appearance, mold temperature should range between 195°F and 220°F.

4. Typical Molding Conditions

Typical injection molding conditions are:

Barrel Temperature, °F	490-550
Melt Temperature, °F	500-570
Mold Temperature, °F	195-220
Screw Speed, rpm	30-60
Screw Back Pressure, psi	0-50
Fill Speed	Medium to fast
Nozzle Type	General purpose or reverse taper
Cycle Time, seconds	25 to 60

5. Nozzles

Ropet alloys are easy flowing crystalline resins that may drool. If melt decompression is available, drool will not be a problem; even general purpose nozzles may be used. Otherwise, a nylon or reverse tapered nozzle should be used. A positive shut off nozzle can be used but extended use may result in excessive wear due to the glass erosion. In all cases, the nozzle should have its own heaters and controllers to prevent freeze off in the nozzle. Nozzle temperature should be above 520°F.

6. Cycle Time

The cycle time required for molding ROPET resins is determined by both the time to solidify in the mold cavity and the time to plasticize the additional melt for the next shot. Cycle times for ROPET compounds are comparable to glass filled PBT compounds. ROPET will cycle rapidly in small thin wall parts but will require proportionately longer cycles in larger parts. Actual cycles will have to be determined for each part.

7. Gating

ROPET alloys will mold well with any common type gate. Small gates may be used because ROPET flows well. However, gates smaller than .060 inches in diameter or width should not be used in order to avoid fiber orientation and breakage. As mentioned previously, warpage resistance of ROPET is inherently very good. However, further reductions in warpage may be obtained through the use of multiple gating which minimizes the flow length and reduces orientation of the glass fibers.

8. Residence Time

ROPET compounds have good thermal stability. Generally an injection molding machine should be sized to the job such that 30% of the barrel capacity is used in each shot.

SUMMARY AND CONCLUSIONS:

ROPET resins are a new family of engineering thermoplastic molding materials. They are based on the development of a new class of polyester-acrylic alloys which are readily moldable, low in warp, and have good toughness. These properties are obtained in a resin which approaches glass-reinforced PET in stiffness and heat resistance. The resins are available today as pellets in 30% glass-reinforced, general purpose and flame retarded grades. Because ROPET resins are alloys, they may be tailored to specific applications and property requirements. They may be molded on conventional reciprocating screw injection molding machines to give parts which display an excellent balance of mechanical and electrical properties, dimensional stability, and a superior surface appearance.

TABLE 1

Surface Appearance of Thermoplastic Polyester Resins

Composition	60° Gloss, % Reflectance	
	85°C (185°C)	100°C (212°F)
ROPET 400	58	74
GR-PET	NA	5
GR-PBT	61	71
ROPET 500	57	70
Flame Retarded GR-PBT	NA	67

TABLE 2

Shrinkage of Glass-Reinforced Polyester Resins

Resin	Mold Temp. °C	Mold Shrinkage mils/in		Additional Shrinkage[1] mils/in	
		Length	Width	Length	Width
GR-PET	100	3.0	7.1	1.4	2.4
GR-PET	140	3.4	9.2	0.5	1.4
GR-PBT	100	3.6	6.5	1.0	1.2
ROPET 400	100	2.8	6.2	-0.2	0.3
ROPET 500	100	2.1	6.1	0	0.9

[1] After 24 hours at 150°C

TABLE 3

Mechanical Properties of ROPET 400

PROPERTY (Units)	ASTM Test Method	ROPET 400	30% GR-PET	30% GR-PBT
Izod Impact ft-lbs/in	D 256			
Notched 1/8" 23°C		2.0	0.8	1.7
Notched 1/8" -40°C		1.7	0.8	NA
Unnotched 1/8" 23°C		14.0	NA	15.0
Tensile Impact (ft-lbs/in^2)	D 1822	74.0	30.0	45.0
Heat Deflection Temperature, °C	D 648			
264 psi		218	224	207
66 psi		245	250	218
Tensile Strength, psi	D 638	16,500	17,700	17,300
Flexural Modulus, psi	D 790	1.2 X 10^6	1.35 X 10^6	1.1 X 10^6
Elongation at Break, %	D 638	2.7	1.6	3.0
Specific Gravity, gm/cc	D 792	1.53	1.59	1.53

TABLE 4

Mechanical Properties of ROPET 500

PROPERTY (Units)	ASTM Test Method	ROPET 500	30% GR-PET	30% GR-PBT
Izod Impact ft-lbs/in	D 256			
Notched 1/8" 23°C		1.9	1.0	1.1
Notched 1/8" -40°C		1.5	0.8	NA
Unnotched 1/8" 23°C		13.0	NA	13.0
Tensile Impact (ft-lbs/in^2)	D 1822	65.0	NA	40.0
Heat Deflection Temperature, °C	D 648			
264 psi		218	230	205
66 psi		245	NA	215
Tensile Strength, psi	D 638	16,000	17,400	17,000
Flexural Modulus, psi	D 790	1.2 X 10^6	1.3 X 10^6	1.25 X 10^6
Elongation at Break, %	D 638	2.5	1.5	2.3
Specific Gravity, gm/cc	D 792	1.64	1.65	1.65

TABLE 5

Electrical Properties of ROPET 400

Property (Units)	ROPET 400	30% GR-PBT
Comparative Tracking Index, CTI (Volts)	395	320
Dielectric Strength, 73°F, 50% RH (Volts/mil)	529	>489
Arc Resistance (sec)	112	123

TABLE 6

Electrical Properties of ROPET 500

Property (Units)	ROPET 500	30% GR-PBT
Comparative Tracking Index, CTI (Volts)	305	155
Dielectric Strength, 73°F, 50% RH (Volts/mil)	475	425
Arc Resistance (sec)	60	64

FIGURE 1

RELATIONSHIP BETWEEN CRYSTALLINITY AND SURFACE APPEARANCE OF REINFORCED POLYESTER ALLOY

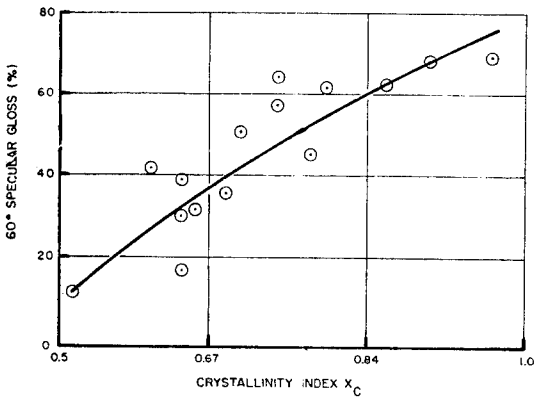
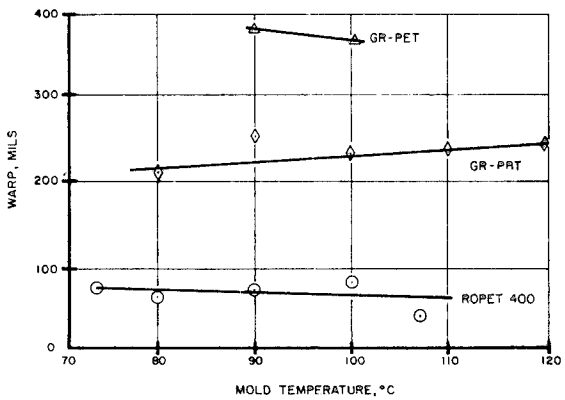


FIGURE 2

EFFECT OF MOLD TEMPERATURE ON WARPAGE OF GLASS REINFORCED POLYESTER MOLDED PARTS (4"x6"x $\frac{1}{16}$" PLAQUES)



NEW POLYAMIDE COMPOSITES EXPAND THE ENGINEER'S CHOICE

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ABSTRACT

Mineral reinforced nylons have been used for several years in the automotive industry as substitutes for die cast metal in exterior components and decorative trim.

As a result of design changes brought about by weight reduction efforts and downsizing, the use of mineral reinforced nylon has become, at the same time, more widespread and size limited.

Innovative applications of engineering plastics have required the development of new grades of reinforced nylon, possessing different balances of properties to accommodate more complex designs and special situations.

This paper explores the progress of mineral reinforced nylon in Detroit through selected case histories: Past successes and failures, current applications, and future directions.

New grades of reinforced nylons are presented which are designed to meet the exterior body and under-the-hood challenges of the 1980's. Engineering design considerations are discussed in light of the unique properties available.

HIGH IMPACT MINERAL FILLED NYLON 6

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INTRODUCTION

Nylon 6 is a high impact polymer. However, mineral fillers are often added to the nylon resin in order to increase its suitability for high modulus applications. But such fillers induce embrittlement which is reflected in lower impact resistance. This effect is undesirable where rugged endurance is demanded, especially at low service temperatures.

This paper will describe two new grades of mineral filled nylon 6 whose impact resistance is found to be two to three times that of the present commercial 66-based mineral filled products in the temperature range of -40°F to room temperature. The new products have high flexural moduli and creep resistance and promise excellent performance in engineering applications under severe service conditions.

RESULTS AND DISCUSSION

A. Level of Fillers:

The drop in impact strength for mineral filled nylon is in proportion to the filler level. But, of course, a maximum of filler is desirable from a consideration of the composite modulus. Therefore, the filler levels of greatest utility are obtained by balancing these two properties.

Unfilled nylon 6 has drop weight impact resistance of some 120 ft.lbs. at room temperature. As Figure 1 shows, the sacrifice in impact is significant at high filler levels. However, the impact is still much higher than for conventional mineral filled systems. Approximately 40% of the unfilled impact is retained at the 35% filler level.

B. Coupling Agent:

Several coupling agents were experimentally tested in connection with a variety of fillers including titanates and silanes. The presence of 0.5 to 1.0% silanes on the filler results in a retention of some 40-50% of the impact of unfilled nylon 6 when the filler level in nylon is 35%.

The absence of a coupling agent from the fillers leads to poor impact (1-5 ft.lbs.) although other requirements for a high impact product are met. The role of coupling agent, in addition to bonding nylon to fillers, is believed to enhance the rate of dispersion of fillers in the nylon matrix. Analysis of fillers which are extracted from compounded formulations shows the presence of grafted nylon chains which cannot be removed by the conventional nylon solvents.

C. Effects of Molding Conditions:

Melt temperatures of 540-580°F and a mold temperature of 180-200°F produce test specimens with high impact resistance. Lower melt and/or mold temperatures produce surfaces with splays or mineral blooms. High magnification study of low temperature surfaces using the scanning electron microscope reveals what appears to be melt fracture as is shown in Figure 2.

The size and location of the cavity gate also appears to exert some influence on the surface appearance. Large gate area is preferred. Also, fast injection speed is found to produce glossy surfaces.

D. Dependence of Modulus on Filler Level:

The flexural modulus of filled nylon 6 increases with increasing levels of mineral fillers. Unfilled nylon 6 has a flexural modulus of 395,000 psi which increases to 740,000 psi with 35% filler loading and to 830,000 psi with 40% filler, Figure 3 shows that this modulus increase is linear between 30 and 40%.

E. Effects of Moisture and Temperature on Impact:

The drop weight impact of dry nylon 6 samples exhibits a high dependence on test temperature, especially between 0°F and 80°F as is shown in Figure 4.

Moisture content also exerts a strong influence on the impact resistance. Figure 5 shows the change in impact when the moisture content is increased from dry-as-molded (below 0.1% moisture) to 0.5% water. The interesting feature of these curves is the cross-over point occuring at about -24°F below which high moisture content is actually a detriment to the impact strength. No explanation can be ventured at this time to explain this phenomenon.

F. Tensile Creep of Mineral Filled Nylon 6:

Tensile creep data representing various temperatures and stress levels are plotted in Figures 6 through 9. The total extension of 1/8" thick ASTM D638 Type II specimens was measured at the time intervals indicated on the creep plots using fixtures that are schematically represented in Figure 10.

When percent strain was plotted vs. time on log-log coordinates, most of the plots were essentially linear, at least for time values greater than one hour. The designer of engineered plastic parts is primarily interested in the strains resulting after hundreds or thousands of hours under load, not those occurring during the first hour. Regression analysis of each set of data for time values of one hour and greater enabled each of the creep curves to be expressed by an equation of the form: $\text{Log } e = m \text{ Log } t + \text{Log } b$. Where e=% strain and t=hours.

Values of slope m, and intercept b, for the combinations of temperature and initial applied stress that were investigated are tabulated in Table 1. A plot of Log b vs the product of stress and temperature was approximately a straight line as shown in Figure 11. Therefore, the equation for this line permits Log b to be expressed in terms of stress and temperature. Similarly, an expression for the slope, m, of the creep curves was obtained by assuming the plot of values of m vs the product of stress and temperature to be linear. Figure 12 show this relationship.

By substituting the expressions for m and Log b in the general creep equation, an equation which expresses creep in terms of the independent variables, time, stress, and temperature was obtained. This design equation, shown at the bottom of Table 1, is useful for estimating creep of mineral filled Type 6 nylon at conditions of stress and temperature at which actual creep tests were not conducted in addition to extrapolating creep data to

times greater than the actual testing time. The equation also tends to average and minimize errors that might exist in one or more of the individual creep curves.

Values of strain calculated with the design equation were generally in agreement with the corresponding experimental values for temperatures of 150°F and greater. This is also shown in Table 1. The agreement at 73°F was inferior, however, due to moisture absorption effects.

G. Melt Rheology of Mineral Filled Nylon 6:

Melt rheology data generated on mineral filled nylon 6 was as expected. Figure 3 shows plots of apparent melt viscosity as a function of shear rate for unfilled nylon and for 35% and 40% mineral filled products. The plots show the familiar non-Newtonian behavior at high shear rates above (10^{-2} seconds). Whereas, there is little difference between the melt rheology of both filled materials, both have higher viscosities than unfilled resin at any given shear rate up to and including 10^{-3} seconds. These curves were generated in an Instron Universal Tester using 4" long capillary with L/D = 66, at 250°C.

H. Mechanical Properties:

As was stated earlier, the addition of minerals to nylon 6 improves its flexural properties. Other improvements are also observed in yield, tensile strength and heat distortion temperature under load. Table 2 summarizes these properties in comparison with unfilled nylon 6 and mineral filled nylon 66 and 6/66 copolymers.

APPLICATIONS

The improvement in drop weight impact resistance of mineral filled nylon 6 over that of filled nylon 66 and 6/66 in the temperature range of -40°F to room temperature, while maintaining good creep, modulus and HDT characteristics, has led to a wide range of applications for which this material is particularly suitable. These include power tool housings, such as consumer chain saws and power drills, and in the automotive industry, louvres and fender and body extensions. Other applications are pulleys, blower jaws and housings. Impact tests on molded parts, such as power tool housings, have given the same excellent results as obtained on laboratory test specimens.

These compounds readily accept paints and primers and have undergone successful testing of several of the automotive systems. Of interest for power tool applications, the composites are light enough to be easily pigmented.

TABLE 1
35% MINERAL FILLED NYLON 6

Temp. (°F)	Stress (psi)	m (Slope)	b Computed Strain@1 hr	Coefficient of Determ. (%)	% Strain @1000 hrs Experimental	% Strain @1000 hrs Calculated*	Difference (%)
73	2,000	.136372	0.212	89.1	0.547 (336 hr.)	0.84	+53.3
	4,000	.109793	0.663	85.8	1.45 (336 hr.)	1.57	+ 8.3
	6,000	.126191	0.953	91.3	2.24 (336 hr.)	2.91	+27.6
150	2,000	.0314681	2.04	98.7	2.48 (574 hr.)	1.64	-33.8
	4,000	.039037	5.59	98.5	7.12 (574 hr.)	5.96	-16.3
200	1,000	.0136574	1.11	73.6	1.21	1.07	-11.5
	2,000	.0218026	2.50	92.4	2.88	2.55	-11.5
	2,000	.0314517	2.77	98.8	3.28 (313 hr.)	2.50	-23.8
	3,000	.0261497	4.93	96.4	5.88	6.09	+ 3.6
	4,000	.0313293	8.26	96.2	10.2	14.47	+41.8
	4,000	.041905	10.66	98.5	13.4 (313 hr.)	13.95	+ 4.1
250	1,000	.0179195	1.11	91.1	1.24	1.33	+ 7.3
	2,000	.0213447	3.27	97.8	3.77	3.92	+ 4.0
	3,000	.0321108	6.34	98.7	7.88	11.60	+47.1
	4,000	.0360178	12.77	97.7	16.4	34.3	+109

*Log e = 5.22 x 10^{-8} S x F (Log t + 33.05) - 0.3475

Where: e = Total Strain (%)
t = Time (Hours)
S = Applied Stress (psi)
F = Temperature (°F)

TABLE 2
PROPERTIES OF MINERAL FILLED NYLONS

Property	Test Method ASTM	Nylon 6	35% Filled Nylon 6	40% Filled Nylon 6	40% Filled 66	40% Filled 6/66
Drop Weight Impact ft.lbs.	D-2444	120	50	30	19	19
Izod Impact. Ft.lbs.						
Notched		1.1	1.0	0.97	0.80	0.90
Unnotched		No break	45	40	33	21
Flexural Stress, psi		16,400	20,000	21,500	20,500	22,000
Flexural Mod. psi X10^5		395,000	7.4	8.2	8.2	8.4
Tensile Stress, psi		11,800	12,800	13,100	13,500	13,500
Tensile Elong.%		200	20	15	15	20
Deflection Temp. °C, 264 psi		65	130	130	130	140
S.G., g/cc		1.13	1.45	1.46	1.48	1.46
Mold Shrinkage W/W		0.013	0.012	0.012	0.012	0.012

Figure 1
The Relationship Between Filler Levels and Drop Weight Impact of Nylon 6

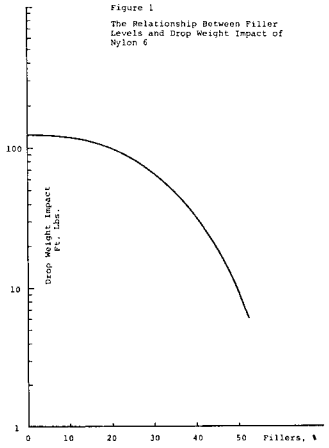


Figure-2 SEM of mineral filled Nylon 6. Surface shows melt fracture for a part molded at low temperature (X=10,000)

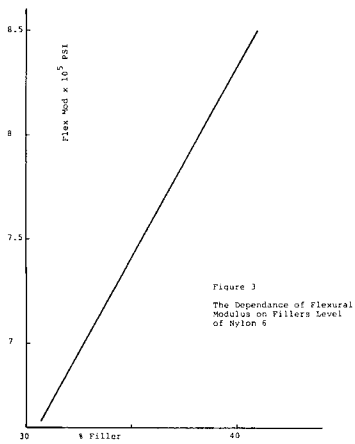


Figure 3
The Dependance of Flexural Modulus on Fillers Level of Nylon 6

Figure - 4 Drop Weight Impact of Mineral Filled Nylon, Dry as Molded ASTM D-2444

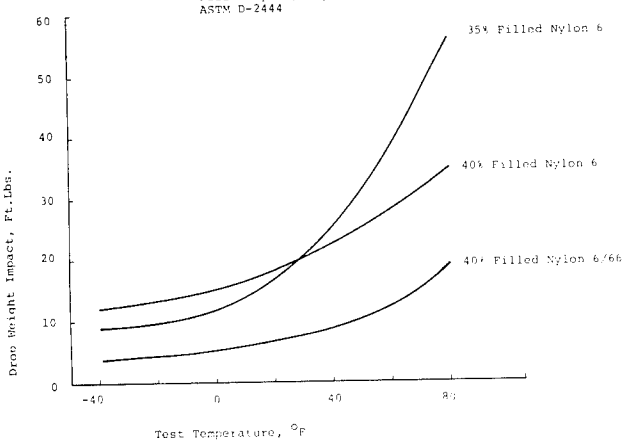


Figure 5

Drop Weight Impact of Mineral Filled Nylon 6, Moisture Effect

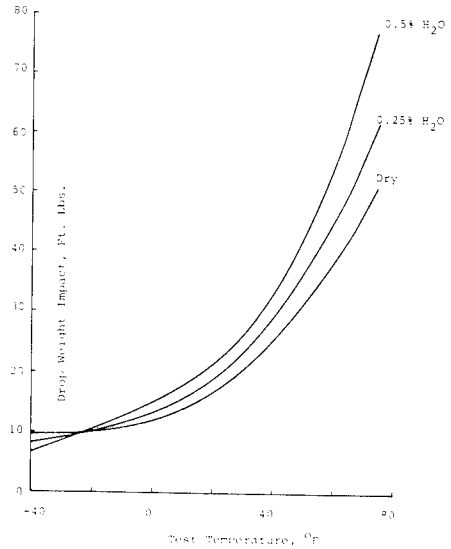


Figure 6

Tensile Creep of 35% Mineral Filled Nylon 6 @73°F (23°C) Dry as Molded

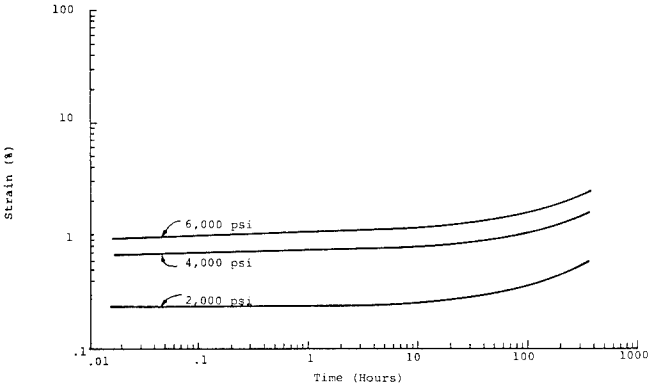


Figure 7

Tensile Creep of 35% Mineral Filled Nylon 6 @ 150°F (65.5°C)

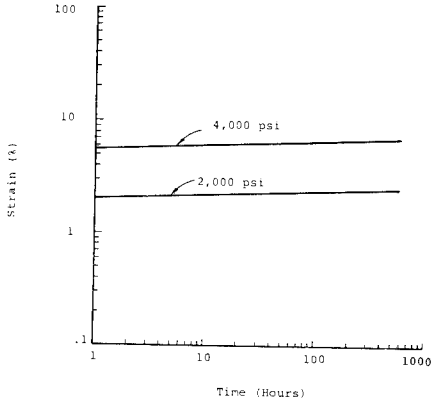


Figure 8

Tensile Creep of 35% Mineral Filled Nylon 6 @ 200°F (93°C)

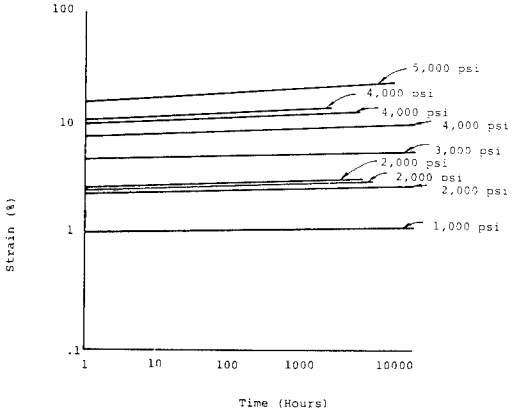


Figure 9

Tensile Creep of 35% Mineral Filled Nylon @250°F (121°C)

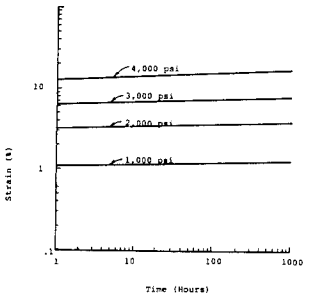


Figure 10

Spring Loaded Creep Test Fixture

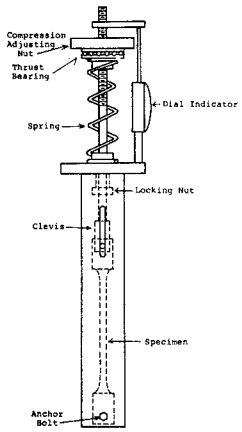


Figure 11

Correlation of Intercept Values for Tensile Creep of 35% Mineral Filled Nylon 6

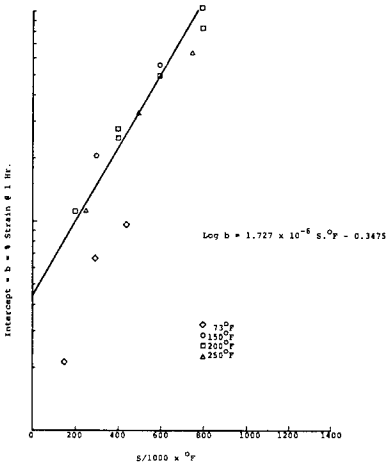


Figure 12

Correlation of Slope Values of 35% Mineral Filled Nylon 6

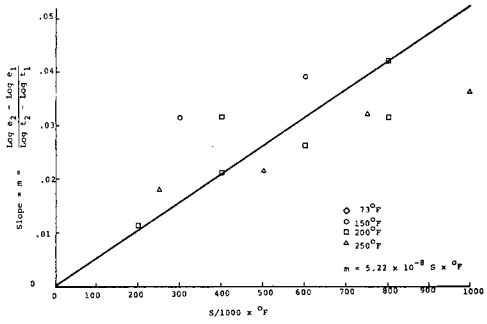
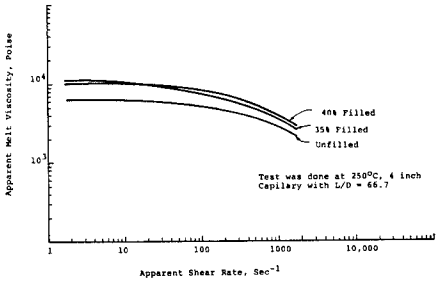


Figure 13

Melt Rheology of Mineral Filled Nylon 6



PROCESS ANALYSIS OF THERMOPLASTIC STAMPING

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INTRODUCTION

Thermoplastic stamping is a forming process in which preheated polymeric sheets, which can be fiber reinforced, are shaped into products under moderate pressure in matched metal dies. The process has similarities with both sheet metal stamping and compression molding.

The process which is examined here is melt-flow stamping. In this process, parts are formed by melt flow at temperatures above the polymer melting point. A second thermoplastic stamping process is solid phase stamping, in which forming takes place below the polymer melting point by a deformation mechanism. Key differences between the two stamping processes are summarized in Table 1.

Both mechanical and hydraulic presses can be used for melt flow stamping of thermoplastics. Mechanical presses close more rapidly and build up pressure more rapidly than do hydraulic presses. In a mechanical press, pressure decreases from the maximum because the part cools and shrinks and/or because there is continuing melt flow. In a hydraulic press, pressure remains at the maximum.

ANALYSIS OF MELT FLOW STAMPING

The flow parameters used for this analysis of thermoplastic stamping are shown in Fig. 1. In this model, the fluid does not fill the space between mold halves initially, and the force applied to the material and its temperature vary during the stamping cycle.

The rheology of other plastic fabricating processes, of several rheometers and of certain lubricating system is, as described by several authors (1-7), similar to the rheology of thermoplastic stamping. None of these references, however, cover the case where applied force and temperature vary and where the mold is not filled initially.

Several simplifying assumptions have been made for this analysis:

(1) Viscosity obeys the power law, $\tau = m(-\partial u/\partial z)^n$, where the coefficient m is independent of temperature.

(2) Sheet temperature is uniform at time t = 0.

(3) Mold temperature is constant.

(4) The effect of fiber orientation and of long fiber mat on flow can be neglected.

(5) The movable mold half first touches the blank at time t = 0.

The flow equation which shows the total stamping force exerted by the press is derived from the standard equation for conservation of momentum, the power law viscosity relationship and a material balance. It is given by Wilkinson (7) as

$$F = \left(\frac{2\pi m R^{n+3}}{n+3}\right)\left(\frac{2n+1}{n}\right)^n\left(\frac{1}{h}\right)^{2n+1}\left(U_p\right)^n \qquad (1)$$

To model the cooling process the energy equation (heat transfer) has been uncoupled from the flow equation and is treated separately. The cooling rate for a semi-infinite slab which is in contact with a single surface (8) is used

$$z = \left[1 - \left(\frac{T - T_o}{T_p - T_o}\right)^{1/3}\right](24\alpha t)^{1/2} \qquad (2)$$

The energy of crystallization is incorporated into the specific heat to obtain α. At the interface between solid and molten plastic, $T = T_m$ and $z = z_s$, and therefore

$$z_s = \left[1 - \left(\frac{T_m - T_o}{T_p - T_o}\right)^{1/3}\right](24\alpha t)^{1/2} \qquad (3)$$

$$= C_1 t^{1/2} \qquad (4)$$

where

$$C_1 = \left[1 - \left(\frac{T_m - T_o}{T_p - T_o}\right)^{1/3}\right](24\alpha)^{1/2} \qquad (5)$$

The interface position equation can be combined with a mass balance equation, neglecting density changes,

$$V = \pi R^2(h + 2z_s) = \pi R_o^{\,2} z_o \qquad (6)$$

to give a solution for the thickness of the fluid layer

$$h = \frac{R_o^{\,2} z_o}{R^2} - 2C_1 t^{1/2} \qquad (7)$$

This value for h is then substituted into equation (1) to give a general flow equation for thermoplastic stamping

$$F = \frac{C_2 R^{n+3} u_p^{\,n}}{\left(R^2{}_o z_o / R^2 - 2C_1 t^{1/2}\right)^{2n+1}} \qquad (8)$$

where

$$C_2 = \left(\frac{2\pi m}{n+3}\right)\left(\frac{2n+1}{n}\right)^n \qquad (9)$$

In commercial stamping operations the total force applied to the mold is usually higher than that indicated by equation (8), and the time required to solidify the part is much longer than the time needed to fill the mold. For this special case, i.e., the mold is filled before the maximum force of the press is applied, further simplification is possible. The material balance between initial blank and formed part

$$\pi R_o^2 z_o = \pi R_f^2 z_f \tag{10}$$

is combined with the general flow equation (8) to give the relationship between the force, F_f, and time, t_f, needed to fill the mold

$$F_f = \frac{C_2 R_f^{n+3} u_p^n}{\left(z_f - 2C_1 t_f^{1/2}\right)^{2n+1}} \tag{11}$$

Data for the closing speed of hydraulic presses are reported by Marker and Ford (9) and Silva-Nieto, et al. (5). Each paper shows the closing speed to be essentially constant until maximum pressure is reached. Under such conditions the time required to fill the mold can be calculated from the change in thickness between blank and part

$$t_f = \frac{z_o - z_f}{u_{pH}} \tag{12}$$

When this value is substituted into equation (1) it gives an operating equation for stamping thermoplastic parts on a hydraulic press when the mold is filled before maximum press pressure is reached

$$F_f = \frac{C_2 R_f^{n+3} u_{pH}^n}{\left(z_f - 2C_1\left(\frac{z_o - z_f}{u_{pH}}\right)^{1/2}\right)^{2n+1}} \tag{13}$$

For a Newtonian fluid where n = 1 and m = η, this relationship reduces to

$$\frac{F_f}{\pi R_f^2} = \frac{3\eta R_f^2 u_{pH}}{2\left(z_f - 2C_1\left(\frac{z_o - z_f}{u_{pH}}\right)^{1/2}\right)^3} \tag{14}$$

where $F_f/\pi R_f^2$ is the pressure applied to the projected area of the part.

DISCUSSION OF RESULTS

An analytical approximation for stamping of thermoplastics has been developed by making several simplifying assumptions. The most important of these assumptions are:

(1) That viscosity is independent of temperature. Viscosity does in reality change with temperature, and since there is a temperature gradient through the material thickness, there must also be a viscosity gradient. The more generally valid assumption $m = \eta_o e^{-aT}$ does not permit a simple analytical solution.

(2) That sheet temperature is uniform at the start of the stamping cycle. In practice, the surface temperature of the sheet as it emerges from an IR oven will be higher than the center temperature. There will also be cooling prior to contact from the movable mold half.

(3) That cooling rate can be represented by cooling of a semi-infinite slab. Since cooling actually takes place from both surfaces, the real center temperature will be lower than the model indicates.

The usefulness of equations (8), (13) and (14) as guidelines for process optimization and for cycle time estimates will have to be verified experimentally. (The authors expect to report the results of such experiments in a subsequent presentation.) Generally, the relationships predicted by these equations coincide with stamping experience. For example, the curves in Fig. 2, which have been calculated from equation (14), show that the force required to fill the mold increases with increasing part diameter and with increasing draw down ratio. (Draw down ratio is the ratio of part area to blank area, i.e., $\pi R_f^2/\pi R_o^2$. From a material balance, this ratio equals z_o/z_f.) Although not illustrated in Fig. 2, calculations also show that the required stamping force increases sharply with decreasing part thickness.

The effect of mold closing speed on stamping force, as pictured in Fig. 2, is unexpected, but does not contradict experience. The indicated increase of needed tonnage with increasing press speed at the higher speeds, and the existence of a tonnage minimum with some combinations of certain operating parameters were not anticipated. This closing speed-press force relationship will have to be examined more closely.

Quantitatively, the curves in Fig. 2 fall within the range of process variables which would be expected from stamping experience. For example, when stamping a part of 320 mm (12.6") diameter x 2.5 mm (.1") from a 2.8 mm (.11") gauge blank which covers 90% of the mold area, Fig. 2 predicts that 7 MPa (1000 psi) will be required to fill the mold on a press closing at 4 mm/s (9"/min). This pressure is calculated from the projected area of the part. The equivalent press force is 560 kN (63 tons), a value consistent with the expectations, that a part of this size can be made on a 100-ton press. (Note: Curves in Fig. 2 and other calculations are for a nylon-6 based composite, Allied Chemical Corporation's STX®-250 stampable sheet).

Although first calculations are encouraging, the applicability of these simplified flow equations for thermoplastic stamping remains to be proven by experiment.

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NOMENCLATURE

α	Thermal diffusivity
η	Newtonian viscosity
τ	Shear stress
C	Constant
F	Stamping force
h	Thickness of molten plastic
m	Viscosity power law coefficient
n	Viscosity power law exponent
R	Radius of flow front
t	Time
T	Temperature
T_m	Solidification temperature
u	Velocity
V	Volume of plastic
z	Coordinate in mold travel direction

Subscripts

f	Flow has stopped
H	Hydraulic press
o	Initial conditions
p	Mold
s	Solidified plastic

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Table 1. Thermoplastic Stamping Processes

	Melt Flow	Solid Phase
Forming Temperature	>Melting point	<Melting point
Mechanism	Melt flow	Deformation
Part shape	Gauge can vary	Uniform gauge
Orientation	Little or none	Substantial
Reinforcement	Long, short fibers	Usually none
Use temperature	Polymer limits	Has plastic memory

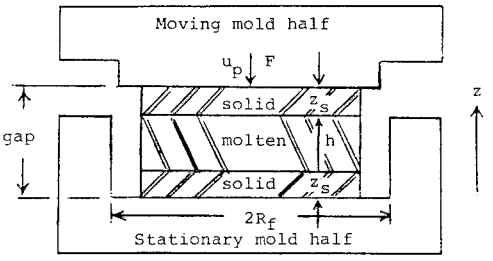

Fig. 1. Flow model for thermoplastic stamping

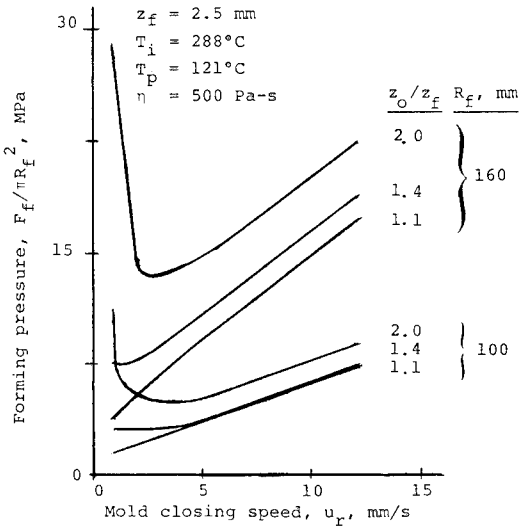

Fig. 2. Hydraulic press: Minimum forming pressure for constant part thickness

GR NYLON-6 (STX® SHEET)[1] STAMPING

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INTRODUCTION

The stamping system for glass reinforced nylon-6 sheet (GRNS) is best described as a fast compression molding process, with the potential to reach cycle times of 20 seconds. The system can use the mechanical presses found in most steel stamping plants, or hydraulic presses found in compression molding plants.

This paper summarizes the conclusions reached over several years of production and more recent development experience using GRNS.

The design comments which follow point out the methods which led to fast, consistent production cycles, and describe the performance achieved leading to successful applications.

I. THE DESIGN OF PROCESS EQUIPMENT FOR SATISFACTORY PRODUCTION PARTS

The stamping process is described in figure 1.

Blanks are heated in an oven until the nylon is well above its melt point. The objective is to deliver the heated blank to the press at a uniform temperature regardless of ambient temperature, recent heat history of the blanks or operator actions.

The hot blanks are transferred to a heated die. The press is closed to the bottom of the stroke. The objective is to perform these steps quickly at controlled temperature and with precise blank placement.

The press is allowed to dwell at close while the part cools. The press is opened, and the part ejected. The objective is to ensure fast, economical production, at the quality desired.

OVENS

It is important to recognize that for efficient production the process is continuous. The heat balance at all points of the stamping process is important; in some applications it is critical.

Production IR ovens developed by many plastics stampers for materials other than GRNS are generally unsatisfactory.

The key GRNS oven design items are selection of the basic heating element, the heat control system, and the mode of transfer of the blank through the oven.

GRNS is sensitive to radiation intensity and can degrade at the surface before the center of the blank is adequately heated. IR radiation at 3 to 4 μm is the preferred range.

An efficient low temperature heat source[2] about 10-15 cm (4-6") from the surface gives a uniform blank temperature. This is especially important for appearance applications.

The most satisfactory control results from feedback of the blank surface temperature (via an IR sensor) to the last three heating zones. Thermal output in these zones is increased or decreased at a preselected level to ensure uniform blank temperature.

Radiation should be evenly distributed over the total area of the blank. The heating elements should extend at least 15 cm (6") beyond the blank carrier to ensure uniform heating. In wide ovens, additional controlled lateral heating zones may be used to even out center to side temperature variations.

The carrier belt or tray transfers the blank from zone to zone through the oven. It must support a hot blank which will tend to sag. For surface applications, the blank must be heated on a carrier surface that does not interfere with uniform heat absorption. A preferred technique uses a solid metal tray coated with TFE for ease of release.[3] Tray temperature must be controlled to a maximum of 315°C (600°F) to avoid decomposition of the TFE. Non-surface applications can be heated on a wire belt with wires running in the transverse direction only.[4] This feature allows for easier manual pick up and belt cleaning.

The design of the oven should also include:

1. Provision for adequate length, 5 or 6 zones will allow for most situations.
2. The mechanism for moving the carrier belt or tray through the oven to allow for precise indexing in each zone.
3. Flexibility to change zone length as required.
4. Means to remove fumes from the operating area.
5. Means to remove blanks from the oven or separate blanks from the heat source in the event of fire or emergency.
6. Compliance with safe practices in heat insulation and radiation shielding.

PRESSES

Both mechanical and hydraulic presses can be used for stamping GRNS production parts.

Experience has shown that fast closing straight sided mechanical presses of up to 24 strokes/minute give excellent results.

1. The press is normally modified with a limit switch to allow dwell on bottom dead center (bdc). A timer to restart after dwell is recommended.
2. The press should have an adequate pneumatic clutch and brake system.
3. Typical steel stamping presses may be of too short a stroke to take advantage of the deep draw capabilities of the GRNS stamping process. Mechanical presses faster than 24 strokes/minute will probably work well, but have not been demonstrated.
4. OBI and other gap presses are unsatisfactory because press characteristics lead to a lack of parallelism.

Hydraulic presses can also produce good results.

1. Presses close to the bottom of the stroke and remain at pressure until opened.

2. If the press is designed for steel stamping, it will probably have insufficient cooling in the hydraulic oil system to allow for continuous use at dwell times of 15 seconds or more.

3. Hydraulic presses use fast, intermediate, and finally at contact, slow closing speeds. Glass reinforced nylon-6 demands a high closing speed. This may entail increasing the pump size. Both increased speed of close and improved smoothness of closing will result. Presses that at contact close at 75 cm (30")/min. will work on some parts; tripling speed at close will result in the ability to stamp a larger part size at the same pressure, and decrease cycle time through a favorable reduction in other process variables.

In all cases, once the blank has been contacted by both halves of the die, it is important that pressure be applied quickly and smoothly. Hesitation in closing, or a delay in pressure build-up will show up in marks or incomplete flow in the part.

DIES

Dies must be of the vertical flash design (figure 2), similar to those used for SMC. Because GRNS flows through small spaces, shutoffs must be 0.002" clearance for a flash free condition.

Die construction is similar to that used for SMC dies.[5] It uses pins and heavy heel blocks for shear edge guidance, an ejector system, and cooling lines made to operate in the range of 180-270°F. Dies must be built to accommodate the shrinkage of GRNS (0.6%).

In contrast to SMC dies, more intricate work can be readily stamped into the part. There can, however, be no large mash-out areas. Large holes which occur perpendicular to the ram direction are better pierced as a secondary operation. Frequently these cutouts can be re-used as part of the material input for further stamped parts. Flash free holes can be molded in, around pins or posts closing to 0.002" clearance on the opposite die half.

ANCILLARY EQUIPMENT

Piercing and punching tools must be ground to sharp edges, hardened and flat ended with adequate support on the punch button (figure 3). Taper in the hole is about 3% on a part thickness of 2.5 mm (0.100"). Holes should be pierced immediately after stamping while the part is still warm. Fixtures and tools must be carefully dimensioned for the correct quality part. Round, clean holes can be drilled.

II. PROCESS VARIABLES

Production conditions to seek are:

	Reason
1. Low die temperature in the range 80-130°C (180-270°F)	Speeds cooling, decreases cycle.
2. Low melt temperature in the range 290-315°C (550-600°F)	Speeds cooling, decreases cycle.
3. Fast speed at close in pressure range 3.4-14 mPa (500-1000 psi) Hydraulic: 60 cm/min at close and up. Mechanical: 15 strokes/min and up.	Improves ability to fill cavity, allows other variables to be reduced resulting in decreased cycle. Allows a lower tonnage press.

We conclude that presses which have slow speed at close can be used at the expense of slower cycles and increased tonnage.

As an example, a 1.36 kg (3 lb) automotive surface part was stamped in a 2700 kN (300 ton) hydraulic press closing at about 50 cm (20")/min and also in a mechanical press of similar size closing at 24 strokes/min.

Conditions necessary to stamp to surface quality were:

Press type	Hydraulic	Mechanical
Melt temperature	315°C (600°F)	315°C (600°F)
Die temperature	132°C (270°F)	93°C (200°F)
Cycle time	50 seconds	30 seconds
Dwell time	35 seconds	15 seconds
Part weight	1.5 kg (3.3 lb)	1.36 kg (3 lb)

Key observations were the ability to get adequate flow at lower die temperature, the resulting more rapid cooling time, and a lower part weight.

The process conditions of the faster closing mechanical press are of economic advantage to the producer.

III. THE DESIGN OF GR NYLON-6 PARTS

Automotive parts which have been successful are those where heat, impact, and creep resistance, oil contact resistance and rigidity are important factors in the applications.

Primarily, these are under the hood parts such as oil pans, transmission pans and covers (figure 4). Initial GRNS pan designs showed similarity to steel pans but designers soon used the potential of a tough and strong plastic material that could be stamped into any shape. Pans can be designed to accommodate a deep draw; adjacent parts or weldments can be integrated into a single stamping, saving on assembly and tool costs; and pans can include molded-in inserts when necessary. In this way, the cost of raw material is offset by reduced manufacturing and assembly costs.

Oil pans require sealing to prevent leakage. Proper flange design, appropriate gasketing and correct assembly procedures will assure good results. The flange should be flat and parallel with its mating surface.

A bead of room temperature vulcanizing silicone rubber (RTV) can be used as a formed-in-place gasket.[7] A groove is provided in the flange surface to accommodate this bead. Totally satisfactory sealing can be obtained with moderate bolt torque.

Conventional gaskets should be moderately soft[6] in order to conform to minor irregularities. Stress risers may be added to increase localized pressure and improve sealing.

Since the use of plastics for oil pans incorporates an additional element of creep beyond the gasket into the system, some means should be provided to compensate for torque loss. Belleville spring washers, increased bolt torque, longer bolts and similar techniques may be considered.

The available GRNS materials range from a combination of short glass fibers and fillers at about a 60% nylon level (STX-250)[1] to a lamination of a similar composition with long glass mat. This latter material type forms the basis for the structural-under the hood (STX-363)[1] applications. Its resistance to distortion when bolted to a steel part and heat cycled (as in the oil pan application) is excellent.

A second type of automotive application has shown success in prototype. GRNS is one of the few thermoplastic materials which has strength, stiffness, creep resistance and temperature resistance combined with the ability to be formed into large, thin parts such as a hood inner.[8] Preshaped blanks are formed into a complex series of hat-shaped channels (figure 5) which provide support to the outer metallic skin, and the hemmed edge. These parts experience temperatures of 350°F during paint oven exposure.

Some other stamped GRNS parts now in volume production are smaller, and are manufactured from surface grade material (they are semi-decorative in the application). These parts have ribs and bosses, fine and coarsely textured surfaces, raised lettering, holes variously molded, pierced or drilled. Two parts have been in production for several years. The first, a riding mower transmission lever cover, and the second, an engine shroud, do a tough functional job where exposure to UV, heat, impact and vibrational stress is routine.

GRNS parts in common with all solid thermoplastics parts are susceptible to sink marks. These can be disguised and minimized conventionally by placing bosses on curved surfaces, placing ribs behind feature lines and using a wall-to-rib thickness ratio of 10:4 or more. Sink marks above bosses may be reduced by extending the core pins into the wall section by about 0.010 inch. Because GRNS has excellent strength and holding power, automotive specifications can be met using bosses smaller in diameter than usually found in other materials (figure 6).

Class A surface approval has been received on a small automotive part.

CONCLUSIONS AND SUMMARY

The combination of the hot flow stamping process and GRNS composite materials available is finding a number of large volume applications because of the favorable cost/performance balance. The reasons are:

1. The process can produce about half a million parts/year from a single die.
2. The process can use existing press equipment; capital input into ovens and ancillary equipment is minor.
3. The material has a superior balance of properties; modulus, creep resistance, heat distortion, impact resistance, and oil/gasoline resistance are excellent.
4. The material does not cure and is recyclable. It has unlimited shelf life as long as protected from moisture pick up.
5. Parts from this material can be prototyped using Kirksite tooling. Low volume production is also feasible using Kirksite.
6. The material is paintable to a Class A surface.
7. The material is 20% less dense than SMC.
8. The combination of GRNS and stamping produces parts of greater design freedom than steel parts at a lower weight. Lower costs are achieved if parts are integrated or if deep draw requires multiple stamping.
9. The combination of material and process produces a part of less glass and polymer orientation than a comparable injection molded part. Large, thin, tough GRNS parts capable of functional use are made available for the first time.

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Mr. Dunning is Product Manager for the STX Department, Fibers Division, Allied Chemical Corp. He previously held positions in development and marketing in the Film Department. He received an MBA from Fairleigh Dickinson University in 1972, and is a graduate chemist and polymer technologist of schools in London, England. He had 15 years experience working with many plastics materials and processes until he emigrated to the USA in 1967.

During the past seven years, he has worked on the development and commercialization of stamped nylon sheet. He is a member of SPE and the Society of Manufacturing Engineers.

Lowell G. Ward

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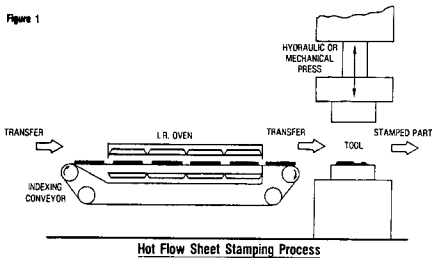
Figure 1



Hot Flow Sheet Stamping Process

Figure 2

Shear Edge Detail
Hot Flow Stamping Die

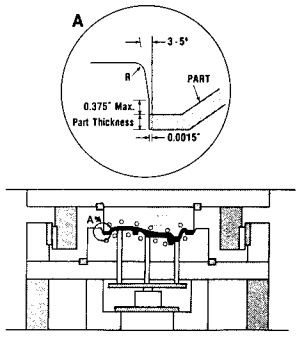


Figure 3

Piercing

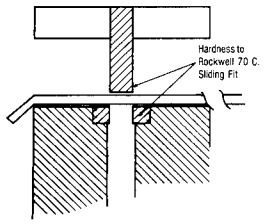


Figure 4

Flange Detail

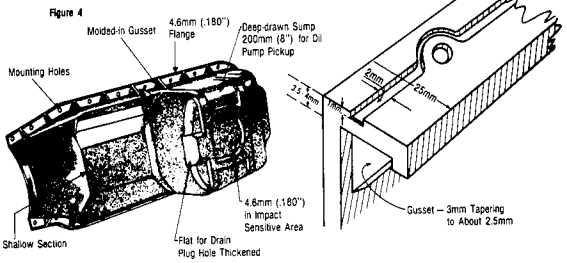


Figure 5

Hood Inner Construction

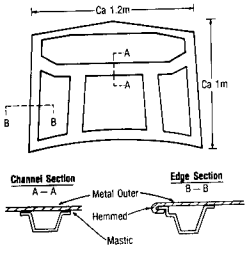
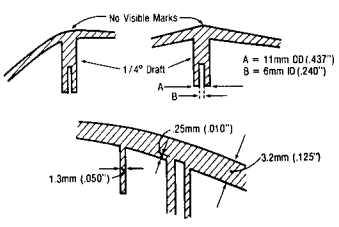


Figure 6

Bosses, Ribs & Fastenings



AUTOMATED PROCESSING FOR HOT STAMPED POLYPROPYLENE SHEET

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John F. Harms

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Chevrolet-Flint Manufacturing
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INTRODUCTION

Features of primary importance in the design of certain non-structural parts for the 1980 Citation were minimum weight, high impact strength and good sound deadening characteristics. Fender skirts and splash shields offered the most potential as parts for possible application of such parameters. These design constraints pointed toward the use of a thin gage, tough material with noise absorption characteristics, such as a high molecular weight polyolefin. Consequently, an investigation into the feasibility of using hot stamped plastic sheet in lieu of conventional injection molded plastic was initiated. Figure 1 illustrates the 1980 Citation wheel house compartment, containing a fender skirt and splash shield, as currently produced at Chevrolet.

This paper will briefly outline initial planning, and cost and material considerations as part of the Introduction. It will then discuss, in detail, the process engineering design and build of tooling and equipment, material handling/processing, and installation through production of the complete operation. The paper concludes with an overview of advantages/disadvantages of the stamping process as viewed after approximately six months of production.

INITIAL PLANNING

At the time this process was being investigated, the plastics research group was working with a material supplier on an experiment in stamping disc brake dust shields. The data collected by this group generated further testing, which suggested consideration of that supplier's high impact polypropylene. This type of material appeared to offer the most potential for the Citation parts application. Figure 2 shows the early experimental brake dust shields.

COST CONSIDERATIONS

The Industrial Engineering Department, in conjunction with the Master Mechanic's Department, developed cost data for the injection molded parts versus a hot stamped part. Figure 3 depicts the front fender skirt. The main cost advantages appeared to be in the areas of net production and labor involved. The capital investment for the stamped process was comparatively low, especially when the decision was made to use hydraulic presses for optimum control versus conventional presses without dwell characteristics.

No sooner had planning started on the first project, when a parallel project on a second part was initiated, which reduced capital investment figures for the total project. Due to the higher volume involved the concept of in house extrusion of sheet material then became attractive and economically feasible.

The second project, the engine compartment side splash shield, was planned for use not only on the Chevrolet Citation, but also on the Buick, Oldsmobile and Pontiac versions of the "X" car. This "corporate volume" provided an additional disincentive for conventional injection molding. Figure 4 depicts the side splash shield.

Considering the context of the two projects, the final decision was made to proceed with the hot stamped parts using a 12 second cycle target for one left and right hand simultaneously. For the splash shield project, a four cavity die operation (two L.H. and two R.H.) was decided upon due to the high production requirements and smaller part size.

MATERIAL CONSIDERATIONS

Close contact was maintained between the Chevrolet Engineering material group and the material supplier in selecting the most appropriate material for the operation. Although preliminary studies suggested that polypropylene offered the best physical properties, characteristics of polyethylene were compared and contrasted with those of polypropylene in selecting the best overall material. Polyethylene has a low melt temperature, and possibly better flow characteristics in the match metal form die, but it did not meet the physical requirements specified by Engineering, such as strength at elevated temperatures and ability to withstand high impact at cold temperatures. Polypropylene of the fractional melt family was superior with respect to those desired characteristics; and accordingly, was the material finally chosen.

PROCESS ENGINEERING

FORM AND DEVELOPMENT

The original process and subsequent cost analysis had been made at an early stage; however, they served as guide lines to getting the project into gear. The Chevrolet Engineering Die and Pattern Group was enlisted to set-up a draw development very similar to that used in sheet metal draw processes. A left and right hand model were used, keeping the draw and form attitudes in mind at all times. The front fender skirt was quickly discovered to have back draft and overlaps, so position adjustments were made. Figure 5 illustrates the front fender skirt draw development tip. The front and rear of the skirt were swung out of car position sufficiently to achieve a good form attitude and adequate trim conditioning. This technique is used frequently in sheet metal, but generally requires added operations to correct. It was felt that added operations would be unnecessary in this case due to the fact that plastic can be trimmed at die angles not acceptable in sheet metal processing.

It was decided that a prototype form die should be made in kirksite, and die conditioning could be incorporated from the start, (i.e., run-off, trim ledges and form ring). This prototype could prove extremely valuable in development because of lack of knowledge of shrinkage, handling, etc., and lack of data for comparison. Figure 6 provide a sketch of the prototype tool proposal.

DETERMINING OPERATIONS

Once the tip angles, swing out angles, and trim conditions were established, further processing was possible. Secondary trim operations were analyzed using plastic skins from the form model. Figure 7A, B & C illustrate front fender skirt die process picture sheets. A determination was made to trim the parts in two operations separating in the latter. The picture sheets were constructed in conjunction with a flow chart, because it was now feasible to make press determinations (i.e., size, tonnage, action, etc.).

HANDLING (AUTOMATIC VS HAND)

At this point it was necessary to determine how the hot sheets would be fed to the form die and the subsequent trim operations. A field study pointed out that hand loading of the hot form was impractical. Loading and unloading of the secondary operations would also utilize more labor than justifiable in the proposed cost estimates. The decision was made to completely automate the

operation. This compounded the task ahead for process engineering, as will be explained in more detail in the later discussions on material and installation.

DESIGN AND BUILD

PRELIMINARY MODELS

Utilizing the physical build-up approved on the preliminary plasters, plus past sheet metal die experience, the pattern shop was now able to make models for take-offs in hard surface plasters to be used as patterns for kirksite prototype tooling. This model had to provide for the predicted polypropylene shrink (.015 in/in) plus kirksite shrink. Also, as a precautionary measure, press spotting aids were cast to insure a match metal fit in the areas of form, just in case the kirksite finish required was not obtainable in the casting process.

PROTOTYPE TOOLING

The castings did require 100% spotting to the plaster aids. The male punch was mastered and the cavity spotted to it, using wax for simulated plastic clearance. The ring was also spotted, even though it was to clear the material by .015" to .020". The only pressure applied to the ring was its own weight. Four equalizer spacers were provided, upon which the ring would come to rest, giving a uniform clearance when the ram descended.

The sheets were heated in an electric furnace and hand loaded into the form die. Parts were made with, and without, the aid of the draw ring. Engineering was able to determine the approximate sheet size and thickness for subsequent designs. Numerous parts were hand trimmed and sent to Chevrolet Central Engineering for field and laboratory tests.

MODELS AND TOOLING AIDS

Final part design approvals were received during the early model and subsequent prototype tooling period. Because the Die and Engineering Center has a numerically controlled wood mill, a decision was made to order n/c to cut the master models (both the standard 1:1 and the shrink model) by scale factoring the cutter output data. This worked satisfactorily on the front fender skirt project, and minimized the hand finishing required by the pattern makers. Figure 8 illustrates the front fender skirt model. The finished shrink model was then married to the run-off or die conditioned surfaces, and after further trim refinements, a hard surface female plaster was poured. Tooling aids for kellering and spotting were then produced from these plasters.

PRODUCTION TOOLING

It is an important design criteria of the draw/form operation to cool the form die and simulate the heat transfer necessary to minimize the dwell (die closed) period of the overall cycle. An outside source was contacted concerning the prospect of purchasing an aluminum casting with integral stainless steel cooling tubes. This source was confident that this could be done and would perform well.

The secondary trim dies were designed in conventional sheet metal style, with two exceptions:

1. Light weight castings were utilized (i.e., aluminum pads, larger cores, and thinning ribs).
2. A hydraulic trim, pierce, and separate fixture was planned for the front fender skirt because of the shape of the part, and the hole piercing required. Figure 9 and 10 depict a cross section of the trim and hydraulic pierce dies.

Since the decision had been made to completely automate the operation, it was necessary to assure that provisions could be designed into the production tooling to accommodate the lift and carry of the automatic loaders and unloaders. This will be discussed in a later section. Having no empirical data for trim shear, etc., tooling/press tonnage and load relationships were based on soft aluminum as a guide. Light weight sheet metal could also be run on these tools, if necessary.

Design engineering generated the trim profile from the physical aid, and the process for cutouts etc., was established (see process sheets, Figure 7). The form die was expedited to get it into try-out as soon as possible, since the need for try-out and show parts was fast approaching

A manual load and unload set-up was made at the build shop, similar to the prototype trial. Samples for the Citation were to be made production tooling for the first car build. The parts were formed, hand trimmed, and drilled to qualify dimensions.

The build program was closely followed to insure that trim-line transfer was correct as to gage, etc. Most problems encountered were resolved through radius changes and minor trim changes.

The plastic material does not locate like sheet metal, nor does it accept common types of gaging as used in sheet metal processing. So a lot of experimentation was required to learn the best way to position, gage and hold these parts, as will be discussed in the section on installation and production.

AUTOMATION

Sketches were made from conceptions during the design phase of the tooling, depicting how the "blank" sheets were going to move into the oven, out of the oven, and into the form die, etc..

Efforts were made to contact and utilize established oven sources. These efforts failed to produce feasible solutions. Finally, a previously unknown source was contacted. After several meetings, it was agreed that the specified design perimeters could be accomplished.
The automatic loading and unloading transfer device was designed by a source that specialized in press line automation. Primary emphasis was placed on loading the hot sheet into the form operation, transferring it through the trim dies, and most importantly, determining how to quick-cool it prior to the first trim. Quick cooling is an essential requirement, because shrinkage must be complete prior to a trim and pierce operation. Figure 11 illustrates an automation flow diagram. Several concepts were reviewed and final designs developed.

First try-out was performed on schedule, using parts formed with production tooling and hand trimmed parts. The oven was not integrated into the system at that time. There were numerous changes incorporated after this try-out to gain better control of the parts. Subsequent try-outs further enhanced the debugging of the system, and reduced the number of iterations needed in shuttling the parts through the many stations.

OVEN CONSIDERATIONS

As previously mentioned, sheet heating and handling was considered a key to the success of this project. Subsequently, several aspects were investigated and explored. It appeared that conventional methods could not be satisfactorily utilized. Polypropylene, when heated to near melt, is very sticky. There was a need for penetrating heat (due to the insulating properties of polypropylene), and a conveyance method capable of holding the sheet at these elevated temperatures.

Infra red heating took care of the penetration aspect, but conveyance remained a problem. The best approach seemed to be chain mounted cam grippers (called a "tenterette") proposed by the oven source. A purchase order, for the oven, was placed with this source. Their designs were submitted, and subsequently approved. Again, much was learned after this try-out, and numerous improvements were incorporated. The unit was shipped to Chevrolet-Adrian Manufacturing at the earliest opportunity for installation.

PRESS CONSIDERATIONS

During the early stages of the stampable plastic project, new presses were appropriated; however, these were of the conventional mechanical type. Studies showed that low tonnages and bottom dwells necessitated hydraulic type presses. Surveys were conducted to find the type needed to meet production needs and comply with Chevrolet standards. Figure 12 shows an overview of the hydraulic press.

MATERIAL PROCESSING

Raw material specified by Chevrolet Engineering for fender skirts and splash shields is a high impact, low melt flow polypropylene copolymer. Glass reinforcements and/or fillers were not deemed necessary, both from a cost and a functional standpoint. As mentioned previously, a primary function of the end product "mud flaps" lies in their ability to resist wheelhouse stone impacts and maintain their non-structural, flexible characteristics at low temperatures. Figure 13 shows a view of these parts as installed on a vehicle.
Although the original specification called for fractional melt flow resin (synonomous with high impact), a 2-3 range melt flow might suffice for the necessary impact resistance. Fractional melt is a carry-over from the process of thermo-vacuum forming, where high molecular weight/hot strength is a processing requirement. Sheets made from fractional melt material exhibit minimal sagging and tearing during the vac-form process. For hot stamping, however, the temperatures are lower (approx. 310° F), and thus the sheet is easier to handle without "self destructing" in process. The main disadvantages of fractional melt flow polypropylene are reduced extruder output as compared to 2-3 melt flow, and slightly higher initial cost per pound. Line try-outs of 2-3 melt flow material are currently being evaluated. Sample parts using this material are to be tested for impact strength and other physical properties. Figure 14 displays a chart comparing high and low melt flow material.

MAKE OR BUY SHEET

The 1980 Citation tooling volume planning rate was approximately half a million vehicles per year. An additional quarter million units were planned as volume for the other car divisions. Stamped plastic fender skirts were designated for Chevrolet, while splash shields were required for Corporate usage. This calculated out to be approximately 1.3 million pounds of plastic per year, requiring 2.6 million pounds of sheet to be either purchased or made in house, due to the 50% regrindable offal generated in the stamping process. Figure 15 depicts a blank layout showing offal.

Weighing the capital investment cost of a six-inch sheet extruder line against cost penalties incurred from buying extruded sheet

(including freight expenses, etc.), basically resulted in a cost wash-out.

Therefore, the decision was made to procure an extruder for in-house sheet manufacture. Additional considerations influencing this decision were:

1. Valuable experience would be gained within Chevrolet in sheet extrusion.
2. Expected pounds per hour output of the extruder exceeded volume requirements, thereby creating capacity for future applications of stamped plastic.
3. Less chance of supply problems resulting from an outside extruder source failing to keep up with orders.
4. Potential for in-house research/development activities in improvement of sheet quality and process performance.

Figure 16 shows the 6" extruder and 84" sheet die.

HEATING AND HANDLING SHEET

Hot stamping, or solid phase forming, of polypropylene requires introducing heat to the sheet immediately prior to forming. A temperature of between 300° and 315° F brings the material within its crystalline transformation point, and yet keeps it at least 100° F below its melting point. The plastic becomes soft and tacky, but permits mechanical transferring and lifting while maintaining its thickness. Figure 17 charts the relationship between temperature and crystalline forming state of polypropylene.

It should be noted that from an energy-related point of view, there exists the possibility of running sheet "hot" out of the extruder directly into the forming die, thus reducing or eliminating the need to impart heat into the plastic. However, the logistics of doing so, as well as the mechanical considerations, precluded the possibility in this application. It seemed much more practical to produce 2 or 3 sheets at a time off the extruder line, bank and store them on pallets, and move them over to the stamping line as required. Other factors were flexibility (two different blank sizes are required for the two different parts), and potential capacity (a 6" extruder can produce sheets faster than two lines can use them). Figure 18 shows banked pallets of extruded sheet.

Heating a typical sheet of polypropylene .070" x 28" x 72" in size to the required temperature takes about one minute. Therefore, an indexing oven with approximately 10-12 second sheet dwell between infrared heaters was chosen as the only practical method of maintaining a 12 to 15 second line rate. Heater profiles range from 1000° in the first station down to 350° in the last station. Four main heater stations bring the material up to temperature, and two auxiliary "hot box" stations hold it at temperature while awaiting pick-up and transfer into the form die. Optical pyrometers indicate material temperature, and activate high/low alarms if a set point is not held. Figure 19 illustrates the infrared oven (loading end).

Mechanical handling of the sheets through the oven to the last stations is the most sensitive part of the entire process. Each hot sheet must arrive at exactly the same place to facilitate proper loading of the die. An operator loads the stiff "blank" sheets, which are at room temperature, into the oven, one at a time, on every automatic index cycle. Transfer mounted chain grippers carry the material at its outer edges through the four primary heat stations. The hotter the sheet becomes, the more it sags in the middle; total sag amounts to about 7 inches in the fourth station. An inclined teflon-coated fiberglass belt then conveys the sheet (simultaneous with grippers releasing the edges) up and forward in a flat plane to the pick-up/transfer station. At this point the press line automation picks up the sheet and loads it into the form die. Figure 20 shows the exit end of the infrared oven.

PRELIMINARY DEVELOPMENT

A few different types of material were tried out during early fender skirt prototype stages and later pilot line runs. For the most part, however, the originally specified and approved material performed best, and is still used on a production basis. Try-out sheets, cut to size, were procured from an outside extruder source. No significant materials evaluations were attempted in these early runs, due to the urgent need to establish process consistency relating to heat input, draw die dwell, and dimensional stability.

Heat input was obtained through the use of an electric oven with one sheet at a time heated on an aluminum "cookie tray". Sheets were held in the oven for specific times/temperatures, and checked with a hand held optical pyrometer to measure uniformity. Two operators picked the sheet out of the oven, hand carried it up a platform into the draw die, located it in the die, and then cycled the press to form draw panels. Figure 21 shows the electric oven used in try-out.

Draw die dwell was set initially for six seconds - a time based entirely on what was hoped to be the production cycle time later developed. The die was set in a conventional metal stamping press wired to stop on bottom dead center. Press tonnage was 300 ton, providing approximately 375 PSI over 1600 square inches of plastic sheet. It should be noted that the production draw press (100 ton hydraulic) provides only 125 PSI over the same blank and performs very well. Figure 22 displays the draw die as set in the Hydraulic press.

There was little dimensional consistency in the early parts. Consistency of gage thickness (.070") was very good. However, despite efforts to control heat input and die swell, the shape of the parts varied beyond tolerances.

No two cycles of parts would fit on the inspection fixture the same way. Draw form/shape varied, thus causing trim lines and holes to vary likewise. Lab checks indicated the material conformed to all physical properties specifications. Therefore, attention was focused on the process.

Three factors were judged to be primarily responsible for the variations in part dimensions:

1. Manual loading of blanks into die was causing material temperatures to vary, due to time increment changes involved in locating the blank in the die. Hence shrinkage and springback would not remain constant.
2. The mechanical press would not always stop exactly on bottom, due to inherent variable response time (electrically and mechanically) in the ram-stop energizing process. Over or under bottom dead center changes die clearance during dwell/cure.
3. Trimming and piercing consistently was impossible due to the varying-form draw panels not nesting properly on secondary die locators and gages.

Figure 23 illustrates the fender skirt draw, trim, and separated panels.

Since parts had to be made (sample, show job requirements, etc.) it was decided to accept the present situation for the time being, and hand work the parts to qualify dimensions. The only possibility for improvement at that time was to expedite the production equipment and get it running on a consistent automatic cycle that should result in dimensionally correct parts.

INSTALLATION TO PRODUCTION

The failure of previous try-outs of stamped plastic to produce dimensionally correct parts increased the urgency to complete installation of production equipment which would permit an automatic run. The order in which items were received at the Adrian Plant is as follows:

1. Draw Die
2. Automation
3. Presses
4. Trim Dies
5. Ovens
6. Extruder

Prior construction of wet deck foundations and power supplies facilitated immediate start of installation procedures to an approved plant layout plan. Auxiliary equipment such as conveyors, granulators and mold temperature control units were received and available as needed. Installation was followed by try-outs, de-bugging, problem and solution identification, and finally production. The first line (fender skirts) took approximately 13 weeks to complete, primarily due to extensive trim die changes. The second line (splash shields) took approximately seven weeks to complete, aided by what was learned on the skirt line.

FLOOR PLAN/LAYOUT/INSTALLATION

A considerable "plus" that facilitated installation was the fact that equipment did not have to be squeezed into tight locations surrounded by existing machines. The open, available floor space allocated to stamped plastic resulted in an efficient layout for both the lines and the extruder. Figure 24 depicts the final floor plan layout.

Presses were spaced to allow sufficient clearance for the spray-mist draw panel cooler, hydrostatic automation drive and linkage, numerous conveyors to remove offal trimmings, and a granulator and belt transfer common to both lines. The extruder was situated near the raw material silos with its out-put end facing the stamping lines. Extruded sheets could either be banked or taken directly to the lines if required.

Press installation was fairly straightforward. The hydraulic units located on the crown, had to be mounted and hooked up separately, as did surge tanks for air counter-balance. Otherwise, the presses were set on location in one piece, as received from the vendor. Leveling, lining, and maintaining center distances were accomplished in minimal time, followed by wiring and piping to complete the installation.

Concurrently with hooking up the presses, the automation was temporarily set-up between the presses to establish its rough location and fabricate the proper tie bars. When the presses had been tried out and cycled properly on manual controls, the automation was pulled back out and the dies were set. Die feed levels and center distances were checked. The automation was then set back in place and located in its final position.

Extreme care was taken to maintain exact alignment of the automation, due to its one-piece lift draw bar design: a drive at rear end of automation transmits force through reverse pivot linkage to a bar tied in with identical pivot arms at both extreme end of the 60 foot long unit. This draw bar design provides a simultan-

eous and level lift of all pivot arm mechanisms without any binding or undue stress, and eliminates the need for separate assist cylinders with equalization problems. Wiring and piping of the automation was completed in approximately two weeks, with an additional week required to refine interlocks between the presses and transfer operations in an automatic mode. Figure 25 illustrates the draw bar principle.

The infrared sheet heating oven was the last stamping line unit to be installed. It had to be broken down for shipment and erected on location in front of the draw press. Once the increment of index had been set for the sheet pick up point, the oven was wired and piped and cycled cold to check sheet handling and delivery. Considerable mechanical adjustments in the feed and exit stations had to be made to accommodate proper sheet placement in the pick-up station, and to allow necessary jaw clearance for the press automation to clamp, lift and carry the sheet into the draw die. Figure 26 shows the fender skirt stamping line, and Figure 27 the splash shield stamping line.

The extruder, being the last piece of equipment to be received, was installed in two stages. First, the screw barrel, main drive and control panel units were installed, followed by the downstream stack rolls, pull rolls and slitter units. Bulk material handling equipment to provide plastic to the machine was a considerable part of the overall installation, as shown in Figure 28. Setting up the DC drive sheet line system was also a significant factor. Installation and wiring were completed in approximately four weeks. Since the extruder was delayed past the stamping line equipment, a decision to start stamping try-outs and early production with purchased sheet was made. Figure 29 shows the extruder downstream end.

TRYOUTS AND DE-BUGGING OF TOOLING AND EQUIPMENT

This discussion of try-outs is limited to the fender skirt line since it was the first one set-up. The most difficult portion of the line to cycle was the oven-to-draw die operation. Sheets were tried through the oven, gradually increasing heat in-put and adjusting locations until the optical pyrometers read approximately 305° F. When the jaws were aligned at the draw die, a few sheets were run on automatic through the die and removed for evaluation. It was apparent immediately that existing transfer rest and pick up locators were not going to perform their function of consistently positioning the panels for proper transfer into the last two dies. The draw panels were too flexible and flimsy to locate by their own weight, and there was more variation of the blank edges than anticipated from the draw operation to enable location with edge wiper guides. Figure 30 depicts the transfer jaws and nests.

Therefore, it was decided to establish a proper oven/heat/draw automatic cycle, and bank draw panels for subsequent manual try-out through the trim dies, in order to qualify part dimensions. Meanwhile the transfer rail locators could be "tuned in" to the shape of the draw panels. It should be noted that the visual appearance of the draw parts was very encouraging as compared to the appearance of earlier tooling try-out parts. It was obvious that the hydraulic press was doing a much better job of "setting the form" due to its ability to consistently stop on bottom-dead-center. Also the uniform heat application from the infrared oven, and the constant time increment from heating to draw operations, was now resulting in draw panels that were identical in dimensional characteristics, including shrinkage related lengths.

The most serious problem incurred during try-out was the significantly off-location trim lines and hole locations experienced by running the draw panels manually over the two trim dies. No matter how much care was taken to properly position the parts on the male die locators, the final trimmed fender skirts deviated from inspection fixture tolerances by as much as 12 millimeters. It was determined that two primary factors were responsible for this condition:

1. Draw panel shape and form was finally correct, causing the panels to nest differently on the trim dies than did the incorrect panels from earlier try-outs.
2. Existing trim die gages were not adequate to locate the panels in the same place consistently, regardless of the form/shape of the parts.

Figure 31 illustrates trim die locating provisions.

The only other problem worth mentioning was the scrap/offal trimming conditions. Cut-outs and holes "slugged up" after only 10 or 20 hits. Some of the trimmings failed to properly fall down the sheet metal chutes into the conveyors.

Fortunately, at this point in time, approximately four to five weeks remained until volume production had to be run, given "down to the wire" timing. The decision was made to pull the trim dies and send them back to the vendor for re-work, having the new draw panels to use as a guideline. At the same time slug conditions could be improved. A set of inspection marker panels was prepared for locating trim line and hole locations. These changes took three weeks, and the dies were returned to the plant with only two weeks left to get production running.

By this time the extruder had reached the stage of tryout and was progressing satisfactorily. Through the combined efforts of the production set-up operator, the vendor and process engineering personnel, good sheet was being made in a time frame of about two weeks. The only significant revision required was changing the main screw drive gears to provide more torque for melting the fractional melt flow material. This success greatly reduced Chevrolet's potential dependence on outside extruded sheet for early production use.

PRODUCTION PROBLEMS AND SOLUTIONS

As soon as the revised trim dies were set-up, and transfer nests were altered to assist carrying the panels on location, attempts were made to "crank-up the line" for production parts. However, several problems remained to be solved, and several new problems arose in the process. These problems and their solutions are outlined as follows:

PROBLEM: On a complete automatic cycle, parts would vary in dimensional characteristics from perfect to about six millimeters out of specification in trim and hole locations. Figure 32 shows parts on the inspection gage.

PROBLEM: Parts would not load automatically into last trim die (hydraulic trim/pierce/separate) without catching and hanging up in the open throat area of its 45° angle side slides.

SOLUTION: This die had to be revised to incorporate longer stroke slide cylinders to increase daylight space, and the automation loader station required auxiliary clamp cylinders to contain parts from bouncing or slipping as they entered the die area. Figure 33 illustrates the hydraulic trim die loading and locating features.

PROBLEM: Several trim die areas continued to slug up, even though drop-out areas were provided with normal clearances.

SOLUTIONS: Unlike sheet metal cut-outs, the plastic pieces "expanded" in size after being trimmed, and they lodged on undercut ledges and walls, prohibiting drop through. This "expansion" was apparently due to excessive springback of curved surfaces to a flat plane. The only workable remedy was to disassemble the affected die sections and grind away metal to triple conventional sheet metal slug clearances. Figure 34 depicts typical cut-out slugs and trim offal.

PROBLEM: Hot sheets transferred through the oven failed to release from the carrier chain cam grippers, causing mis-located or mangled sheets in the final station. On other occasions, cold sheets would not enter the grippers properly and fall on to the heaters, causing the material to catch fire. Figure 35 shows the chain cam grippers.

SOLUTION: It was found that left to right adjustment of the girpper assemblies was very critical, and dependent on cold sheet blank width for optimum operations. For example, a pallet of sheet for the fender skirts should be cut to a nominal width of 72 inches. However, variations in the extruder shearing operation can result in a pallet of sheets being 71-3/4" wide, and another pallet containing sheet 72-1/4" wide. A wide sheet could enter the gripper throat depth too far, get pinched, and fail to release at the exit end. A narrow sheet could miss the grippers entirely and fall below onto the heaters. Since there are about 200 small grippers integral with the index chains on each side of the oven, attempting to increase the throat depth (and hence the tolerance for accepting variable size sheets) was deemed impractical. The actual solution was two-fold:

1. The extruder operator was better able to control sheet width with experience with heat settings related to shrink, and shear sensitivity to other variables. The sheets therefore became more consistent in size. Figure 36 shows the extruder shear assembly.
2. The oven operator was instructed to tape measure the sheet size of each pallet before starting into it. Then, if a variation from pallet to pallet is detected, he was to alert the stamping lines set-up operator so gripper assembly left-to-right adjustment could be set accordingly.

Fire potential was diminished through the installation of automaic fire protection equipment to supplement hand held extinguishers.

PROBLEM: Typical stamping line cycle time was 15 seconds. The engineering goal was 12 seconds. Draw press six-second dwell time was and is the primary cycle limiting function. Attempts to cut the dwell time to 4 or 5 seconds resulted in panels with insufficient form definition, and excessive shrinkage caused by early release from the water cooled die.

SOLUTION: Electrical changes were made in the press-automation "mechanical interlock" portion of the circuit to allow simultaneous movement of the presses and automation up and down, rather than incremental movements. After a few jaw wrecks, this feature enabled a reduction of 1-1/2 seconds, to 13-1/2 seconds overall. Work is ontinuing to provide features for smoothing out and speeding up automation travels. The possibility of a "super chiller" system for the draw die is being investigated. The goal of 12 seconds cycle time should be reachable through a combination of the above items.

PROBLEM: Extruder heat profiles resulted in a plastic melt temperature at the screw tip of the 540° F. This temperature was too high, causing the burn-off of polypropylene stabilizers and an increase in melt flow rate/decrease in impact resistance. Figure 37 illustrates extruder melt and pressure indicators.

SOLUTION: The screw was removed, sent back to the vendor, and recut to decrease compression ratio and shear. This led to low temperatures at the same RPM. Output remained at approximately 2100 pounds per hour, considered very good for fractional melt flow material.

PROBLEM: Trimming operations produced so much offal that conventional automatic regrinding equipment was severely taxed. The expected 50% trimming regrind was augmented by extruder start-up scrap, and sheets pulled out of the oven exit station whenever the stamping line automation stopped due to a line malfunction.

SOLUTION: The in-line conventional granulator was replaced with a high capacity unit with specially designed blades. A small granulator was placed on a standby basis to regind extruder ribbons and other miscellaneous scrap. Figure 38 depicts the automatic handling of trimmings through the granulator installation.

CONCLUSION

Workable solutions have been found for the primary problems associated with manufacturing hot stamped polypropylene parts. On a practical basis, the process is a viable alternative to injection molding for large thin-walled parts. It has the distinct advantage of a four-fold increase in productivity based on gross cycle time, and a twofold increase based on direct labor manpower if performed with an automatic transfer unit. In addition, the reduction in material wall thickness (normally half that of injection molded parts of comparable surface area) offers a cost and weight savings potential. The primary disadvantages are relatively long learning curves as compared to a single operation injection mold, and the high percentage of regrind inherent in utilizing a large rectangular blank in die cut operations. The overall cost potential, however, remains attractive when compared to injection molding for certain types of parts.

The process offers what is presently the primary means of producing extremely high impact polypropylene parts. Injection moldable grades of polypropylene, by virtue of their higher melt flow rates, cannot meet the physical property requirements possible with stampable plastic.

For large parts with high projected surface area in line of draw, clamp tonnage required for injection molding, may require up to a 3000 ton machine. The capital equipment cost of high tonnage injection molding machines is significantly higher than incurred in a complete automated stamping line, especially if conventional sheet metal presses are available as surplus equipment for the trimming operation.

Although typical injection molding runs at 80 to 90% efficiency (relating net to gross cycles), and stamped plastic seems to run between 65 to 80%, stamping efficiency can and should improve as the state of the art develops. Analysis of the most frequent causes of downtime indicates that accuracy and reliability of sheet and panel handling are the primary concerns. New oven conveying methods, die load, jaw designs, and die locating provisions are already showing good potential for improved productivity for future applications.

Figures mentioned in this text are available upon request from:

Chevrolet-Adrian Manufacturing
1450 E. Beecher Street
Adrian, Michigan 49221

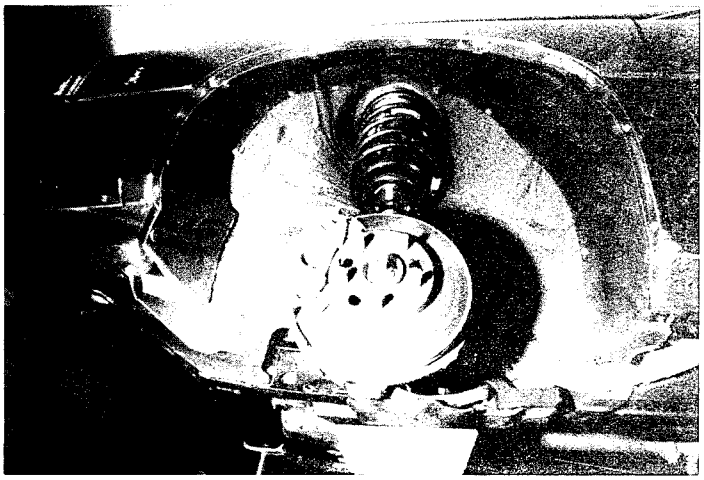

Figure 1 - 1980 Citation Wheel House Compartment

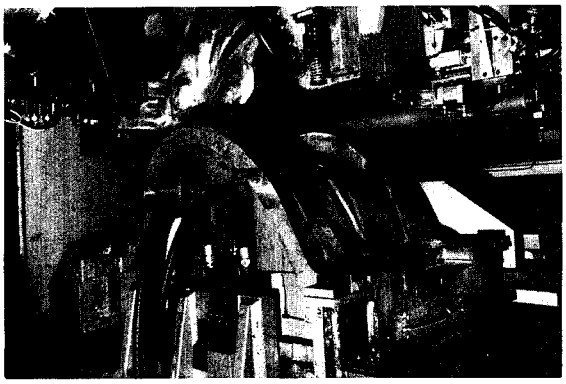

Figure 22 - Draw Die Set in Press

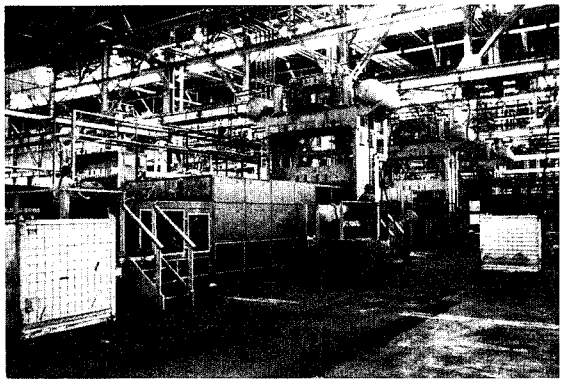

Figure 27 - Splash Shield Stamping Line

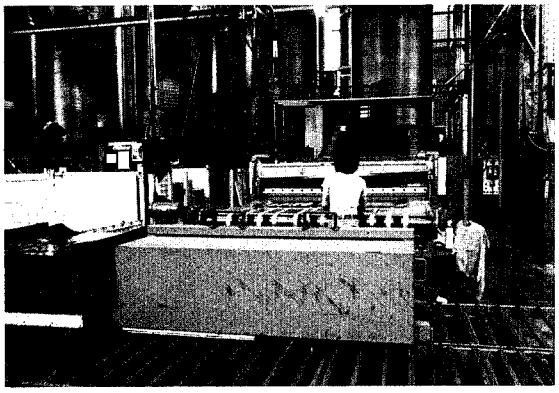

Figure 29 - Extruder Downstream End

THERMOFORMABLE POLYPROPYLENE
A NEW DIMENSION IN FORMING OLEFINIC PLASTICS

by

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Introduction

Historically, the major growth in polypropylene has been in the areas using melt forming fabricating techniques such as injection molding, extrusion and fiber forming. On the other hand, polypropylene has enjoyed only limited success in thermoforming operations such as vacuum forming and stamping. It has distressed producers of polypropylene for years that they cannot take advantage of these lower cost, low energy forms of fabrication.

A major technical difficulty with polypropylene in thermoforming is its poor melt strength, a consequence of the fact that it has a sharp crystal melting point. On the other hand, amorphous polymers which generally are easily thermoformed show a much broader melt transition zone (Figure 1). Typically, in thermoforming operations, a sheet of plastic material must be transported to the forming tool in a state soft enough to be formed yet strong enough not to collapse during the movement. Because of the differences in melt characteristics between amorphous and crystalline materials, amorphous materials such as ABS and polystyrene have dominated this area of fabrication.

Needless to say, if a polypropylene could be developed that would be more suited for these thermoforming processes, there would be a marked increase in use since polypropylene offers a unique combination of low specific gravity and cost when compared with amorphous materials such as ABS.

Laboratory Development

During the past two years, a program at Shell Development's Westhollow Research laboratory has been aimed at modifying the melt properties of polypropylene to obtain a material with thermoforming characteristics more like those of amorphous thermoplastics. Since determining the thermoforming properties of a plastic material on conventional vacuum forming or stamping equipment would require significantly more product than we could practically make in the laboratory, our first effort was to develop a method of screening the various experimental products. Following a test development phase, we selected the measurement of dynamic viscosity[1] over a temperature range from 150-200°C to measure melt strength and indicate consequent thermoformability. The following assumptions are made with respect to the use of this technique as a screening tool.

(1) With dynamic viscosity values over 10^7 poise, a sheet of plastic will be too stiff to successfully vacuum form or stamp.

(2) With dynamic viscosity values less than 10^5 poise, the melt strength will not be sufficient to maintain sheet integrity during the process.

(3) The increment of increasing temperatures required to reduce the viscosity from 10^7 to 10^5, i.e. the "process temperature window", would be an indicator of thermoformability of the plastic. The wider the temperature range the better the thermoformability since a wide process temperature window would result in more uniform sheet consistency and would allow stamping and forming of the sheet at higher temperatures than with conventional polypropylene. This again, should result in better moldings with fewer rejects and less scrap loss.

During the evolution of this program, several laboratory batches of polypropylene were prepared that show melt characteristics significantly different than conventional polypropylene copolymer based on the dynamic viscosity screening test. In Figure 2, two of these test materials, TFPP-1 and TFPP-2, are compared with a good thermoformable material (ABS) and a polypropylene impact copolymer. As shown, the plot of TFPP-1 closely resembles that obtained with ABS and we would expect this material to perform well in both stamping and vacuum forming applications. The TFPP-2 also shows a reasonably wide working process range with a process temperature window of about 30°C. We expect this material to work very well in stamping and to be acceptable for many vacuum forming operations. In contrast, the viscosity/temperature plot for the polypropylene copolymer indicates a very narrow process temperature range.

Thermoforming Trials

Up to this point, all of our information on the thermoformability of these new polypropylenes was based on analysis of mechanical spectrometer data. Since there is a long way between a laboratory prediction and an industrial reality, we produced large quantities of product for confirmation thermoforming trials. During 1978, Shell Chemical Company brought on-stream its new polypropylene polymerization facilities at Norco, Louisiana. A review of our laboratory experimental procedures and the production capabilities of the Louisiana facilities indicated the new plant would have the capability of producing these polypropylene copolymers with improved melt strength. Consequently, a plant production trial was made of the product TFPP-2, and resulted in our having several thousand pounds of this product for commercial-scale thermoforming trials.

Stamping

Arrangements were made to make thermoplastic stamping trials at three different manufacturing facilities. The sheet used in these trials was prepared on a 3-1/2 inch sheet line at the Westhollow Research laboratory. Sheet width was approximately 36" and was prepared at thicknesses varying from 80 to 150 mils. Samples of the various thicknesses of the material were evaluated at each of the three locations. The stamping blank areas ranged up to 36" x 60" and draw depths were up to 8 inches.

As is the case with most processing equipment, each thermoplastic stamping unit used had its own peculiarities and therefore specific conditions for each trial varied somewhat. However, the key to all stamping applications is sheet behavior during movement from the heater to the forming machine. As a starting point in each trial, the temperature range for successful processing on each specific thermoforming machine was first determined for sheets of conventional polypropylene copolymer. This "processing window" was taken as the difference between the sheet temperature where the part would not form well, exhibiting a high degree of spring-back, and the temperature where the sheet sagged and lost its ability to maintain integrity under its own weight. The same temperature window was determined for the TFPP-2 polypropylene. The results of the three trials were averaged and are shown graphically in Figure 3. The TFPP-2 polymer does indeed exhibit a "safe processing" temperature range significantly wider than the polypropylene copolymer. As mentioned before, the wider range allowed the TFPP-2 material to be stamped at a higher temperature and resulted in better part definition with no loss in cycle time.

[1] By dynamic viscosity we mean the measurement of shear stress and rate under oscillatory conditions: specifically dynamic viscosity = η' the component of viscosity in phase with shear rate determined on a Rheometrics mechanical spectrometer at 0.1 sec^{-1}.

Since the improved melt strength of TFPP-2 will allow routine handling of sheet at temperatures above the nominal melting point some exciting future developments are suggested. Currently, stamped polypropylene parts are designed to fit the processing limitations of the polypropylene. With a TFPP material which can be stamped at temperatures above the crystal melting point, the increased flow during stamping will allow placement of ribs and bosses in any desired area. The long term significance of this design freedom is that plastic parts could be designed using the same computer techniques used today to design parts with sheet metal. This freedom of design coupled with the use of glass or other plastic reinforcing materials could lead to new areas of metal replacement.

Vacuum Forming

In testing this method of thermoforming we tested only the TFPP-2 material on laboratory scale equipment using 24" x 24" x .125" sheets. These tests indicated that the enhanced melt strength of TFPP-2 allows successful shallow and medium draw vacuum forming. Sufficient data is not available at this time to assess use with deep draw tooling.

Physical Properties

So far we have only discussed the processing characteristics of this new type of polypropylene. A quick look at several key physical properties of TFPP-2 (Table I) shows that it has physical properties similar to a typical high impact polypropylene. Two items of particular interest are noted when reviewing the data. First, the melt flow of this material is about 4.0. Generally, stamping grades of polypropylene have fractional melt flow. The higher melt flow characteristics of the TFPP-2 product is expected to lead to higher extruder output rate or lower energy usage at equivalent output. Second, the recycle stability of this material is excellent. As shown in the second column of Table I, after eight recycles using 100% regrind, TFPP-2 shows no significant loss in physical properties or increase in melt flow.

Conclusion

A new polypropylene copolymer product has been developed with melt strength that is significantly better than conventional polypropylene. This new family of thermoplastics should find a wide range of application opportunities using thermoforming processes that to date have been dominated by amorphous polymers.

TABLE I

TYPICAL PHYSICAL PROPERTIES OF THERMOFORMABLE - TFPP-2

PROPERTIES	TFPP-2	AFTER 8, 100% REGRIND PASSES
MELT FLOW	4.0	4.5
TENSILE YIELD STRENGTH, PSI @ 2"/MIN	3300	3000
YIELD ELONGATION, % @ 0.2"/MIN	10	12
FLEXURAL MODULUS, PSI	160,000	150,000
HEAT DEFLECTION TEMPERATURE @ 66 PSI ^{o}F	195	195
FALLING DART IMPACT FT-L./IN @ -20^{o}F	180	160
SPECIFIC GRAVITY	0.9	--
IZOD IMPACT NOTCHED, FT-LB @ 77^{o}F	8.0	8.9

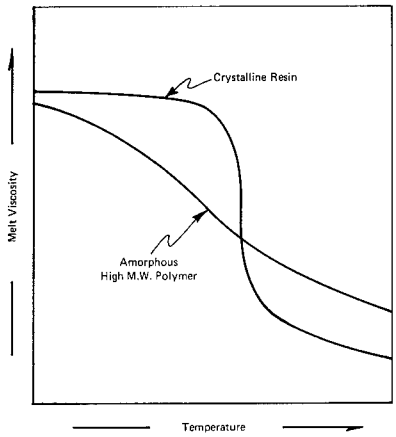

Figure 1. Idealized Melt Characteristics

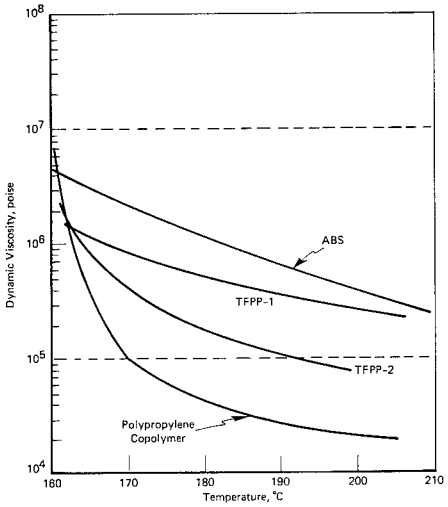

Figure 2. Mechanical Spectrometer Data

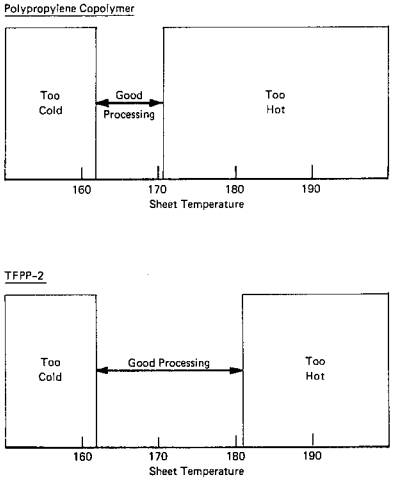

Figure 3. Polypropylene Stamping - Process Temperature Window

ISOCYANURATE-MODIFIED HIGH MODULUS POLYURETHANES

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INTRODUCTION

This paper will describe the chemistry, processing and properties of isocyanurate-modified polyurethanes. These polymers may find use ultimately as high modulus materials. Since they are made by a RIM process, they can have Class "A" surfaces. More fundamentally, isocyanurates, or trimers (since they are chemically the cyclic trimer of an isocyanate), have the advantage of thermal stability.

The isocyanurate ring is inherently much more thermally stable than the urethane group. Whereas model urethanes dissociate thermally to isocyanate and polyol at 150°C,[1] monomeric trimers are stable to about 500°C.[2] Thus, the thermal stability of a polyurethane should be improved according to the level of trimer which can be incorporated.

CHEMISTRY

The chemistry of isocyanurates has been reviewed.[2] Normally, strongly basic catalysts, such as carboxylate anions, are used to cyclize three isocyanates. However, to form a polymer using this reaction imposes some strict limits. These limits derive from the onset of gelation, which theoretically[3,4] and experimentally[5] occurs at 50% conversion. Therefore, formulations containing trimer can be expected to be incompletely cured, especially at normal demold times in a RIM process. As will be shown later, the incomplete conversion will require postcure. In addition, aging effects will be noted. Finally, the crosslink density of an isocyanurate is high; the molecular weight per branch point has been estimated to be 400-500. This value will limit the properties which can be developed.

Experimentally, the conversion can be monitored conveniently by infrared.[6] Normally, it is possible to achieve conversions considerably above those predicted by theory.

A wide number of formulations is possible, depending upon the type of isocyanate and the type and amount of polyol used. The system to be described is based on MDI and a commercially available polyol, because this system has provided better than average properties, as well as excellent processing. The formulation is proprietary, however.

MOLDING CHARACTERISTICS

Although a large number of catalysts are available for trimerizing isocyanates,[2] surprisingly little latitude is available to control the reaction up to the gel point. Unlike the smooth viscosity build normally seen in urethane systems, the mixed reagents for trimer remain at low viscosity, then build viscosity abruptly to gel. The attempt to slow the viscosity build by lowering the level of catalyst results in low conversion to isocyanurate.

After gel, a comparison of exotherm curves (Figure 1) for an isocyanurate and a urethane at the same hard segment level shows differences. Although both systems can reach gel at the same time, and both systems reach the same temperature at two minutes, the isocyanurate cools more quickly than the urethane. This indicates that the trimer does not continue to react.

Once the isocyanurate gels in a mold, only a few seconds more are necessary to demold the part. Typically, demold times can be 20 seconds. The reaction continues to evolve heat, but further conversion to isocyanurate depends on postcure conditions.

POLYMER PROPERTIES

The first parameter we investigated was the soft segment or polyol content. As shown in Figure 2, varying the soft segment content from 25% to 45% (wt) yields materials having flexural moduli at room temperature of 190,000 psi to 375,000 psi. These same materials have tensile elongations at rupture of from 8 to 40%. These figures are not uncommon for a variety of plastics, such as ABS, acetals, acrylics, epoxies and polystyrenes. Impact strength for the isocyanurate system helps to define its relationship to other plastics. The notched Izod is 2.0-3.0 ft-lb/in., which is as good as the better acetals and acrylics. It is better than most styrenes; the high-impact grades show temperature sensitivity, varying from 8 ft-lb/in. at 25°C to 2.5 at -25°C, whereas the isocyanurate does not change over this temperature range.

For more complete description of the impact behavior, the unnotched Izod and Gardner impacts are shown in Figure 3. The Gardner test, defined for coatings by ASTM D-2794, has been a useful means of defining the overall toughness of materials as opposed to the notched Izod, which provides a measure of crack propagation. This figure shows that the unnotched Izod and Gardner give the same type of result, a modest increase in impact strength as the soft segment content increases from 35 to 45%. Below 35% soft segment, however, the impact remains relatively constant. Isocyanurates have impact strengths comparable to those of general purpose polystyrene and the better acetals and acrylics.

Thermal properties distinguish the isocyanurates from other materials. A range of heat deflection temperatures is obtainable, depending upon the extent of postcure. The data in Table I show several facets of postcuring. First, property changes are evident during postcure. The flexural modulus at 180°F decreases steadily, but the heat sag values and heat deflection temperature (HDT) improve. Other properties remain essentially unchanged below 400°F.

The result of the postcuring is that the modulus (as determined by the two low-load tests (heat sag and flexural modulus) is reduced at the intermediate temperature (180°F) and increased at the higher temperatures (250°F, 325°F).[7] This suggests that some increased ordering of hard and soft segments is occurring and not necessarily destruction of the urethane.

Chemically, postcuring increases the conversion to trimer slightly. As the postcure conditions become more severe, the amount of isocyanate in excess of hydroxyls which is converted to isocyanurate increases. The change amounts to 10% additional trimer, but the conversion at 350°F is the same as that at 250°F/1 hr., the standard automotive postcure.

A second facet of the postcure study is the limiting thermal stability. When samples made by the RIM process are heated to 400°F, surface dimpling is noticeable. The visual symptoms also show up mechanically, as indicated by lowered flexural modulus values, reduced tensile and elongation, and lowered Gardner and unnotched Izod impact strengths. Reasons for these thermal stability limits are being investigated.

Finally, delaying the postcure for 24 hours has further harmful effects. (See Table II) The effect is seen to a slight extent at 250°F, but especially in samples cured at 400°F. The HDT and flex modulus values drop sharply. These property changes support the idea that the trimerization reaction must be allowed to continue once it is started in order to obtain maximum conversion, in agreement with J. K. Gillham's interpretation of polymer curing.[8]

The postcure study shows that RIM trimers can be made more thermally stable depending upon the postcure temperature. Figure 4 shows the range of heat deflection temperatures obtained after postcuring samples at 350°F as a function of soft segment level. From 25 to 40% soft segment content, HDT's of 150-170°C can be attained.

However, the HDT data help to place the urethane-trimers among the various available plastic materials. The properties of isocyanurates in general are better than those of acrylics, polystyrene, acetates and acetals. Trimers are not as tough as nylon, which does not break in the unnotched Izod test, nor do trimers compare to materials such as polysulfone or polyamide-imide in combined thermal stability and toughness. However, the impact strength is considerably better than that of unfilled polyesters. Furthermore, the impact strength of the trimer does not change from 25 to -10°C, the temperature range examined. Thus, if toughness is considered, the trimer is similar to materials such as acetals, ABS, epoxies and polystyrene. In impact strength, the trimers rank just below ABS and as good as polystyrene. In thermal stability, as judged by HDT, the trimers are generally comparable to unfilled phenolics, epoxies, and rigid unfilled polyesters.

AGING

Although RIM-processed samples were postcured at 350°F for 1/2 hour, changes were observed between individual samples. The difference is related to the age of the sample. To demonstrate this, we measured the heat deflection temperature of sample cured at 350°F for 30 minutes over a period of four months. The results are shown in Figure 5. The heat deflection temperature climbs steadily from its initial value of 136°C to about 170°C. The limiting value of HDT for this type of system has been shown in hand-mixed, compression molded samples to be just above 200°C. Therefore, one could expect that the HDT will continue to increase, but at a slower rate. Impact strength stabilizes within a few weeks at 0.8 - 0.9 ft-lb.

REINFORCEMENT

The effect of adding milled glass fiber is shown in Table III. The observed effects are much like those reported[9] for milled glass fiber. First, milled fiber promotes nucleation, which results in density lowering from expansion of gas previously dissolved in the components.

The theoretical specific gravities at 15 and 30%, respectively, are 1.39 and 1.60. This foaming action helps to fill the mold and improves surface quality. The major effect of milled fiber is seen in the improved flexural modulus: at 30% the modulus is 665,000 psi, approaching the levels associated with SMC. Milled glass fiber at 30% (wt) is extremely effective in reducing sag both at 325°F and at 400°F. (A preheated aluminum test fixture was used.)

The coefficient of thermal expansion is also improved substantially, although the reaction characteristics, which are different from urethanes, do not affect the orientation of milled glass fiber in parts made by the RRIM process.[9] Finally, the impact is reduced by half due to the presence of milled fiber. To sum up, milled glass fiber helps to improve the material except in impact strength.

CONCLUSIONS

Although theory suggests that conversion of isocyanates to isocyanurates is only 50% at the gel point, molded urethane-modified isocyanurates can be made by a RIM process involving postcure. These polymers are high modulus materials whose outstanding property is thermal stability. Changes in the polymer due to postcure and aging are related to the conversion attained. The addition of milled fiber gives materials having stiffnesses approaching 700,000 psi.

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TABLE I. POSTCURE: EFFECT OF TEMPERATURE

Temperature, C	21	121	177	204
Properties				
HDT, °C	125	136	154	158
Flex. Modulus				
-30 °C	449	450	437	314
21 °C	293	302	279	210
82 °C	164	194	139	144
Heat Sag, in.				
(163 °C, 60 min)	2.0	1.9	1.6	0.3
Conversion, %	58	66	65	53

TABLE II. EFFECT OF DELAYING POSTCURE

Postcure Temp, °C	121		204	
	Immed.	Delay	Immed.	Delay
Properties				
HDT, °C	136	118	158	142
Flex. Mod.				
82 °C	194.0	144.0	144.4	110.3
Heat, Sag, in.				
(163°C, 1 hr.)	1.9	1.7	0.3	0.4
Impact, ft lb	0.7	0.8	0.4	0.4

TABLE III. REINFORCEMENT WITH MILLED GLASS FIBER

Properties	(1/16" P-117B Content, wt. %) 0	15	39
Sp. G.	1.19	1.09	1.29
Flex Modulus, ksi			
70°F	260	326	665
180°F	123	175	395
Elongation, %	12.7	6.1	4.3
Impact			
Gardner, ft-lb	0.72	0.31	0.29
Izod, ft-lb/in	1.15	0.52	0.57
Heat Sag, in.			
325°F/30 min	0.46	0.15	0.04
400°F/30 min	2.47	0.89	0.07
HDT (264 psi), °C	163	151	164
CTE 10^{-6}/ C			
//	132	84	48
⊥	132	118	112

FIGURE 1. ISOCYANURATE, URETHANE EXOTHERMS

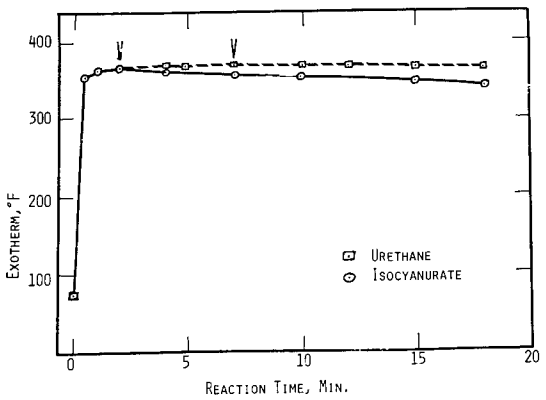


FIGURE 3. RATIO (A/B) STUDY

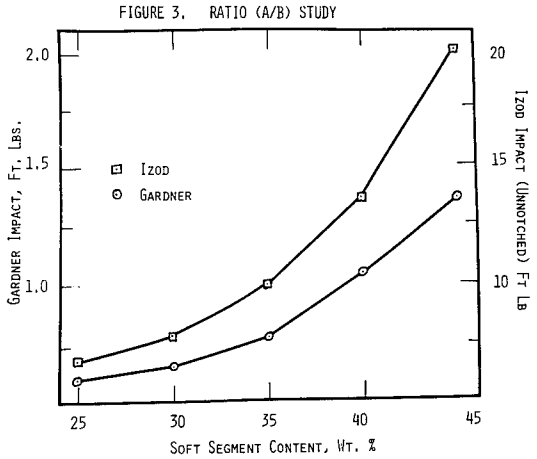


FIGURE 2. RATIO (A/B) STUDY

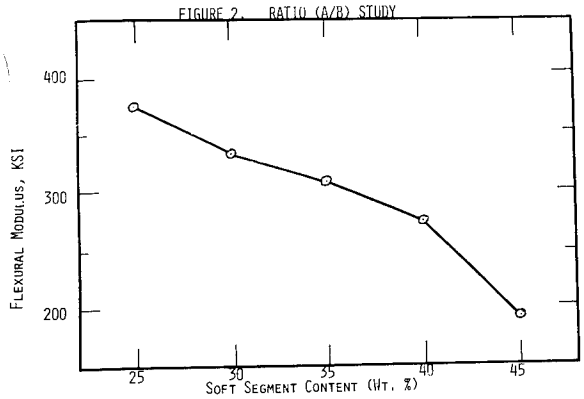


FIGURE 4. RATIO (A/B) STUDY

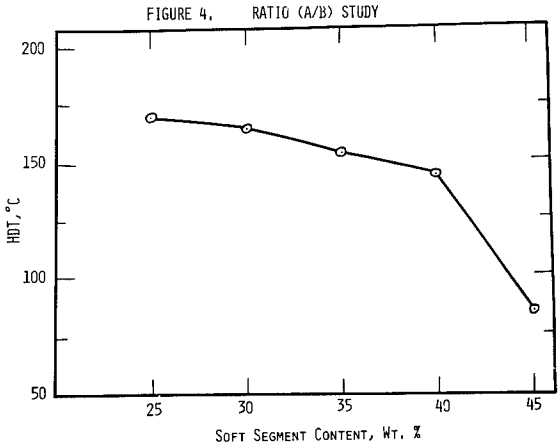
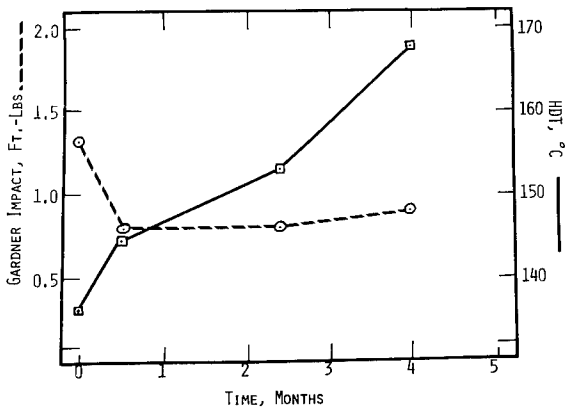


FIGURE 5. EFFECT OF AGING



NEW MATERIALS FOR REACTION INJECTION MOLDING

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INTRODUCTION

Reaction Injection Molding (RIM) can be defined as a plastics manufacturing process in which reactive liquid chemicals are impingement mixed at high pressures and instantly dispensed into a closed mold. Polymerization then takes place in the mold to produce a part. Millions of pounds of urethane chemicals are being processed annually by Reaction Injection Molding to manufacture a variety of automotive and non-automotive parts. Some parts currently produced at General Motors by RIM are fascias, spoilers, and solar collector frames. We are currently studying the feasibility of producing other products such as friendly fenders, air conditioner housings, and truck components for future vehicles.

As a result of the successful growth of the RIM process, a number of chemical suppliers are investigating materials other than urethanes. The factors motivating these new developments are the advantages that RIM offers such as low capital investment, large part capability, and fast part to part cycle times. Investigation has shown that polymers other than urethanes can be made by the RIM process having certain properties, in some cases better than urethanes.

The objectives of this presentation will be to review the work that has been done on the new RIM materials and discuss how they can be applied to produce lightweight plastic body components.

URETHANES: STRENGTHS AND WEAKNESSES

The formulation latitude demonstrated by urethane chemistry has enabled us to produce products for automobiles ranging from seat cushions and energy absorbing foams to elastomeric fascias. The elastomeric body components have met public approval as evidenced by the successful sales of fascia type vehicles over the past years. In the 1978 model year, approximately 25% of GM vehicles contained RIM components.

Developments are still continuing to overcome the problems encountered in RIM manufacturing, namely releasability mold cleaning and long cure times. Breakthroughs to improve the productivity of RIM are necessary to be more competitive with other molding processes. At GM Manufacturing Development, continuous emphasis is being placed on methods of increasing RIM productivity through the use of robots, faster reacting systems, and improved mold releases, both internal and external.

Looking beyond elastomeric fascias, the furthering of RIM for automotive use will be in the application of high modulus reinforcement filled exterior panels and structural components. The aforementioned glass filled friendly fender is the front runner on this avenue. In this application the milled glass contributes to the dimensional stability and stiffness of the part. The paint finish on this part will be an elastomeric type since the fender is designed to "give" and take impacts of the type being experienced on parking lots. Going beyond the friendly fender, we expect future body parts in RIM to be made of still higher modulus materials. These other body parts could be doors, decklids, and load floors.

At GM assembly plants it is desirable to paint the high modulus plastic components of the future as part of the steel body. Painting plastic body parts such as fenders, doors, or deck lids on separate paint conveyors is undesirable because of cost and increased probability of color miss-match. RIM materials will be required that can withstand temperatures obtained in a typical GM paint system. Experience at plants has shown that oven temperatures of 400°F can be reached during line stoppages. High modulus plastic components designed to be painted by an assembly line process must be paint compatible and able to withstand the 400°F for short periods of time. Most urethane candidates tested to date have failed this requirement giving reason to consider new materials for future use.

The isocyanurate systems show promise as high temperature resistant materials. The air conditioner and heater housings mentioned earlier could use this material. Impact resistance is a problem with isocyanurates, and efforts are being made to improve this property.

POSSIBLE NEW RIM MATERIALS

Experimentation has shown that Reaction Injection Molding is a possibility with epoxy, polyester, and nylon 6. Some consideration is also being given to interpenetrating polymer networks (IPNs). To qualify as a RIM system, the following features are required:

FEATURES OF A RIM SYSTEM

1. Two or more liquid monomers
2. Monomers infinitely stable at room temperature.
3. Easily pumped
4. Fast reacting-exothermic
5. No by-products of reaction

EPOXIES

As with urethanes, the chemistry of epoxies can get very complex, and a whole spectrum of properties can be obtained. Basically, the chemicals involved are a resin component and a hardener. The resin monomer consists of molecules containing reactive epoxide groups while the hardener can consist of amines, hydroxyl groups, or anhydrides which react with the epoxide group. A typical reaction can be shown as follows:

$$\text{EPOXY RESIN} + \text{HARDENER (AMINES) (ANHYDRIDES)} \xrightarrow{\text{EPOXY FORMATION}} \text{EPOXY POLYMER}$$

The most widely used epoxy systems in industry have low viscosities, making them suitable for RIM processing. Work has been done using actual Reaction Injection Molding equipment to process certain epoxy formulations. To date, only test plaques have been made. One formulation examined consisted of the following materials:

PRELIMINARY EPOXY FORMULATION

A Side

Epoxy resin - 100 parts (Bis-Phenol A based)
2000 mwt. diol - 20 parts (Impact modifyer)

B Side

Reactive Anhydride - 85 parts

Conventional RIM equipment was used for this experimental run. Since the machine was used primarily for urethanes, great care was taken to assure that the tanks and lines were purged of urethane chemicals. The general processing conditions of this particular epoxy system were as follows:

PROCESSING EPOXY RIM

Mix Pressures	400 psi A side	150 psi B side
Throughput	250 g/second	
Stream Temperature	75-80°F	
Mold Temperature	300°F	
Demold Time	3 minutes	
Mold Release	Silicone based	

The physical properties obtained were as follows:

PHYSICAL PROPERTIES PRELIMINARY EPOXY RIM

Specific Gravity	1.15
Flex Modulus R.T.	320,000 psi
Tensile	6,900 psi
Elongation	1.6%
Izod Impact	3.4 (ft. lbs/in.) unnotched
	<1 (ft. lbs/in.) notched

It should be noted here that the formulation examined is very preliminary and does not represent the ultimate properties that are attainable with epoxy chemistry. This initial trial was only intended to show the capability of a conventional RIM machine to meter and mix epoxy. Since this trial, more work has been done with faster setting systems that react in 45 seconds or less with more conventional mold temperatures of 150°F. These fast systems use hardeners based on mercaptan chemicals or boron trifluoride in combination with tertiary amines.

A wide variety of possibilities exist to make epoxies faster reacting, heat resistant, and with adequate physical properties. For example, epoxies using novolac resins having 2.5 or 3 epoxy groups per molecule can in some cases offer significantly higher heat distortion temperatures compared to the more conventional bis-phenol A type resins. Work is also being done with cycloaliphatic epoxy resins which offer a combination of toughness and high heat distortion temperature. Efforts are also being directed toward developing methods of foaming epoxy systems which should lead to new applications.

Currently, emphasis is being placed on impact improvements since as with high modulus urethanes there is a brittleness problem with epoxies.

POLYESTER RIM

A polyester RIM system designed to mold structural parts has been evaluated on conventional RIM machines. The two liquid components were as follows:

POLYESTER RIM

A side - 600 cps (approximately)
Inert Polymeric Carrier
Blowing Agent

B side - 500 cps (approximately)
Polyester Resin
Peroxide Initiator

Great care had to be taken to assure that the machinery was completely free of any traces of urethane chemicals. Ratio control was not critical with this system because it is an addition reaction. The two low viscosity streams appeared to mix easily. Initially some parts were made without glass reinforcements and appeared to be very brittle. Considerably stronger parts were produced when a continuous glass mat was incorporated into the sample. Some of the properties obtained with glass mat are as follows:

POLYESTER RIM

Specific Gravity - 1.02
CTE - 19.8 x 10^{-6} In/In/°C
Heat Distortion Temp. - 235°C at 66 psi
Flexural Modulus RT - 340,000 psi
% by wt. glass - 15% (continuous 2 oz. mat)

A major shortcoming encountered was the instability of the monomer streams. The A side containing the azo blowing agent had a shelf life of only eight hours. The B side containing the polyester and initiator reportedly had a shelf life of several days at room temperature. Elevated temperatures drastically reduced pot life on both streams. Additional problems were encountered with the poor surface quality of the parts as evidenced by porosity and sinks.

Further work should be centered around extending monomer pot life and improving surface finish. The low viscosity of these types of systems enables good mixing at low pressures and could lead to the development of mat insert molding as a technique for making structural parts in the future. The economics of this type of system are favorable since costs of ingredients are lower than those of polyurethanes.

NYLONS

Any plastic resulting from a condensation or addition polymerization could have possibilities of being made by the Reaction Injection Molding process. Nylons particularly come to mind, since in most cases two separate liquid monomers are used to create the polymer. However, one must give consideration to the by-products of the reaction. Looking at nylon 66 we find that water is produced as a by-product which must be removed. Some nylons fall into this

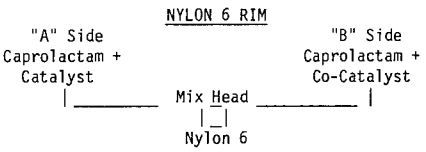
Hexamethylene Diamine + Adipic acid $\longrightarrow$ Nylon 66 + Water

category of producing by-products; but there are exceptions, notably nylon 6 which does not produce any side product. This unique material is produced from a single monomer, epsilon-caprolactam. The chemistry can be described as follows:

NYLON 6

Caprolactam Monomer Mpt. 160°F	Catalysts $\longrightarrow$ 300°F	Nylon 6 Polymer Mpt. 420°F

Caprolactam is a commodity chemical with a current U.S. production in excess of 1 billion pounds. The reaction to produce nylon 6 involves the opening of the caprolactam ring structure to form a linear polymer of high molecular weight. A RIM process schematic for this material would be as follows:



A lot of work was done on the nylon 6 casting process at the General Motors Technical Center during the early 1970s. A low pressure metering machine and press was purchased for this work. The objectives were to produce finished parts directly by polymerization in a hot mold at a temperature below the melting point of nylon 6. A number of co-catalysts were developed, which promoted the polymerization at a fast rate. With the advent of Reaction Injection Molding mix head technology, faster systems based on nylon 6 can now be processed. The newly developed self-cleaning mix heads fed by pumps or metering cylinders will permit filling molds at high pressures compared to the casting process.

Some important points can be made regarding nylon 6 as a reaction injection moldable material. On the positive side, we see a low cost, readily available, high modulus engineering thermoplastic with superior tensile strength and good impact resistance. Indications, based on casting into polished molds, are that release agents are not required. The toxicity of caprolactam is considered low, which is a highly desirable feature of a chemical for plant use. Being a thermoplastic, recycleability is possible. Problem areas are the high heat requirements of the streams and mold. The monomer entering the mold has a very low viscosity and will flash through the smallest opening. During transition from monomer to polymer, there is a very high volume shrinkage in the area of 10%. Caprolactam is very hygroscopic and small traces of moisture hinder the reaction. Fillers must be dried thoroughly.

The merits offered by nylon 6 give reasons to further develop this material for the RIM process.

INTERPENETRATING POLYMER NETWORKS (IPN)

Recently attention has been given to multicomponent systems such as polymer blends or interpenetrating polymer networks. The IPNs are described as combinations of polymers in which the chains of one are completely entangled with the other. In these systems, polymer A is supposedly in no way reacted with or attached to

polymer B. To qualify as an IPN it is required that the two polymers be synthesized in the immediate presence of each other. In theory, IPNs may provide a convenient route for the modification of properties to meet specific property needs. It is believed that IPNs can be produced by the "In-Situ" method such as the RIM process, which makes them ideal candidates for large part production. Three or even four stream mix heads, capable of handling multi-stream systems, are envisioned. A lot of work on this subject is being done at several universities throughout the world with a discovery that in many cases a maxima in tensile strength occurs which is significantly higher than the tensile strength of any individual component taken separately.
Some of the possibilities investigated on a laboratory scale are as follows:

INTERPENETRATING NETWORKS

Polyurethane - Polyacrylate
Polyurethane - Epoxy
Polyurethane - Polystyrene
Polyurethane - Polybutadiene

We at General Motors are interested in examining these type of systems to determine their feasibility for RIM processing.

CONCLUSIONS

Non-urethane materials can be used in conjunction with the reaction molding process. We are receptive to new materials that lend themselves to this process and can provide unique properties. Specifically, we need high modulus impact resistant materials with temperature resistance up to 400°F. Meeting this requirement will allow body parts, structural components, and under the hood applications previously not considered.

Other desirable features of new RIM chemicals are low toxicity, availability, rapid cure, and low cost. We are extremely interested in systems requiring no mold release. Future work is being planned with mat insert molding for structural applications. In this case, good wetting out of fibers is best accomplished with low viscosity systems. Elimination of post cure and materials that may be recycleable are other considerations for new RIM materials.

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BIOGRAPHICAL

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THE MOLDING OF NON-URETHANES BY THE RIM PROCESS

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INTRODUCTION

Reaction injection molding (RIM) is being extended to non-urethane materials such as polyesters, epoxies and nylon-6. In the report material handling differences and machine problems are pointed out with stress on pot life of the component materials. Discussion is based on glass-reinforced and non-reinforced systems and physical properties. A bench scale study of nylon-6 for RIM is presented.

NON-URETHANE RIM

RIM was developed for polyurethanes, which are made by mixing two liquid reactive components (1, 2, 3, 4, 5). There are numerous non-urethane liquid monomers which can be reacted directly to a solid polymer in the mold. Many of these can be divided into two individually stable liquid components which polymerize quickly upon mixing, and thus can be candidates for RIM. For example, epoxies and polyesters, although often used as long pot life, single-component systems which are cured slowly at room temperature or upon demand by heating, can be formulated as two-component systems suitable for RIM. Because of their low cost, availability, and widespread usage as liquid reactive systems, polyesters, vinyl esters, epoxies, and nylon-6 probably represent the most immediately promising RIM candidates. While these materials behave in some respects similarly to polyurethanes, they also have some important differences in behavior which affect RIM machine design, as will be discussed later.

Polymers which are formed from liquid monomers by an addition reaction (one which forms no by-products) are candidates for RIM. Because of the presence of many addition-reactable chemical groups in isocyanates, polyols, epoxies, polyesters, acrylics, phenolics, nylons, and others, innumerable hybrids of these resins are possible. Some condensation reactions (yielding a by-product), such as used to form phenolics and furans, give off volatile by-products which might be used as blowing agents. Some of these systems, as well as interpenetrating polymer networks, might prove useful in RIM.

INCENTIVES FOR NON-URETHANE RIM

Certain advantages of the RIM process provide an incentive for expanding its use to include a variety of new polymers or polymers now molded by some other process.

1. Advantages over thermoplastic injection molding:
   a. Extremely energy-efficient
   b. Fast cycle times possible
   c. Capable of molding large area parts
   d. Low tonnage clamps required
   e. Low cost of monomer compared to molding powder

2. Advantages over thermosetting molding processes:
   a. Eliminates need for batching of short pot life resin mixtures
   b. Eliminates hand measuring and pouring of resins into mold
   c. No resin maturation stage required
   d. Ability to handle highly reactive monomer mixtures

NON-URETHANE PROGRAM

Knowing approximately the monomer and polymer properties required, we first conducted a bench scale search for systems suitable for machine testing. The important properties to be considered were as follows:

1. Monomer pot lives
2. Monomer viscosities
3. Monomer toxicities
4. Ratio of components
5. Effect of fillers
6. Speed and temperature of reaction
7. Green strength after short cure time
8. Visually determined stiffness and impact properties of molding
9. Effects of monomers and flushing solvents on machine components
10. Effects of interactions of solvents and residual monomers on pot life

A limited number of polyester, vinyl ester, and epoxy systems have already been tested on RIM equipment. Nylon-6 requires certain additional machine modifications which must be made prior to testing in RIM equipment.

POLYESTERS

The polyester system, the first non-urethane development for RIM, involved an azo foaming agent in a styrene-free carrier of low or non-existent acidity on one hand and a styrenated resin plus adjuncts such as an organic peroxide catalyst, surfactant and a mold release on the other. Liberation of N_2 resulted on impingment mixing of the two components which yielded a cellular polyester over a density range of 20 to 80 lbs/cu. ft.

The physical properties achieved by foamed polyester indicate a need for improved formulations and possibly improved molding techniques. Thus far it appears that physical properties can be improved with the use of reinforcement in the form of milled glass fibers exceeding 1/8" (0.32 cm) in length. Considerable improvement was achieved with the use of continuous-strand mat, particularly impact and flexural strength. Addition of filler material such as calcium carbonate was necessary to prevent surface crazing. For optimum physical characteristics there is a need to solve the molding problems which result when these materials are used in conjunction with each other.

Stability

One basic problem in all polyester work is that the uncatalyzed polyester and individual polyester components once catalyzed have a short pot life. Also it was found that there was a considerable assay loss of foaming agent in 8 hours and almost a complete loss within 24 hours. This was minimized at a lower temperature or when the small amount of free acidity was neutralized in the carrier resin or more ideally when styrene was used as a carrier. Styrene, however, is too low in viscosity for good handling in RIM equipment or for suspending fibers or fillers which settled out during circulation or shut down, causing eventual blockage of the machine. Increasing viscosity through addition of polymers yielded undesirable moldings.

Unfoamed Polyester System

This type of system was based on a 30% styrenated polyester resin in each component on approximately equal weight basis. In order to compensate for the diluent action of the other component, the catalyst level had to be doubled in one component resulting in a stability of approximately 120 hours at ambient temperature where stability of at least 168 hours is desired. Based on bench scale work the unfoamed polyester system needs additional development before it is usable in RIM.

Comments

Improvement of the resin system for molding foamed and conventional polyesters in RIM is necessary. For foamed polyesters a suitable carrier is required. Stability of the catalyzed resin must be improved particularly in the conventional polyester system. Resin suppliers in the program are examining the problems which surfaced.

EPOXIES

The epoxy resins, known for their versatility, were found to be ideally suited for liquid reaction molding. Crosslinking or cure

is accomplished through the epoxy group or the hydroxy sites where present which react with amines, anhydrides, organic acids, phenolic resins or with other epoxide groups when catalyzed. Most commonly used epoxy compounds are diglycidyl ether of bisphenol A (DGEBA), the novalac, cycloaliphatic and the hydantoin epoxy resins. Epoxies are discussed in various texts (6).

Reactive diluents and flexibilizers, particulate and fibrous fillers were added to enhance physical properties, such as flexural and impact strengths.

From a number of laboratory trials, a diluent-flexibilizer modified DGEBA/methyl tetrahydrophthalic anhydride (MTHPA) system was selected for RIM mainly because it was compatible with traces of material left in the machine from another system that did not yield completely to clean-out efforts. This did not rule out other combinations which could have been selected as well.

Analytical data shown in Table I is presented for unfilled RIM plaques and those reinforced with continuous-strand glass mat molded in a three-minute cycle at 300 - 305°F (149-152°C). These were compared insofar as data were available with unfilled and glass mat reinforced polyol-flexibilized cycloaliphatic diepoxide/MTHPA plaques and based on a three-minute in-mold cycle at 310-315°F (154-159°C). The glass contents are averages of samples taken from selected areas of the panels.

Properties measured at -20°F (-29°C) thru 158°F (70°C) reveal the performance of the polymers over a practical use temperature range. It can be seen that physical properties of each resin system increased with progressively higher glass loading. In general the physical properties of the cycloaliphatic system are better for a given glass content although this is not necessarily the case for unreinforced moldings in comparison. Also the heat distortion temperature of the reinforced cycloaliphatic epoxy system is higher than that of the DGEBA system. On the other hand the coefficient of thermal expansion of the unfilled DGEBA epoxy is significantly higher than that of the glass-reinforced DGEBA epoxy as would be expected. A comparable value for the cycloaliphatic epoxy was not available. Some other systems which were molded at temperatures ranging from 77°F to 350°F (25° - 177°C) were extremely reactive and exhibited varying physical properties.

From the foregoing work there is no doubt that epoxies are suitable candidates for reaction injection molding. Certain physical properties, the coefficient of thermal expansion, flex modulus and tensile strength, are impressive, particularly those of the reinforced members. Other values need improving, such as the heat deflection temperature properties of some systems and impact properties of particulate and milled glass fiber filled systems.

We feel that suppliers of these materials will develop epoxies to meet specific industrial requirements.

PROCESSING OF ε-CAPROLACTAM

We are currently engaged in the development of nylon-6 for reaction injection molding by anionic polymerization of ε-caprolactam because of the combination of cost and polymer properties it affords.

The addition type reaction is straight forward. However, because the caprolactam is moisture sensitive (requiring no more than 50 to 100 ppm moisture for efficient polymerization), special handling is necessary.

Polymerization of ε-caprolactam is dependent on a catalyst/co-catalyst system. The materials added in quantities from .01 to to 20 mole percent cause ring opening and eventual formation of nylon-6.

The catalysts generally used are a variety of strong bases such as metallic sodium, their hydrides, hydroxides, alkoxides. The co-catalysts include acylating agents and components containing tertiary nitrogen in which substituents consist of carbonyl and radical groups, the imides and substituted imides. Isocyanates and acetylcaprolactam were used effectively in this case. Considerable practical information on nylons is published (7, 8).

Process Development

All of the development work consisted of bench scale study. The catalyst and co-catalyst components were prepared separately at 260-280°F (127-138°C) and were of the order of 0.5 - 2.0 mole percent. Polymerization was carried out at 335-340°F (168-171°C). It was not necessary to blanket the materials with nitrogen during mixing and polymerization provided they were handled above 250°F (121°C) to avoid moisture contamination.

Results

Polymerization was almost immediate after combining the catalyst and co-catalyst components and complete in one minute using two mole percent metallic sodium and one mole percent of hexanediisocyanate (HDI).

The oxide and methoxide of sodium also yielded nylon-6 without removal of by-products - water and methanol - which resulted during the reaction with caprolactam in forming the catalyst portion. However, the polymerization rate was slower and the purity of the polymer questionable. For optimum polymerization the water thus formed was removed by azeotropic distillation with toluene, the methanol under reduced pressure. Presence of water affected polymerization more adversely than presence of methanol.

It was found that in a study of the effect of water content on polymerization, with the introduction of various levels of water to a dried source of caprolactam, polymerization efficiency depended on the amount of catalyst/co-catalyst added and type used. Polymerization proceeded reasonably well with 2 mole percent of catalyst but proceeded very slowly or not at all when one half of that amount was used in the presence of .025 and .05% added moisture. HDI co-catalyst was more efficient than acetylcaprolactam.

Polymerization was slow, requiring more than 20 minutes when an eight-fold excess of acetylcaprolactam co-catalyst to metallic sodium catalyst was used. However, a polymer was obtained in three minutes with five more percent of each material.

Plaques molded with 23% by weight of 1/8" milled glass fibers warped due to settling from the low viscosity caprolactam at the molding temperature of 340°F (171°C). Plaques molded with one and two layers of two-ounce continuous-strand mat presented no problem.

Shrinkage of nylon-6 is reported to be 10-15 volume percent. Linear shrinkage (theoretically one third of the volume shrinkage) varied in the plaques depending on the type and amount of reinforcement present as follows:

Unfilled plaque 4.5%, plaque filled with 1/8" (0.32cm) milled glass fibers 3.1%, plaque containing one layer of two-ounce continuous-strand mat 0.9% and a plaque containing two layers of continuous-strand mat 0.07%. Physical analysis of nylon-6 is shown in Table II.

Bench tests indicate that reaction injection molding of nylon 6 is feasible.

OTHER CONSIDERATIONS FOR NON-URETHANE MATERIALS

Pot Life

Polyurethane monomers have "infinite" pot lives if properly stored. On the other hand, many of the non-urethanes have "finite" pot lives, meaning that individual components, even though carefully and individually stored, can harden irreversibly in their respective tanks and lines. This is probably the most serious difference between urethanes and non-urethanes.

Reinforcement and Foaming

Urethanes can be easily formulated to any desired degree of rigidity or flexibility, and are easily foamed. A slight degree of foaming is considered necessary in RIM, and urethanes can often be formulated to give desirable properties without the addition of fibers or fillers.

Epoxies share some of this versatility, but, in general, non-urethanes tend to be hard and brittle and become weak if flexibilized. As a result, glass fibers are commonly used to strengthen and toughen non-urethanes. In some applications, fibers short enough to be slurried in the monomers will suffice, and this practice is fairly well established. In other applications, however, long fibers are required, and additional processing studies will be required to make this practical.

CONCLUSIONS

RIM is now well established in the automotive industry as a practical method of producing polyurethane moldings. The work we have reported here was intended to demonstrate that the same equipment, possibly with a few design modifications, can be used to mold a variety of non-urethanes as well. The principal requirement is that two or more relatively stable liquid monomers should form a useful polymer upon mixing on a molding cycle of about three minutes or less. Addition reactions are normally required for RIM, although it is conceivable that condensation reactions might be used to a limited degree.

We believe that the feasibility of molding polyesters, foamed polyesters, epoxies, vinyl esters, and nylon-6 by the RIM process has been established. Since we are not a raw material supplier or a molded part supplier or user, we have not attempted to develop applications or to develop materials with physical properties suitable for specific applications. We believe this should be done by the material supplier and the molder, keeping in mind the problems described above. With the success of RIM in the automotive industry and the increasing need for large area plastics moldings on automobiles, RIM is expected to broaden into non-urethane applications in the automotive industry in the near future. Non-urethane RIM is being evaluated in competition with urethane RIM, SMC (Sheet Molding Compound), and some other processes, for fenders, door panels, hoods, deck lids, and other large area non-structural parts.

It is also possible, and even likely, that not all non-urethane RIM applications can be satisfied by unfilled polymers or polymers filled with slurried glass fibers. In this event, additional work will be needed to develop processes for using RIM with long glass fibers (greater than 1/4 in. or 0.6 cm.). This might be done by the use of fiber glass mats or preforms, pultrusion, etc. We feel further developments of this nature might be an area where material suppliers, machinery suppliers, and molders could effectively work together to pool their know-how.

ACKNOWLEDGEMENTS

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TABLE I

PHYSICAL PROPERTIES OF REINFORCED AND UNREINFORCED DGEBA/CYCLOALIPHATIC EPOXY SYSTEMS

			RESIN SYSTEM				
			DGEBA PERCENT GLASS		CYCLOALIPHATIC PERCENT GLASS		
		UNITS	0	21.3(3 oz/ft^2)	0	14.7(2 oz/ft^2)	27.3(4 oz/ft^2)
FLEX STRENGTH	-20°F (-29°C)	PSI	12,600	17,300	13,400	19,500	32,500
	77°F (25°C)	PSI	11,500	16,100	9,800	17,000	22,100
	158°F (70°C)	PSI	200	1,800	786	5,540	7,770
FLEX MODULUS	-20°F (-29°C)	PSI	519,000	778,000	459,000	809,000	1,080,000
	77°F (25°C)	PSI	374,000	590,000	300,000	500,000	710,000
	158°F (70°C)	PSI	9,150	71,700	36,400	243,000	376,000
TENSILE STRENGTH	77°F (25°C)	PSI	7,300	8,100	5,700	8,600	13,100
TENSILE MODULUS	77°F (25°C)	PSI	327,000	482,000	270,000	500,000	680,000
IZOD IMPACT-NOTCHED		FtLbs./IN.	--	6.4	0.47	3.33	8.41
IZOD IMPACT-UNNOTCHED		FtLbs./IN.	3.35	7.0	---	---	---
THERMAL EXPANSION (CTE)		(Δ/L)X10^6°F^{-1}	76.7	4.28		---	---
		(Δ/L)X10^6°C^{-1}	138	7.71		---	---
DEFLECTION TEMP (HDT)		°F (°C)	147(63.9)	152 (66.7)	138 (58.9)	176.5(80.2)	482(250)
GLASS TRANSITION TEMP(T_g)		°F (°C)	181.4(83)	181.4(83)	--	--	--

Table II

Physical Analysis of Nylon-6

	Unfilled (Published)	16% Glass (Determined)	32% Glass (Determined)
Tensile Strength, PSI	11,000-14,000	10,316	13,880
Tensile Modulus, PSI	350,000-470,000	562,500	666,000
Flexural Strength, PSI	80,000-450,000	477,500	555,000
Izod Impact, Ft-Lb/in.	0.8-3.0*		
Notched		3.0	9.4
Unnotched		5.0	14.7

*Not stated whether notched or unnotched

THE UREFAB PROCESS
A LOW COST APPROACH TO RIM PRODUCTION

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INTRODUCTION

It could be argued that the leading technological development of the Seventies, in thermoset plastics, is the growth of reactive injection molding (RIM) and its reinforced offspring, R RIM. At the heart of the breakthrough is the automotive industry. Plastics in cars used to be restricted to trim items, some housings, foam cushions and a few under the hood electrical applications. Now plastics are serious contenders for substantial body panel usage in the 1980's. Their use in fact appears inevitable, as the grinding forces of inflation, high energy costs and EPA requirements work in concert. Plastics technology has a proud tradition of rising to challenges. The amazing cure times and production rates of RIM automotive parts reinforce that tradition.

The awesome economic implications of RIM in automotive applications have led some to the conclusion that automotive original equipment is the whole story of RIM. From our viewpoint, nothing could be further from the truth. There is a wide range of industrial items that can be made better and cheaper by a RIM process - but only if the equipment costs, the mold costs and the whold overhead picture is competitive with alternate production schemes. For instance, a fiberglass shop employing 25 people or less is not likely to have the resources to invest several hundred thousand dollars in RIM, regardless of the potential profits. It is simply beyond their scope. If, however, he could get into production at the rate of 100 to 1000 parts per day, with a total investment of say $25,000, the picture may be changed.

The theme of this paper is the development of "POOR MAN'S RIM" a process proved in the field, by which many hundreds of thousands of parts have been shot the past four years. It requires close cooperation between the resin supplier, the mold maker and the producer. If these three work together properly, RIM can out perform and under cut the cost of polyester/fiberglass laminate, molded plywood, metals and vacuum formed thermoplastics, in specific cases.

RIM RESIN SYSTEMS

Let's look at some of the factors involved in getting into RIM on a modest budget. First, the resin system: Our urethane systems do not foam during cure. This eliminates the need for metal molds and high clamping pressures. There is essentially zero pressure in the molds, since the liquid resin is merely displacing air in filling the mold.

The resin system should be relatively insensitive to ambient moisture. This is a formulating responsibility. Isocyanate resins have been found to be 100% stable after 6 months storage in loosely sealed drums - no change in gel time, no tendency to foam and normal hardness and strength after cure.

The RIM resin system should be as low in toxicity as possible - no free TDI, no MOCA curative. Mixing equipment is cleaned immediately after use with non-flammable methylene chloride.

Systems must be tailor-made to meet requirement of the market place. Here are examples of currently available variations.

A) High impact/medium rigidity - Increase the ratio of polyol to isocyanate. For instance, impact strength of FR-8605 is maximized at a poly/Iso ratio of 105-110/100, instead of the standard 100/100

B) Medium impact/maximum rigidity - Decreases the polyol/isocyanate ratio, e.g. to 90/100.

C) Self extinguishing - FR-8562 meets Underwriters Laboratory Rating VO, for production of electronic data processing equipment cabinets.

D) Low temperature impact - FR-8510 resists falling ball impact to -30° C. The same effect is obtained by adding continuous strand fiberglass mat to FR-8506.

E) Lighter weight/lower material cost - Add glass bubbles (e.g. Philadelphia Quartz Co. Q-Cels). Addition of 5% reduces part weight over 25%.

F) Large parts - Most RIM parts under discussion have weighed 2-7 lbs., and equipment was developed for this area. Parts weighing 30 lbs. have been made with the same equipment, simply by doubling or tripling the gel time. There is no technical reason to prevent production of 100 lbs. or larger parts.

TOOLING

After resin requirements have been defined and met, the most important consideration is tooling. Most firms start with polyester/fiberglass molds, with which they are familiar. In all cases, they switch to high temperature epoxy tooling for serious production. Molds made with polyesters tend to deteriorate due to exothermic temperatures, which may reach 180° F. FR-47 Surface Coat and FR-40 Epoxy Laminating resin are used in aircraft tool fabrication for 350° F. service, so they are unaffected in urethane molding.

Toolmakers may incorporate electrical heating tape (e.g. Briskheat, Columbus, Ohio) into the laminate. It is useful for morning startup or when molds have cooled off. In production, the exothermic heat of the isocyanate/polyol reaction makes auxiliary heat input unnecessary.

A manufacture of snare drum and bass drum heads make the rims by the RIM process (pun intended). Cross section of the circular rim is about .375". Aluminum molds are used at 250° F. Total cycle for mold closing, resin injection, cure and mold stripping is about 25 seconds. Millions of parts have been made with no release agent, because the urethane compound contains built-in release.

Fiberglass molds require release application every few shots. We evaluated dozens of materials from many suppliers before settling on FR-1045 and FR-1046. The latter is recommended for parts which are subsequently painted.

THE UREFAB PROCESS

We call the injection procedure described herein the "UREFAB" process, to distinguish from capital intensive RIM. The step-by-step production cycle of a typical 3 lb. part, .125" thick, would go like this:

1. The pre-warmed molds are wiped with Release 1045 or 1046.

2. Molds are closed with any type of spring clamp. The molds are fitted with plastic tubing for entry and exit ports. The mold is tilted in such a fashion that no air is entrapped at the top of the mold during filling.

3. The two component internal mixing/dispensing equipment is turned on and volume output is adjusted to desired level. (See equipment discussion below). Filling is done at the rate of 6 - 12 lbs./minute, with care that no turbulence occurs in the molds. The air is simply swept out ahead of the urethane, so no pressure build up occurs.

4. As soon as material pours from the exit tube, the trigger is released and both plastic tubings are clamped shut.

5. The operator goes down the line, filling mold after mold, with no equipment cleanout between. By the time he has filled all molds (for instance, ten), the first mold has been opened, release agent applied and reclosed. The process can then be virtually continuous production.

6. If there is an interruption of more than 15-20 seconds, the operator clears the static mixing chamber with methylene chloride, then blows air through to vent solvent fumes.

7. Mold dwell time is in the 3 minute area. At that time the urethane is set but still rubbery. This facilitates removal from undercuts. The part, however, must be placed on a restraining fixture to assure proper contour after full cure. The fixtures are usually of simple plywood construction. Parts can be stacked elsewhere after about 10 minutes cure on the fixture, without concern about distortion.

MIXING/DISPENSING EQUIPMENT

The gel time of "Urefab" compounds such as FR-8506 can be varied from less than a minute to 3 minutes. Standard material gels in 55-60 seconds in a 100 gram mass at 75° F. (23° C.). This makes two component mixing equipment mandatory. Considerable equipment development was undertaken by Fiber-Resin Corporation in 1976-1977, in cooperation with several manufacturers. It lead to the development of equipment with these salient features:

1. Pumps are air-driven, requiring a compressor in the 15 cubic ft./min. area for pumping about 12 lbs./min. of mixed polyurethane.

2. The entire unit is air-tight, so moisture sensitive isocyanate can be stored in pumps, piping and hoses for months without clean-out.

3. Static mixing is recommended. Since both viscosties of our compounds are in the 500-1400 CPS range and are approximately 1/1 by volume, the two components mix easily with no visible color striations.

4. Ratios can be changed from 2.0/1.0 to 1.0/2.0 by a simple adjustment of a variable drive unit.

A suitable mixing and dispensing unit is the 5-12 machine, manufactured by J. Johnson and Sons, Glendale, California. Cost is in the $4,000. area, plus accessories as desired.

MARKETS FOR "UREFAB" POLYURETHANES

Initial acceptance of "Urefab" parts was to replace cast epoxy and polyester/fiberglass parts. New uses are proliferating as design engineers take advantage of the toughness, cure speed, broad spectrum chemical resistance and other properties of these compounds. Here are some typical end uses for "Urefab" moldings.

Rims for drum heads.
Automotive aftermarket - Flares, spoilers and louvres for vans and off-road vehicles.
Other automotive parts - Grilles, fascia, wheel decorations.
Imitation wood products - picture frames, logs, handles, decorative wall pieces.
Pump and dredge components.
Rub strips and doors for aircraft interiors.
Computer housings.
Electronic data processing cabinetry.
Furniture - secretary chair backs, pedestal bases, captains chairs.
Doll houses.
Battery cases.
Medical equipment (dialysis machines, knee caps)
Cast aircraft models.
Womens shoes.

EFFECT OF GLASS REINFORCENT ON RIM POLYURETHANES

RIM compounds are characterized by Durometer hardness (ASTM D-2240), flexural strength and modular (ASTm D-790), and falling ball impact. The latter is a one pound steel ball that is dropped in 1 foot graduations on a .125" thick sample placed on a steel base. For greater severity, the sample is bridged between .500" end plates over a 5" span. Plaques can be chilled in a dry ice/alcohol bath to determine low temperature impact properties.

The standard product (FR-8506) has a Durometer hardness of 68 - 72 and excellent room temperature impact resistance to the falling ball. It loses this impact resistance at about 10° F. (-12° C.) 10-15% reinforcement with continuous strand glass mat extends the low temperature impact resistance to below -30° F. (-34° C.). The validity of this laboratory procedure was confirmed by tests on a 36" long container designed for missile components. The required impact test consisted of loading the container with 40 pounds of sand and dry ice. When the container was chilled to -20° F. (-29° C.), it was dropped on edge from 4 feet height onto a concrete floor. (This roughly simulates a container accidently falling from the tail gate of a truck in the Artic). With no glass reinforcement, the container cracked. With glass mat reinforcement it was impossible to damage the part.

Automotive RIM procedures use milled glass (or other) fibers to improve properties. Initial data with our RIM products indicates a great increase in stiffness (Flexural modulus) with 15% milled glass. Moduli are inversely proportional to fiber length in FR-8506.

Hollow glass bubbles can reduce weight of a RIM part by 25%, and thus reduces cost significantly. It was felt that the fragile glass microballoons might be reduced to glass fragments during pumping and mixing of components. In practice, laboratory hand mixes and machine dispensed resin/glass balloon compounds show little difference in density.

CONCLUSION

Information is presented on a low cost RIM procedure which has been proven in several years production experience. Polyurethane resin properties can be varied to meet a wide variety of end use requirements. Continuous strand glass mat enhances impact and flexural strength.

Plastic tooling and mixing/dispensing equipment are discussed in relation to the RIM process.

FLEXURAL PROPERTIES OF FR-8506

	Flexural Strength, PSI	Flexural Modulus, PSI
As is	4600	148,000
10% continuous glass mat	9900	368,000
15% chopped fiberglass, 1/4"	6600	149,000
15% chopped fiberglass, 1/8"	4700	128,000
15% milled fiberglass, 1/16"	3500	232,000
15% milled fiberglass, 1/32"	4100	323,000
5% glass bubbles	5300	121,000

IMPACT RESISTANCE OF FR-8506

As is	Pass 10 ft-lbs.
10% continuous glass mat	Pass 10 ft-lbs.
15% chopped fiberglass, 1/4"	Pass 10 ft-lbs.
15% chopped fiberglass, 1/8"	Pass 10 ft-lbs.
15% milled fiberglass, 1/16"	Pass 10 ft-lbs.
15% milled fiberglass, 1/32"	Pass 10 ft-lbs.
5% glass bubbles	Pass 10 ft-lbs.

PROPERTIES OF FR-8506

Resin type	Non TDI isocyanate, polyether type, polyol cure. Non-Moca system
Ratio A/B	1/1 by weight
Colors	Standard tan or black. Other shades available.
Density	1.1 ± .05
Viscosity, cps	
Part A	250-500
Part B	1300-1700
Gel time, 100 grm. @ 77° F.	55-65 seconds
Heat resistance temp., ° F.	160
Elongation, %	50
Tear strength, ASTM, Die C, lbs./lin.in.	550
Tensile strength, psi	4100
Ultimate compressive strength, psi	15,750
Flexural modulus, psi	
77° F.	148,000
Coefficient of expansion, in./in./°F.	
(-20 to + 160° F.)	9.0×10^{-5}
Shore D hardness @ 77° F.	
10 minutes	30
20 minutes	60
overnight	70
Shore D hardness @ 160° F.	54
Impact resistance (1 lb. steel ball dropped on 1/8" sheet on steel base)	Pass 11 ft. lb., @ 30° F., and 77° F.
Izod impact, notched, ft.lb./in.	1.3
Demold time, 1/8" - 1/4" thickness	
R. T. mold temperature	10-20 minutes
150° F., mold temperature	2-3 minutes
250° F., mold temperature	15 seconds
Chemical resistance, 24 hr., immersion	
24 hours in Methyl Ethyl Ketone	No visible effect
24 hours in 30% H_2SO_4 @ 150° F.	No visible effect
24 hours in 40% NaOH @ 150° F.	Surface dulling

FLEXURAL PROPERTIES OF FR-8562

	Flexural Strength, PSI	Flexural Modulus, PSI
As is	5,700	196,000
10% continuous glass mat	10,100	298,000
15% chopped fiberglass, 1/4"	5,700	178,000
15% chopped fiberglass, 1/8"	4,300	135,000
15% milled fiberglass, 1/16"	7,000	271,000
15% milled fiberglass, 1/32"	7,100	254,000
2.5% glass bubbles	3,900	270,000

FLAMMABILITY TESTS WITH FR-8562

1) Per UL 478
Specimen size .125" x 1" x 4", vertical position 1" blue tip flame, 30 second exposure.

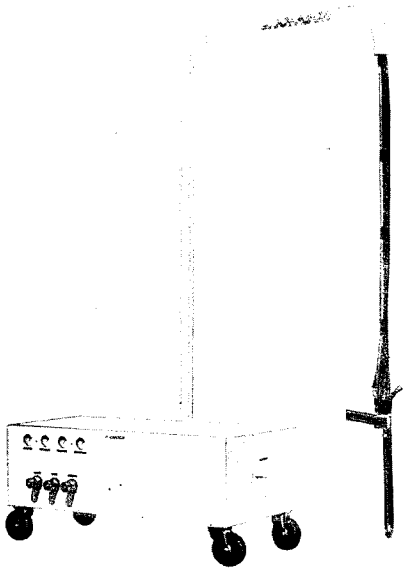
Results: Self-extinguishing in 1-5 seconds
Conclusion: Meets UL 94 V-O

2) Multiple flame exposure per UL 478
Specimen size .125" x 1/2" x 4", vertical position exposed to flame 5 times, 5 seconds

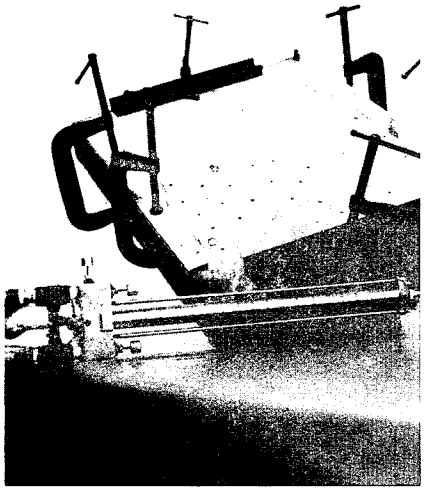
Results: Self-extinguishing in 7 seconds
Conclusion: FR-8562 self-extinguishes after repeated ignitions.

AUTHOR'S BIOGRAPHY

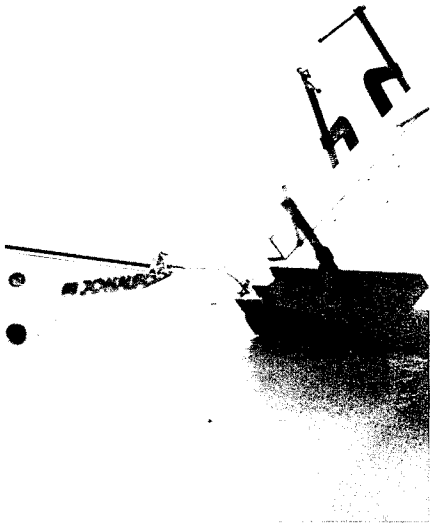
Andre B. Kerr received the M. S. in Chemistry from Lehigh University in 1951. He has had a variety of laboratory, sales and management positions with Union Carbide Corporation and Furane Plastics since that time. Mr. Kerr is Vice President and General Manager of Fiber-Resin Corporation, responsible for operations of their California and Michigan plants.



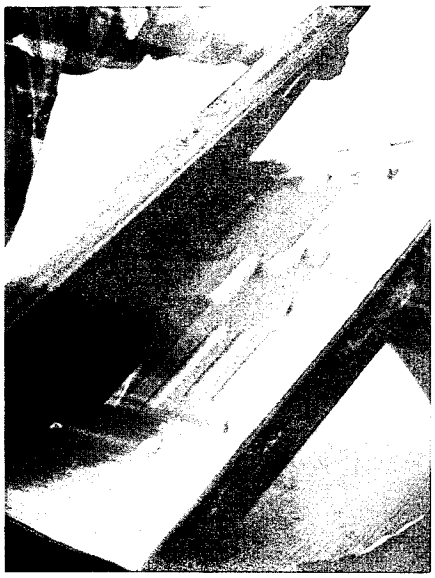
Mixing/dispensing equipment for the "UPEFAB" Process



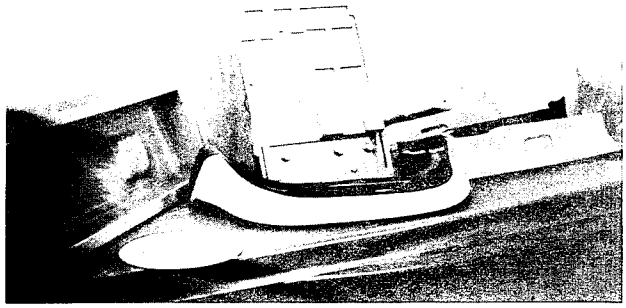
Epoxy/fiberglass mold ready for resin injection.
Note: Plastic tubes for resin intake and exit, and static mixing head in foreground.



Resin injection at the rate of 12 pounds per minute.
Mold is tilted to prevent air entrapment.



Demolding the finished part.



Typical parts made by the "UPEFAB" Process.
Weights range from 4 ounces to 25 pounds.

SPECIAL EFFECTS OF SPHERICAL GLASS FILLERS ON R.I.M. AND B.M.C.

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When non-reinforcing fillers are added to polymer systems, they tend to modify certain of the polymers physical properties adversely. Coupling agents sometimes help increase these values but the overall affect is for the mixture to behave more like the fillers. Tensile strengths and impact are reduced, while the material has a higher flexural modulus and is brittle like the inorganic filler.

A technique to use the high filler loading and the benefits that accrue, is to allow the filler and polymer matrix to work independently of one another--the opposite of a coupling agent--were the filler acts more like greased ball bearings.

This paper will show that high filler loadings can be achieved with glass spheres to obtain good moldability, surface smoothness, economics and high compressive strength, without losing impact strength and flexibility.

Multiple component systems such as R.I.M. require as low a viscosity as possible for effective mixing. Angular fillers and high aspect fillers raise viscosities geometrically as opposed to uniform spherical particles. If only spherical fillers are used, the energy required for mixing a filled system is greatly reduced. Viscosities can be predetermined using the Einstein formulae as well.

Introduction

The use of fillers in plastics is taking on increasing importance. Fillers are being used not only to extend precious petrochemicals but to enhance the processability of the plastic as well as its physical properties. Most fillers are chosen for their economic impact and not necessarily for their contributions to overall performance. Only high aspect ratio fillers eg. mica-fiberglass have been considered as modifiers of properties and non-reinforcing fillers disregarded as only a replacement for resin.

With greater concern being shown for product liability, weight-cost effectiveness, this attitude is changing. Current and future needs require higher performance systems which will utilize more costly fillers.

Since the rheology of any molding material, whether its R.I.M. (Reaction Injection Molding), injection or compression molding, must be optimized; then fillers with minimal affect on viscosity are a prime requisite. Spherical particles which are innert chemically and have low oil absorption, are an ideal candidate. Solid glass beads fit this description perfectly.

Non-reinforcing fillers in a polymer matrix affect the physical properties, therefore it is necessary to minimize adverse results. As a specific filler is increasingly added to a plastic, the plastic takes on more of the physical properties of the filler. When glass beads are used as the non reinforcing filler, adverse physical properties usually attributed to filler loading can be minimized.

The economics of using glass beads to replace fillers such as clays and carbonates must be balanced against the improved physical properties of the molded part. In the case of reaction injection molding where the beads would compete with fibers to reduce thermal coefficients of expansion, then they have a considerable economic advantage.

Theoretical

Fillers are used in plastics for some of the following reasons:

1. Reduce resin content
2. Reduce exotherm
3. Reduce shrinkage
4. Improve surface smoothness
5. Improve surface hardness
6. Improve dimensional stability
7. Improve thermal coefficient of expansion
8. Improve compressive strengths
9. Modify electrical properties
10. Improve chemical resistance

As you can see there are a multiplicity of reasons to use fillers in plastics. The spherical filler-microsphere or glass bead as I shall call it, has several advantages over all other fillers, its sphericity and low oil absorption. Geometrical calculations show that a spherical particle has a minimum ratio of surface area to volume. This means that for a given weight of glass beads, the total surface area is less that an equivalent weight of any other filler. The amount of shear between glass beads filled resin is lower than for any other particle. Consequently it is the easiest material to mix in multiple component systems. See Figures 1 and 2.

In reaction injection molding where ease of mixing is extremely important, glass beads because of their rheological innertness, provide an effective solution to the filler problem.

Injection molding filled polymers both thermoset and thermoplastic are enhanced with glass beads. Higher filler loadings (on a volume basis) can be obtained with glass beads than any other filler and less fiberglass damage is detected. In some instances, glass beads enhance the flow of high aspect fillers through a mechanism described as a ball bearing effect.

The sphericity also yields better stress distribution in a polymer matrix than irregularly shaped particles, and the high inherent strength of the glass beads show up as high compressive strengths in various plastic systems.

Oil absorption varies for most fillers but the fire polished surface of the glass bead is completely non absorbent.

Irregularly shaped fillers tend to interlock when used in high percentages in a polymer matrix. This inferference or buttressing of angular fillers causes reduced impact strength and fatigue characteristics in the plastic. Glass beads on the other

hand show higher flexural strength than irregular shaped quartz but a much lower flexural modulus. In other words an equal amount of glass beads made a stronger more elastic part. See Figure 3.

Zinc Stearate coated calcium carbonate filler has been reported to improve impact properties of thermoset molding compounds because of a similar effect. The stearate acts as an abhesive[2], which is a material used in the form of a film or coating applied to one solid to prevent or greatly decrease the adhesion to another solid in intimate contact with it. Just the reverse of a coupling agent. Glass beads can be obtained with abhesive coatings as well as a number of different coupling agents.

One unique property of glass beads is that their viscosities can be determined when mixed in resinous systems.[3] The glass beads must occupy less than 30% of the total volume of the composite, the relative viscosity of the filled and unfilled polymer (M/M_o) may be expressed as a function of the partial volume (C) occupied by the filler particles. By considering such a system to be one in which nonsolvated glass beads were dispersed in a viscous Newtonian fluid, Einstein derived the following expression:

$$\frac{M}{M_o} = 1 + 2.5C$$

Since experimental data for simple filler-liquid systems do not fit the Einstein equation, it has been modified with a hydrodynamic factor B. The value for the hydrodynamic factor varies (B) = 1.91 for loosely packed spheres and 1.35 for tightly packed spheres.

$$\frac{M}{M_o} = \frac{2.5C}{1-BC}$$

The disc brake caliper piston is an example of high filler loading. This part had to have an extremely low thermal coefficient of expansion as well as excellent thermal shock reisitance and chemical resistance. See Figure 4. It utilizes glass beads with coupling agents.

The bow handles pictured in Figure 5 are dynamic parts that must withstand a great deal of flexing. Glass beads utilizing abhesive coatings were selected to give not only fatigue resistance but withstand the impact of the arrow leaving the bow.

Since a smooth surface with high gloss was required glass beads were chosen to fill this epoxy BMC part.

TYPICAL PORPERTIES OF CP-25 Caliper Piston

Property	Units	Value
Flexural Strength	psi	14,200
Flexural Modulus	psi	2,415,000
Tensile strength	psi	7,000
Modulus of Elasticity	psi	217,000
Compressive Strength	psi	22,200
Notched Izod Impact Strength	ft.lbs/in notch	.78
264 psi Heat Distortion Temp.	^oF	over 517
Coefficient of Thermal Expansion 72^{o}F - 248^{o}F	in/in/^{o}C x 10^5	1.3
Specific Gravity	----	1.94

TYPICAL PROPERTIES OF BY- 28 Bow Handle

Property	Units	Value
Flexural Strength	psi	12,600
Flexural Modulus	psi	887,000
Tensile Strength	psi	7300
Modulus of Elasticity	psi	104,000
Compressive Strength	psi	17,500
Notched Izod Impact	ft.lbs/in	3.05
264 psi Heat Distortion Temp.	^oF	394
Coefficient of Thermal Expansion	in/in/^{o}C x 10^5	2.95
Specific Gravity	----	1.5

TYPICAL PROPERTIES OF TG - 11 Trigger Guard

Property	Units	Value
Flexural Strength	psi	22,500
Flexural Modulus	psi	1,730,000
Tensile Strength	psi	12,900
Modulus of Elasticity	psi	171,000
Compressive Strength	psi	26,800
Notched Izod Impact Strength	ft.lbs/in notch	.76
264 psi Heat Distortion Temp.	^oF	322
Coefficient of Thermal Expansion	in/in/^{o}C x 10^5	2.97
Specific Gravity	----	1.81
Color		Optional

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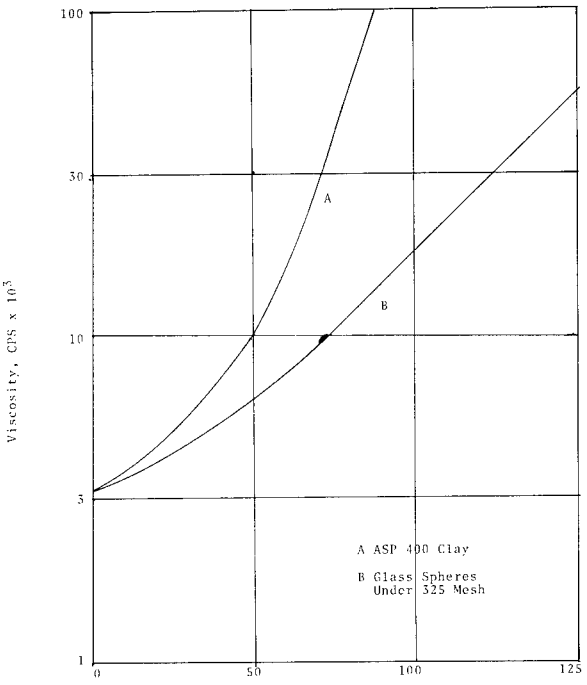

Figure 1. Effect of clay vs solid glass spheres on polyester resin viscosity.

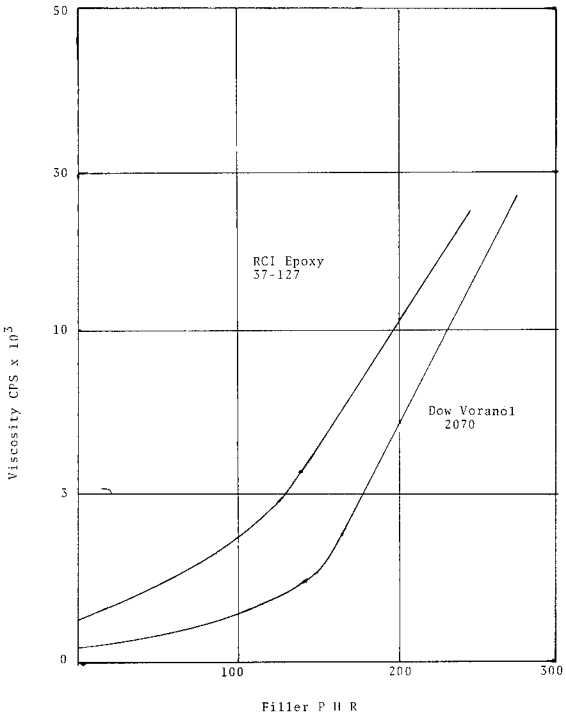

Fig. 2 Effect of Beads on Different Resins

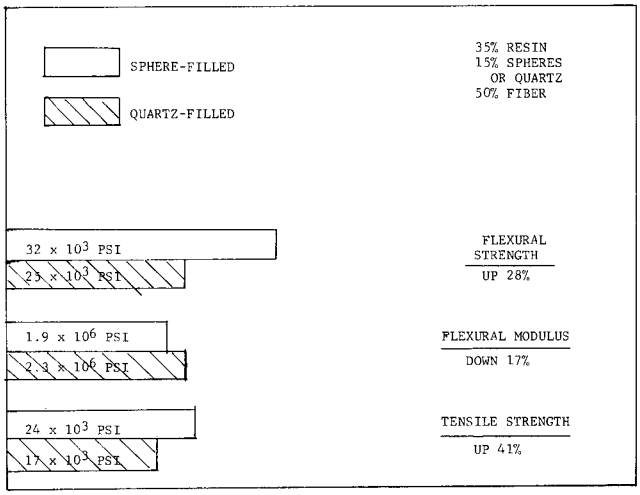

Figure 3. Sphere-filled vs quartz-filled epoxy laminates.

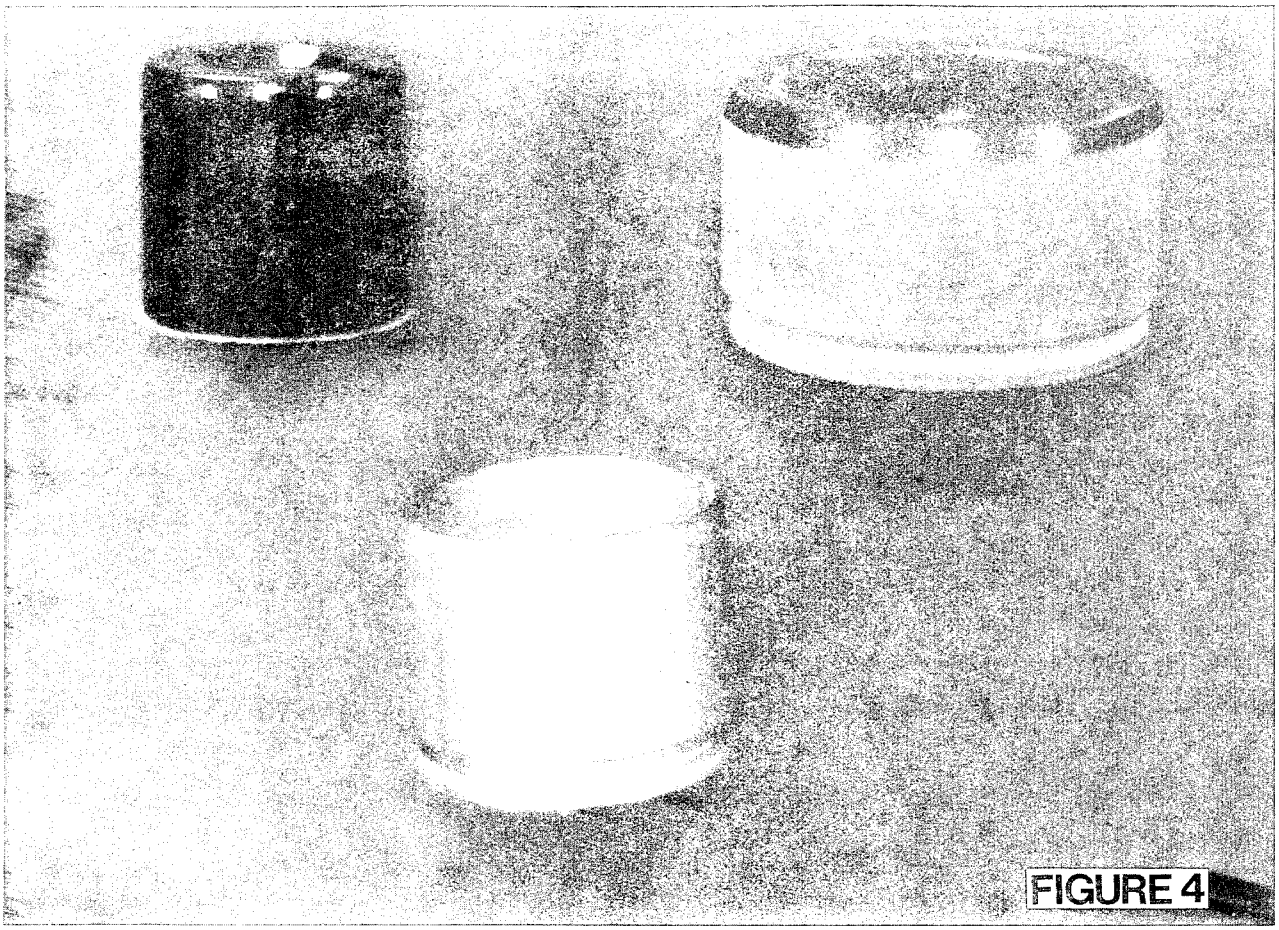

FIGURE 4

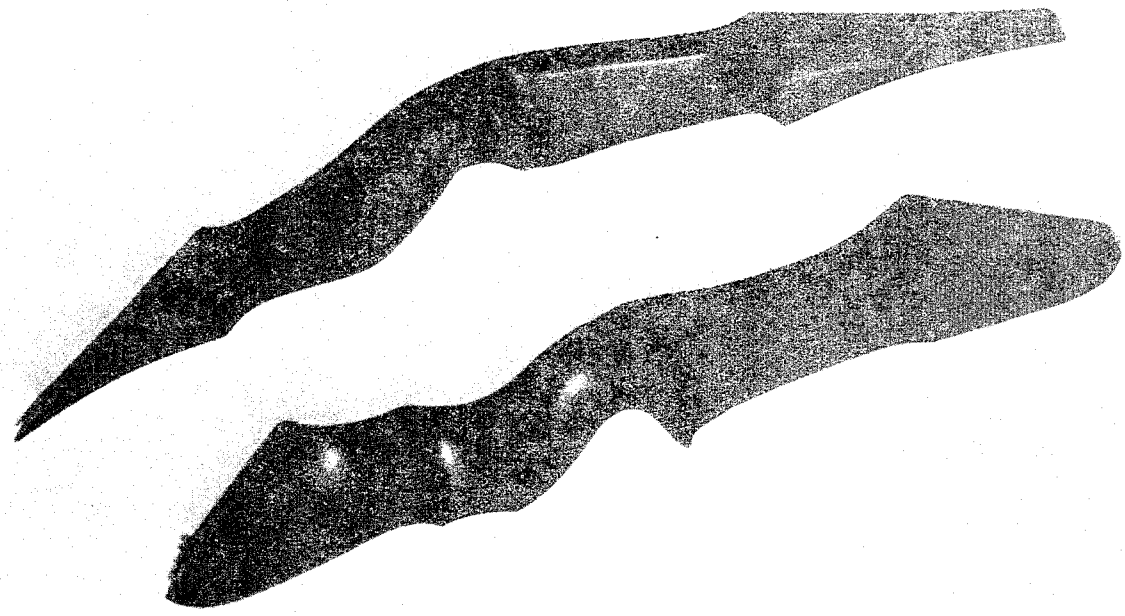

FIGURE 5

HIGH PRESSURE STRUCTURAL FOAM: DEVELOPMENTS IN OBTAINING SPLAY-FREE SURFACE FINISH IN MEDIUM-PRICED ENGINEERING RESINS

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INTRODUCTION

During the last decade, structural foam has found numerous applications in a number of industries; indeed, in computer housings it now appears to be the material of choice. In the automotive industry, however, the technology has found relatively few applications. The original underhood applications of low pressure foam have only in the last few years been augmented by the now common high pressure foam glove box doors. This market has flourished primarily due to economies in cycle, amount of material and finishing costs. However, these economies appear only truly effective on surfaces that ultimately possess a textured surface and, as a result, automotive exterior applications have not appeared to date.

In this paper, we will introduce certain recent developments in high pressure structural foam that we strongly believe will offer the designer, for the first time, a class "A" automotive exterior finish in structural foam. Even though we have experienced extremely promising results with this process to date, we do not claim it as a panacea to cost, weight and quality problems faced by the automotive industry. Rather, we will indicate certain applications in which we believe that the advantages of this sytem will be displayed to the greatest possible extent.

FARREL HIGH PRESSURE PROCESS - STANDARD SEQUENCING

The capability that is described above is an evolutionary one, and has been under development and in production for over fifteen years. We will not discuss coincident developments in low pressure foam here. We will rather start with the obvious concept that the purpose of research into both systems relating to surface finish is the same: To transfer the resin from the charge state to the mold in such a manner that it sets up with minimum surface effects of the transfer. The difference lies in how that reduction in surface defects will take place; whether by heating the mold, super fast injection speed, or co-injection, each process has its own limitations. Our position is, however, that the limitations imposed by high pressure foam are the least difficult to deal with in a production situation. This is so because high pressure foam is similar enough to injection molding to allow an injection process engineer to make the transition swiftly, and to deal with a machine running high pressure foam in the same way he would treat that same machine running any slightly unusual injection molding project.

How is this capability achieved? The basic high pressure foam concept is based upon two distinct concepts:

(1) The polymer and chemical blowing agent are maintained in the barrel at a temperature just below that necessary to activate the chemical blowing agent. The foaming agent is activated by the sheer heat of crossing the restricted nozzle valve, and completes the foaming reaction only after it has entered the mold.

(2) The mold is packed out, at a volume reduced by the insertion of a core into the part. The mold is subsequently expanded after the part is formed.

The system described above has several advantages -- in certain applications -- over low pressure foam molding. Please note the sequence of operation (Fig. 1-4), currently in use on a number of Farrel machines equipped with the high pressure option.

ADVANTAGES OF THE BASIC PROCESS:

As can be seen, the key factors in this sequence are not speed or screw configuration, but rather temperature and pressure control. The system as described yields a number of advantages. First, by adjusting sequencing and timing, the cell structure and skin thickness can be altered. Because the mold can be shimmed and the expansion distance can be adjusted, part density can also be altered (density being proportional to shot size over final volume). Most important to high-volume application, however, is the concept that curing begins immediately, resulting in a 30-40% reduction in cycle time.

Because the blowing agent only activates inside the part and has no function other than maintaining an established external geometry, much thinner sections (.085" before expansion, .036" in non-expanded areas) and much higher weight reductions (typically 50%) are possible than in low pressure foam molding. Finally, because certain areas in the part are left solid, the physical properties of the part can be adjusted to meet attachment requirements. Thus, the part can ultimately be value engineered -- it can be designed to minimize resin costs.

DISADVANTAGES

Obviously, adding the third plate increases the cost of the mold; we find the increase is 10-15% for each direction of expansion. In addition, articulating tools suffer wear at a fairly accelerated rate in kirsite or aluminum, but this effect appears to disappear in a P-20 (or equivalent) steel mold.

Secondly, the weight reduction as a function of tooling cost will decrease as the amount of projected area decreases. There are some parts that are simply not applicable to the process, primarily those that have 50% or more of the surface covered with difficult hole configurations. The process appears to work very well on "window frame" type applications, though; these geometry types allow a surprising amount of area to expand.

GAS SEALING - A MAJOR ADVANCE

During the last two years, the system described above has gone through a major modification. A method was developed to produce a high gloss, splay-free surface with potential for color matching. Please review the sequence of operations (Figs. 5-9). As might be expected, the sequencing, pressures and temperatures are controlled very carefully; for instance, the timing of the exhaust allows us to control the degree of surface gloss without tooling alterations. Beginning with the early developments, an attempt has been made to ensure the versatility of the above system. We have attempted to process as many materials as we can -- and, in the process, have refined the system to develop the control necessary for complex shapes in engineering materials. We have had a great deal of success in the engineering polymers. We have tried several grades of each, and we will here detail highlights of the present state of our research into each of these polymers.

(1) Modified PPO - Easy flow, SF and N300 work with little difficulty. The white colored material is especially

promising, since it does not appear that color dispersion will vary significantly due to microscopic splay, even at high color loadings necessary to hide the natural color of the resin.

(2) ABS - UL-VO grade does not seem to present a problem; neither burning during injection nor severe plate-out were encountered. We have recently been experimenting with plateable ABS and have been very encouraged with the results.

We anticipate having test samples for automotive evaluation by June, 1980 in realistic parts.

(3) ABS-Polycarbonate blends - We are very encouraged by this development, since it indicates a major limitation of low pressure (charring of material). Color consistency is not as good as with ABS, but the surface quality is excellent. The material appears to lend itself very well to the process.

(4) Polycarbonate - We have had some very impressive results with injection molding grades of polycarbonate; the first is almost as brilliant as acrylic.

In the near future, we intend to process several upper-range engineering polymers, primarily nylon and polysulfone. Our results to date indicate that we are well within the capabilities of our apparatus, and we foresee no significant difficulties with these specialty materials.

ANTICIPATED MARKETS

While high pressure structural foam has many potential uses in the automotive marketplace, there are two areas that appear to offer the greatest near-term return, using existing technology, principally in the passenger car market. The first is in wheel covers where it appears that a high pressure foam plated surface will soon obtain automotive acceptance; the second is in exterior panels, specifically trunk lids, quarter panels and hoods.

We anticipate early acceptance by the automotive industry of the concept of high pressure structural foam panels for the following reasons:

(1) The process has been developed to the point where it appears to be easy for the processor to obtain an acceptable exterior "A" surface part.

(2) The part-to-part consistency is good enough to allow minimal machine attention once set-up is completed.

(3) There are a number of machines currently in production in various automotive facilities that can be very easily converted to high pressure foam.

(4) The machines now available are of the appropriate size and configuration to mold parts as outlined above.

These factors allow us to recommend the following hypothetical trunk lid "first part", which could be operational for the 1982 model year. The clamp tonnage requirement of 1 to 1-1/2 tons per square inch of projected area would allow a part up to 25" x 40" to be molded on a 1000 ton machine. In modified PPO, such a hypothetical part would be 100 ounces or less in weight at a thickness of a quarter inch -- including provisions for attachment bosses and reinforcing ribs. The part would be virtually as rigid as a steel part, and would cost less than $12.50 prior to being painted along with the rest of the automobile.

CONCLUSION

In this paper, certain aspects of high pressure structural foam technology have been discussed. Particular emphasis was placed upon detailing how the technology is evolving, and how previous research into various materials and sequencing arrangements has led to a versatile system. Various resins of particular interest to automotive end users were discussed along with our research goals for the near future.

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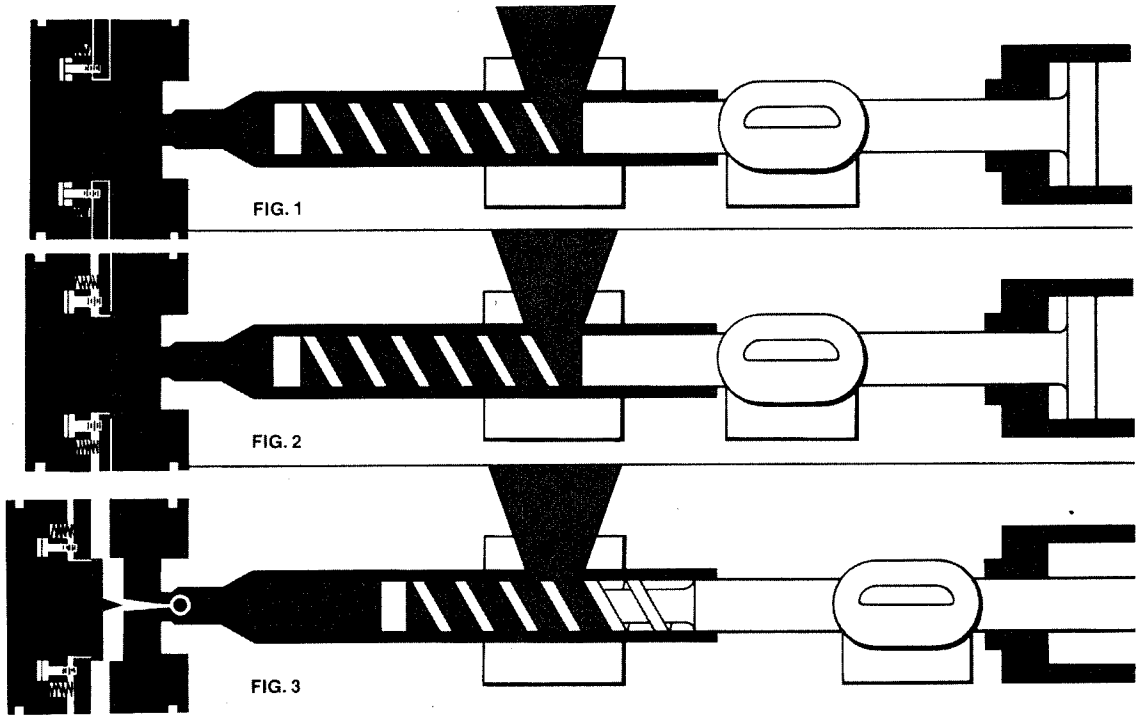


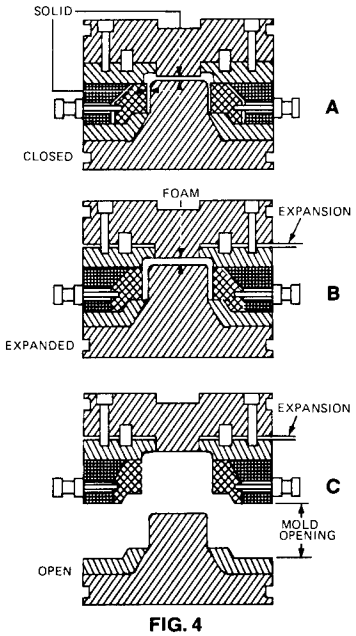


FIG. 4

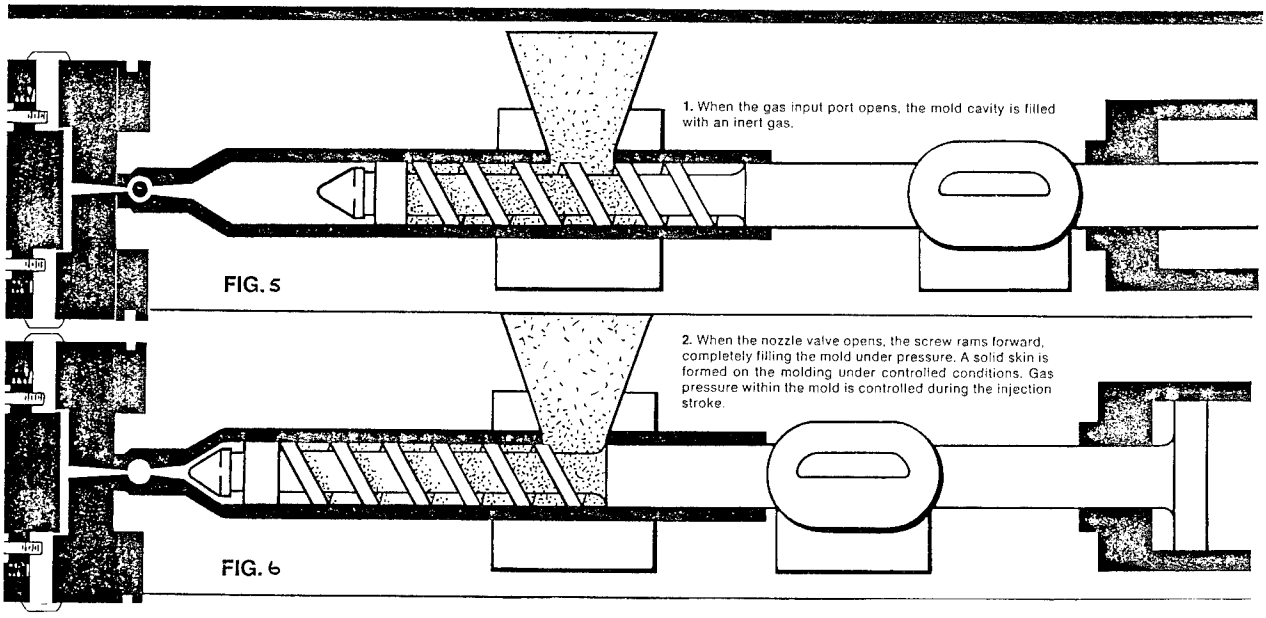
Fig. 1 - When the nozzle valve opens, the screw rams forward, completely filling the mold under pressure. A solid skin is formed on the molding under controlled conditions.

Fig. 2 - After injection is completed, the nozzle valve shuts and the platicator begins refill at constant back pressure. Foaming begins at completion of mold fill, with the mold cavity volume expanding at a controlled, balanced rate.

Fig. 3 - The mold is opened, the part is removed, the plasticator is full and ready to inject a shot into the mold. The closed nozzle valve holds the plasticated melt blend under constant pressure.

Fig. 4 - A technique for producing more complex parts. This demonstrates that expansion is not limited to the plane of platen motion, but can be built into the mold and controlled independently.

FARREL GAS-SEALED HIGH PRESSURE FOAM MOLDING PROCESS

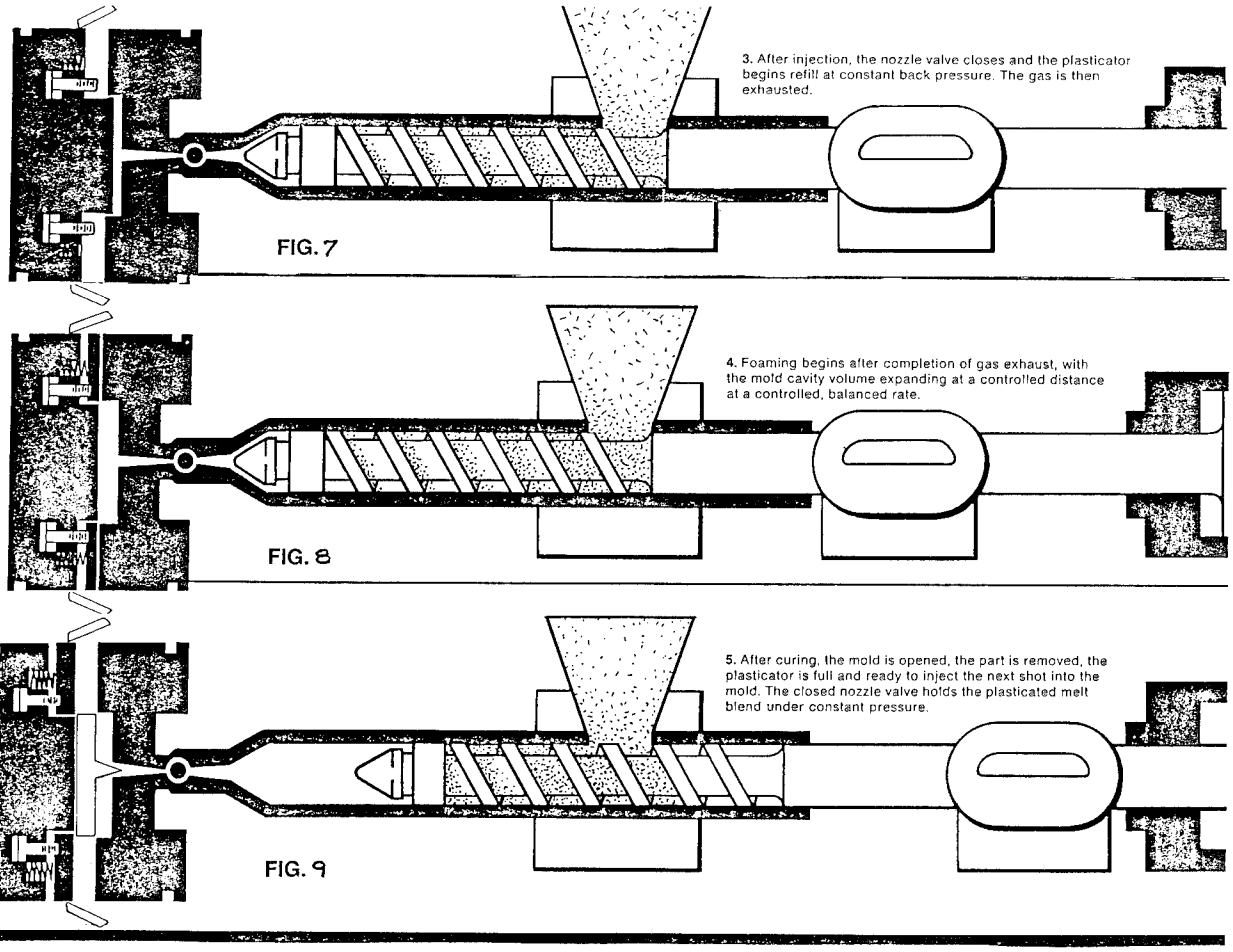


1. When the gas input port opens, the mold cavity is filled with an inert gas.

FIG. 5

2. When the nozzle valve opens, the screw rams forward, completely filling the mold under pressure. A solid skin is formed on the molding under controlled conditions. Gas pressure within the mold is controlled during the injection stroke.

FIG. 6



3. After injection, the nozzle valve closes and the plasticator begins refill at constant back pressure. The gas is then exhausted.

FIG. 7

4. Foaming begins after completion of gas exhaust, with the mold cavity volume expanding at a controlled distance at a controlled, balanced rate.

FIG. 8

5. After curing, the mold is opened, the part is removed, the plasticator is full and ready to inject the next shot into the mold. The closed nozzle valve holds the plasticated melt blend under constant pressure.

FIG. 9

INJECTION MOLDING CLASS A SURFACES WITH TMC REINFORCED POLYESTER COMPOUNDS

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INTRODUCTION

The use of glass reinforced polyester has been increasing at a fast rate in the automotive industry. Paramount advantages in considering polyester composites as a useful alternative to metal are weight reduction and cost effectiveness.

To enhance the use of polyester, methods of increasing productivity have to be realized. Emphasis is currently being placed on using less labor intensive molding methods, namely injection molding.

Although injection molding of thermosets has been proven to be a viable process for many years, a restriction has been the molding of large exterior automotive components such as front ends, that require a class A surface with excellent dimensional control and the required physical properties.

We have found that incorporating a relatively new compounding system called TMC (Thick Molding Compound) with injection molding, provides the processor with greatly increased formulating flexibility and many property advantages.

This paper will not dwell upon the advantages of injection molding over other molding procedures. However, some of the inherent problems of injection molding which are alleviated through the use of TMC will be discussed.

The general topics that will be reviewed are:

- Compounding procedures
- Obtaining a Class A surface with good dimensional control
- Minimizing the loss of physical properties during the injection molding process

COMPOUNDING PROCEDURES

The thermoset molding compound is a composite of polyester resin, thermoplastic co-polymer, catalyst, mold release agent, pigment, inorganic filler and fiber reinforcement.

There are three methods of preparing compound for injection molding. These are BMC, SMC and TMC.

BMC is a batch process which provides material in bulk form and can easily be charged into a stuffer. The mixing process allows the flexibility of using high filled systems, but it also results in extensive glass degradation, producing parts with insufficient overall strength.

SMC has the advantage of being a continuous process and having minimal glass degradation. However, the glass impregnation process places viscosity restrictions on the formulation to be used and the shape and form of the mat (1/4 inch maximum thickness) provides undue hardships in charging the stuffer.

TMC, with its unique method of saturating the glass on the impregnating rolls before it reaches the polyethylene film, is a continuous process with minimal glass degradation. (See Figure I).

The TMC compound can be produced in sheets as much as 2 inches thick, or in bulk form like BMC which would make it easy to charge the stuffer.

Because of its unique method of impregnating the glass, TMC allows a great deal of formulating flexibility. Highly filled systems where chemical thickeners are not even necessary can easily be manufactured, thus eliminating the necessity for a maturation time.

EQUIPMENT

In our study of injection molding, the major emphasis has been placed on the physical properties obtained under varying conditions of formulating, compounding and molding.

Unless specified otherwise, the compound used was TMC cut in billet form of approximately 10 lbs each and molded using a reciprocating screw feed at 15 rpm.

The injection molding machine was a 700 ton HPM injection molder with a 3/4 inch nozzle, 1 inch sprue, a 4.5 inch diameter reciprocating screw interchangeable with a plunger. Compound was fed through a hydraulic pressurized stuffer. The mold was a compression molding tool for a 1972 Buick Grill Opening Panel (GOP) which was modified for injection molding.

APPEARANCE

A characteristic of TMC, which helps with the appearance of a molded part is the excellent flow it provides, when compared with BMC or SMC. This, coupled with the ability to process a high thermoplastic and filler loaded formulation provides a Class A surface on the molded part. Formulations containing a 25% glass loading have been processed with a Master Batch viscosity of as high as 5×10^6 cps (TF @ 1 rpm).

TEST CRITERIA

In order to get a good understanding of injection molding and the parameters that affect physical properties of the molded part, it was decided to study and compare the following.

1. Compounding procedure: BMC, SMC, TMC
2. Glass length: 0.25, 0.50, 0.75, 1.00 inches
3. Type of glass: Hard, soft
4. Screw speed: 7.5, 15.0, 23.0 rpm
5. Molding viscosity of compound
6. Feeding system: Reciprocating screw, plunger

All the formulations used in these tests were prepared with MR-13031* and thermoplastic solution with 25% of 0.5 inch hard finish glass and 40-60% filler blend.

As evidenced in Table I, the glass degradation occurring in the BMC mixing process is reflected in the lower physicals compared to SMC and TMC.

Increasing the glass length from 0.25 inches to 0.50 inches has a positive effect on physicals (Table II). However, as the glass length is increased further, no appreciable improvement is obtained. This is most likely due to the glass degradation occurring as the compound passes through the 0.75 inch nozzle making the longer glass length unimportant.

The use of soft glass increases the tensile strength at the expense of flex and impact strength.

Another factor which seems irrelevant is the screw speed used. Increasing the screw speed from 7.5 to 23 rpm had no appreciable effect on physicals (Table III). This implies that most of the degradation occurs during the passage of the material through the nozzle, gates and runners. This will be investigated in the future.

*USS Chemicals Polyester Resin.

A critical factor in loss of physicals is the viscosity of the material being molded. As the viscosity is increased, the physical properties drop, as illustrated in Table V. This is due to the added energy being applied to the high viscosity material to push it through the barrel, thus degrading the glass further.

It was also found that a fast injection rate helped produce a better surface appearance.

The excellent flow of TMC would be a factor in requiring less energy to push the material through the barrel, compared to SMC or BMC. Some glass degradation occurs as the material is pushed through the stuffer, which is also dependent on flow and viscosity.

However, the appearance of the molded part was found to be better at the intermediate viscosity (14 x 10^6 cps). Therefore, a compromise on appearance and physical properties may have to be made.

A dramatic though not surprising increase in physical properties was obtained by switching to a plunger feed instead of screw. Obviously, there is less glass degradation with the plunger.

CONCLUSIONS

It is evident that there are some factors that can be carefully controlled, to optimize the compounding and molding process such as glass length, molding viscosity and the use of a plunger instead of a screw.

All aspects of mold design, including the nozzle and sprue diameter, runner length and avoidance of any sharp changes in the direction of flow are very critical

The use of TMC, with its formulating versatility and minimal glass degradation complements any good molding process to produce the utmost in molded part quality.

Biography

Mr. Aram Mekjian is a Molding Research Specialist at USS Chemicals, Linden, New Jersey.

He joined USS Chemicals in 1976 and has been active in polyester resin development for the molding industry. His professional background includes product development of dyestuffs, dyeing auxililiaries and polymer additives for thermoplastics at Ciba-Geigy Corp.

Mr. Mekjian has been a member of SPE since 1972. He holds a BS degree in Chemistry from Valdosta State College, Georgia and a MS degree in Chemistry from Fairleigh Dickinson University in New Jersey, where he is currently enrolled in the MBA program in Industrial Production (1981).

TABLE I

Effect Of Compounding On Physicals Of
Injection Molded Grill Opending Panel*

	BMC	SMC	TMC
Flexural Strength, psi	9600	12400	12900
Flexural Modulus x 10^6 psi	1.4	1.6	1.7
Tensile Strength psi	3700	4300	4700
Notched Izod ft lb/in	2.6	4.0	4.0
Unnotched Izod ft lb/in	3.4	4.5	5.1

*All formulations contain 25% of 0.5 inch hard finish glass
Compound viscosity: 2-10 x 10^6 cps
Reciprocating screw @ 15 rpm

TABLE II

Effect Of Glass Length On Physicals Of
Injection Molded TMC In Grill Opening Panel

25% Hard Finish Glass Length (inches)	0.25	0.50	0.75	1.00
Flexural Strength, psi	9900	12900	12800	13000
Flexural Modulus x 10^6 psi	1.3	1.7	1.7	1.6
Tensile Strength, psi	3000	4700	4500	4800
Notched Izod ft lb/in	2.6	4.0	4.0	3.9
Unnotched Izod ft lb/in	3.9	5.1	5.1	5.0

Compound Viscosity: 2-10 x 10^6 cps
Reciprocating screw @ 15 rpm

TABLE III

Effect Of Glass Type On Physicals Of
Injection Molded TMC in Grill Opening Panel

25% of 0.5 Inch Glass	Soft Finish	Hard Finish
Flexural Strength, psi	11600	12900
Flexural Modulus x 10^6 psi	1.5	1.7
Tensile Strength, psi	5200	4700
Notched Izod ft lb/in	2.9	4.0
Unnotched Izod ft lb/in	4.3	5.1

Compound Viscosity: 2-10 x 10^6 cps
Reciprocating Screw @ 15 rpm

TABLE IV

Effect Of Screw Speed On Physicals Of
Injection Molded TMC In Grill Opening Panel

Reciprocating Screw Speed rpm	7.5	15	23
Flexural Strength, psi	13100	12900	12300
Flexural Modulus x 10^6 psi	1.7	1.7	1.6
Tensile Strength, psi	4800	4700	4600
Notched Izod ft lb/in	3.8	4.0	3.7
Unnotched Izod ft lb/in	5.0	5.1	5.0

Compound Viscosity: 2-10 x 10^6 cps
25% of 0.5 inch hard finish glass

TABLE V

Effect Of Compound Viscosity On Physicals
Of Injection Molded TMC In Grill Opening Panel

Compound Viscosity x 10^6 cps	2.0	14.0	29.0
Flexural Strength, psi	12900	12100	9800
Flexural Modulus x 10^6 psi	1.7	1.7	1.4
Tensile Strength, psi	4700	4300	3800
Notched Izod ft lb/in	4.0	3.0	2.4
Unnotched Izod ft lb/in	5.1	4.3	3.5

25% of 0.5 inch hard finish glass
Reciprocating screw @ 15 rpm

TABLE VI

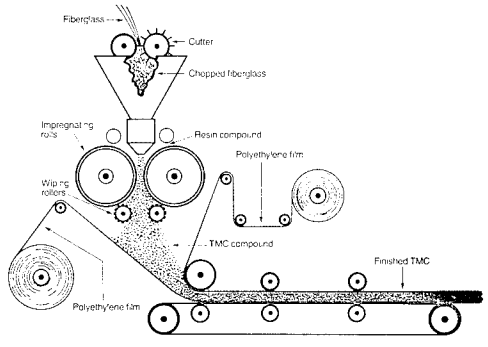
Effect Of Feed System On Physicals Of
Injection Molded TMC In Grill Opening Panel

	Reciprocating Screw @ 15 rpm	Plunger
Flexural Strength, psi	12900	19100
Flexural Modulus x 10^6 psi	1.7	1.7
Tensile Strength, psi	4700	6700
Notched Izod ft lb/in	4.0	5.3
Unnotched Izod ft lb/in	5.1	8.5

25% of 0.5 inch hard finish glass
Compound Viscosity 2-10 x 10^6 cps

Figure 1

TMC™ Schematic



EFFECT OF ENVIRONMENTS ON THE FATIGUE BEHAVIOR OF SHEET MOLDING COMPOUNDS

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Introduction

Application of fiber reinforced plastics have been expanding rapidly from the aircraft industry to the automotive industry. For automotive applications, these plastics are exposed to environments such as water, gasoline and other environments while bearing loads. Thermoplastics such as PMMA, polystyrene, polypropylene, etc., are known to have their mechanical behavior severely affected by the presence of some environments. In order to ensure safe design, knowledge of the effect of these environments on the mechanical behavior of fiber reinforced plastics is necessary.

Among the works that have been done on the effect of environments on fiber reinforced plastic include the investigation by Sumsion and Williams [1] where the effect of water and high temperature on graphite epoxy composites are studied; Cessna et al [2] studied the modes of high frequency fatigue failure in glass reinforced and unreinforced thermoplastics. The effect of moisture on unstressed epoxy resins and composites have been investigated by many authors [3,4,5,6]. However, there is limited amount of information available on the effect of environments such as water, gasoline, alcohol etc., on the fatigue behavior of fiber reinforced plastics. This paper presents the preliminary findings of a research program to investigate the effect of different environments on the mechanical behavior of fiber reinforced plastics; particularly the effect of water and isooctane on the fatigue behavior of glass fiber reinforced polyester.

Materials

The polymer studied is compression molded glass fiber reinforced polyester supplied by Somerville Industries Ltd., code number G-1005-30. It contains 30% fiber reinforcement. Sheets of nominal thickness of 0.125 in. containing fibers of random orientation and distribution are used to make the specimens. Fiber diameters as measured by electron microscopy are approximately 2.5×10^{-4} in. A typical stress strain **curve** for the material is shown in Fig.1.

A drawing of the fatigue test specimen is shown in Fig. 2. It is a part of the ASTM D-638 type I tensile specimen and it is cut using the "Tensile Kut" milling cutter. Sharp edges of the specimen are rounded with no. 4000 sand paper. The total free length of specimen was determined using the geometrical relations as outlined in Ref. [2] to ensure that failure will occur at the transition from the straight portion to the curved portion of the specimen.

The liquids used are distilled water and reagent grade isooctane.

Testing equipments and method

The fatigue testing apparatus is shown in Fig.3. A VSP-150 flexural bending fatigue machine fabricated by Fatigue dynamics Inc. has been modified for plastic testing with a special plastic attachment. The bending fatigue machine provides constant amplitude excitations and the resistance of the polymer specimen is recorded with a transducer. The signal is displayed on an oscilloscope screen so that any reduction in the resistance of the specimen can be detected. Fatigue lives were determined at a drop in the resistance of the material by 10% from the original flexural strength. The testing frequency was 13.3 cps, there was no significant increase in the temperature of the materials during the tests. Completely reversed bending strain are imposed on the specimens.

An environmental chamber is attached to the clamping unit of the machine so that the specimen is completely immersed in the liquid for the whole duration of the fatigue experiment. The fatigue lives of the material in water and isooctane were performed on specimens that have been immersed unstressed in these liquids for a period of 40 days and these specimens are completely immersed in the liquid for the whole duration of the fatigue test.

Absorption tests are also carried out by measuring the weight uptake of the liquid into the polymer at different intervals of time. Weight measurements are accurate to 0.0001g.

Results and discussion:

a). Absorptions:

The abosrption of water and isooctane into fiber glass reinforced polyester is shown in Fig.4. The experimental points are the mean of a group of 15 measurements. After 40 days, the weight uptake does not seem to reach saturation and the absorption experiment is still continuing. Isooctane does not show a large amount of absorption but there is a definite amount of intake. Water shows a large amount of absorption up to more than 2%. There was no significant increase in dimensions of the specimens due to absorption after a 40 day period.

b). Fatigue results:

As a preliminary criterion for fatigue failure, a drop of 10% from the original flexural strength of the material was adopted to determine fatigue lives. The stress versus fatigue lives of the polymer in the different environments are shown in Fig.5. Specimens tested in water show a drop in fatigue lives from those in air at the same applied stress. Drastic reduction in fatigue lives of the materials is observed in isooctane. At a stress of 8000 lb./in^2, the fatigue lives of specimens in isooctane is about two decades less than that of specimens tested in water. This appears to contradict with the absorption results since isooctane shows less absorption into the unstressed polymer. The explanation for this behavior is the subject of a further investigation.

c). Appearance of failures:

Observation by eye reveals two types of cracks. For specimens where the applied stress is small, the fracture line (type I) resembles the crazing line in thermoplastic material. Fig.6a shows these fracture lines for a specimen that was tested in water under an applied stress of 7700 psi. These fracture lines start to form at about 10^3 cycles and multiply continuously. The flexural resistance of the material drops 10% after 10^5 cycles. When the applied stress is high, type II fracture line is observed to occur on top of type I fracture line (Fig. 6b). Close observation using the scanning electron microscope reveals that type I fracture corresponds to fracture in the matrix material only (Fig. 7a). The fracture surface shows significant amount of cold draw and there appears to be no fiber present. Type II fracture however shows debonding between the fibers and the matrix material (Fig.7b). There is no significant cold draw in type II fracture surface and the fibers remain intact indicating failure was at the interface. The above were observed for specimens tested both in air and in water indicating that for a 10% decrease in strength, the mode of failure is not different for specimens in water as compared to in air.

During the testing program,some specimen seem to show considerably shorter fatigue lives compared to the majority of others subjected to the same applied stress. The fatigue lives of these specimens are only about 2% of the lives of the majority of other specimens. Scanning electron microscopic observation reveals that these specimens have many fibers lying on the surface of the material (Fig.8) as contrasted by few fibers observed in others. The failure in these specimens appear to start at the fiber

matrix interface and propagate across the matrix. The fracture line runs along the length of the fiber and transfers from one fiber to the next. This type of fracture can be understood in the flexural fatigue tests and the behavior in axial push pull fatigue tests remains to be investigated. The above observations indicate the importance of process variable on the fatigue lives of the material.

In a static bending test performed until type II fracture is achieved many fibers can be observed to have debonded from the matrix material. Scanning electron microscopy shows that failure is due clearly to debonding. In the vicinity of the fracture region, there is a deformed zone which has the appearance of a crater pattern. (Fig.9). The polymer material has undergone cold draw but the crater pattern is peculiar. This appears to be the deformation of the surface layer only and is certainly the characteristic of this layer. This is also another subject of further investigation.

Conclusion:

This paper presents the preliminary findings of a testing program on the effect of different environments on the fatigue behavior of fiber reinforced polymers. For the particular material tested, the following conclusions are made:

- Both water and isooctane absorbs into the polymer. After a period of 40 days, water shows 2.3% absorption by weight and isooctane shows 0.5%. Both do not show saturation after 40 days.
- The fatigue lives of specimen tested in water and in isooctane are shorter than the fatigue lives of specimens tested in air. Specimens tested in isooctane show a drastic reduction in the fatigue life, much more than the effect of water even though the absorption of isooctane into the unstressed polymer is less than that of water.
- At 10% loss of flexural rigidity, the flexural fatigue failures of glass fiber reinforced polyester sheet molding compounds start within the matrix material. Debonding between the fiber and the matrix is observed at a subsequently bigger drop in flexural rigidity. This is observed to occur in both air and water.
- Due to processing variables, some specimens contain more fibers on the surface. These specimens have much shorter fatigue lives than others with the fracture starting at the fiber matrix interface and running along the fiber length.

The research program is continuing on axial push pull type of fatigue and also on the particular effect of isooctane.

Acknowledgements:

The authors wish to express appreciation for the financial assistance from the National Science and Engineering Research Council of Canada through grant number A0413; and the materials supplied by Somerville Industries Ltd. The technical assistance of Mr. M. Quinlan is appreciated.

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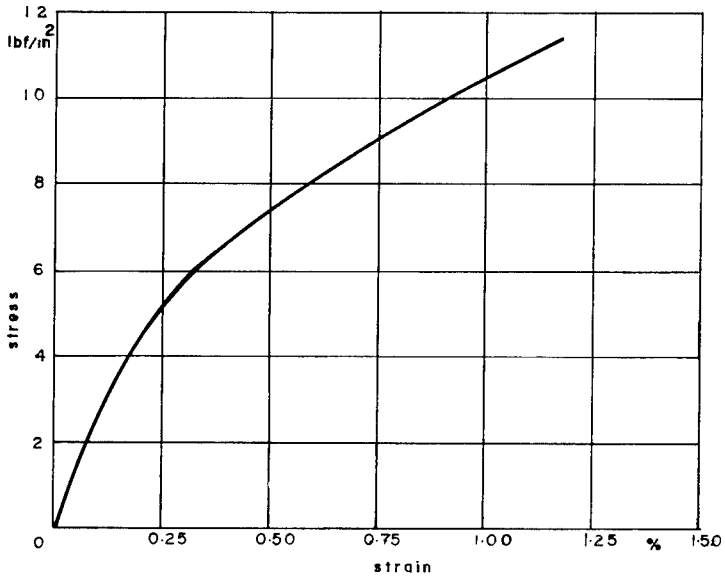


FIGURE 1: Tensile stress strain curve

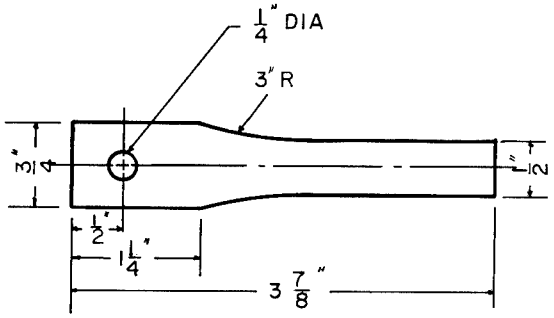
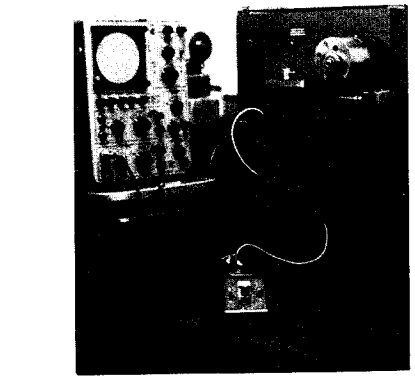


FIGURE 2: Flexural fatigue specimen



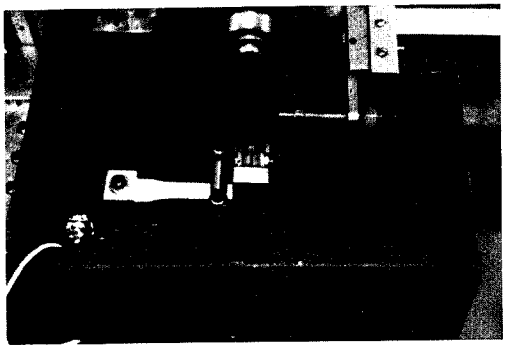


FIGURE 3: Fatigue testing apparatus

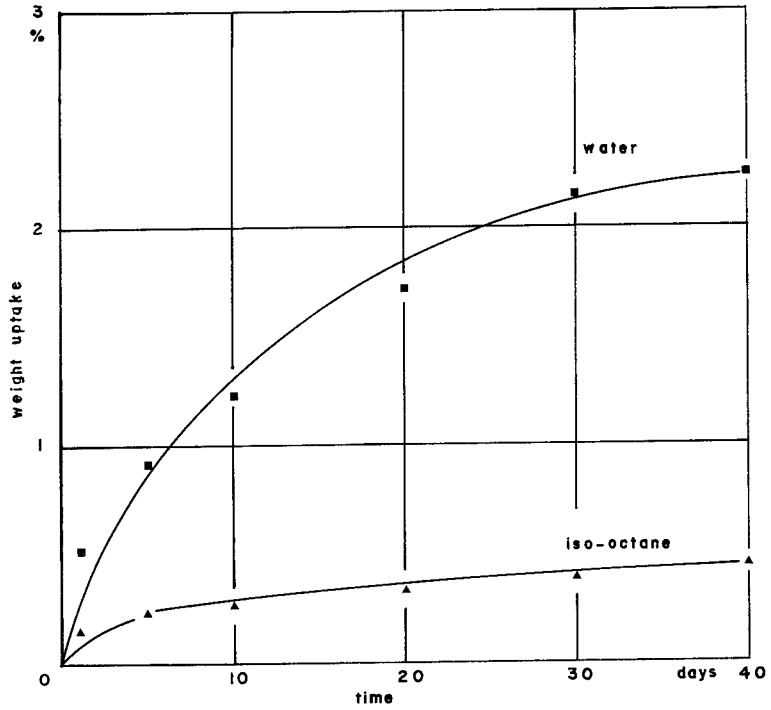


FIGURE 4: Absorption of water and isooctane into fiber glass reinforced polyester

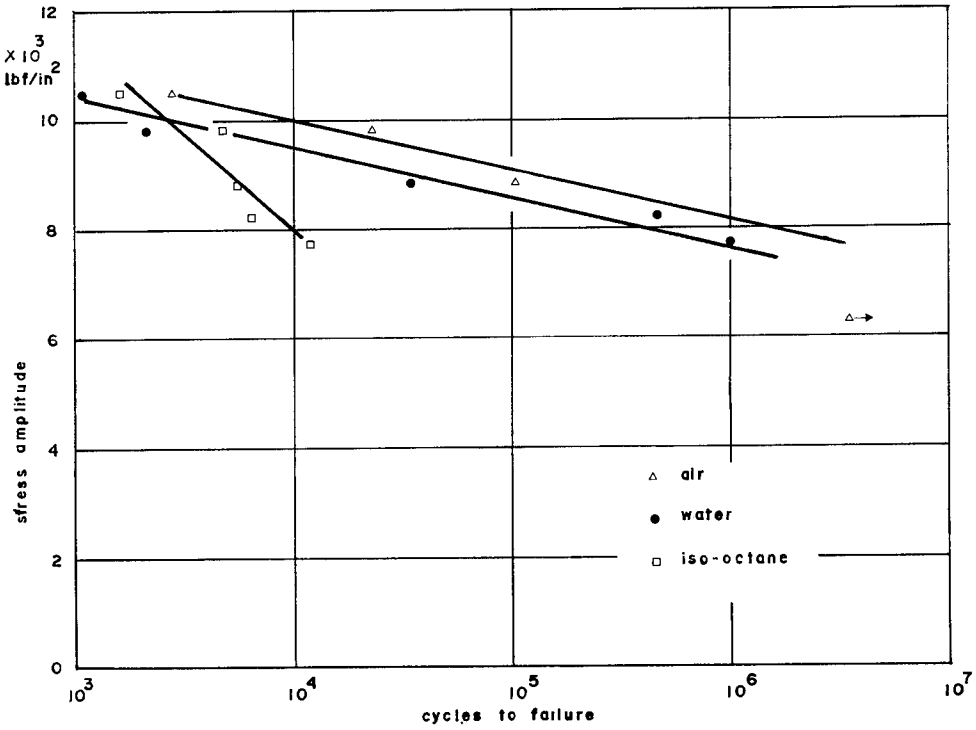
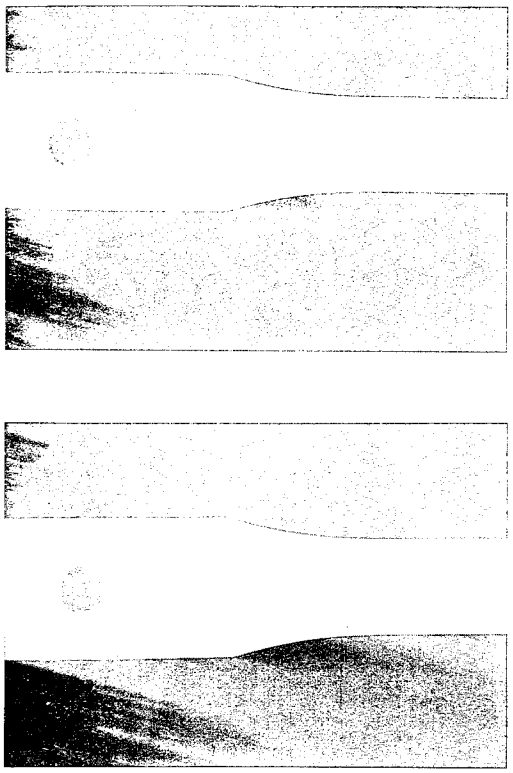


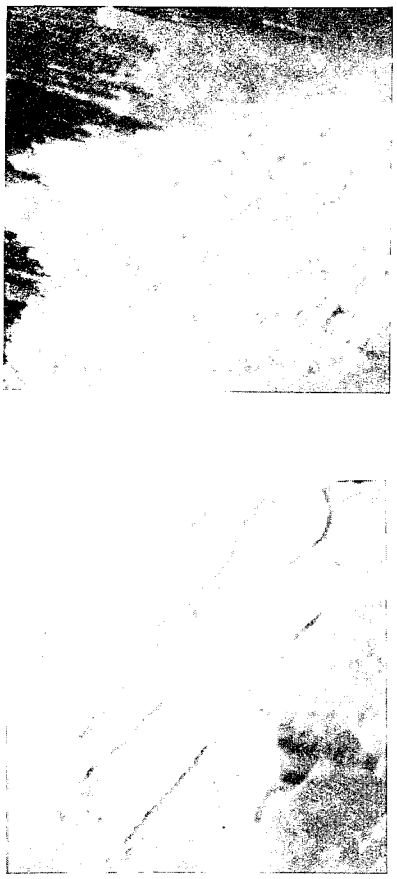
FIGURE 5: Fatigue life of the polymer in different environments



type I
(a)

type II
(b)

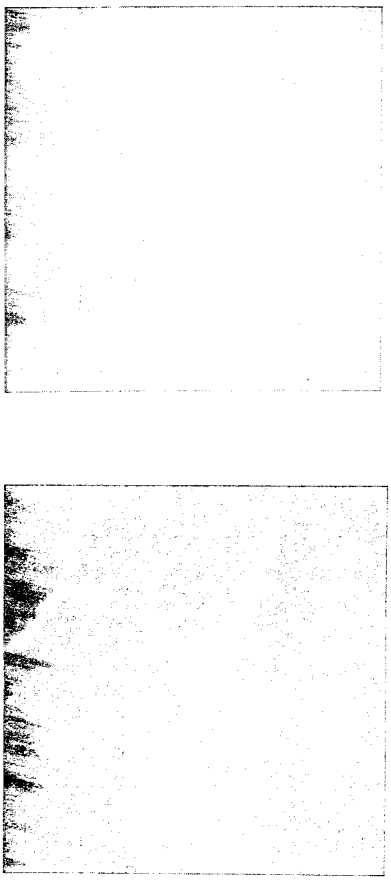
FIGURE 6: Appearance of the fracture surface



type I
X 1700
in water

type II
(b)
X 1700
in water

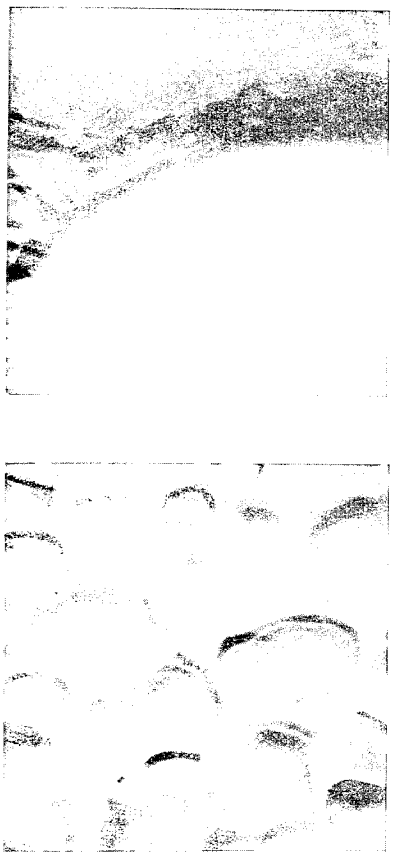
FIGURE 7: Microstructure of fracture surface



X 420
in air

X 800
in air

FIGURE 8: Surface of specimen having short fatigue lives



X 45

X 1800

FIGURE 9: Crater pattern on the surface of static fracture specimen

FATIGUE LIFE PREDICTION IN FRP BY ACOUSTIC EMISSION ANALYSIS

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INTRODUCTION

Listening to acoustic emissions (AE) while an object is under stress is a type of non-destructive testing that is finding rapidly widening areas of application. One approach is to continually monitor a critical area and listen for the exponentially increasing noise associated with crack formation and growth under a constant load or continuous fatigue. This technique is currently being applied to nuclear reactor equipment and military aircraft.

Another technique frequently used in pressure vessel and pipe line qualification, is to proof test the structure to a load considerably higher than the service load (appropriate to the design safety factor) and use AE to identify crack growth associated with incipient failure. The obvious advantage is that defects can be located and repaired, even behind insulation or underground, before the part is placed in service and before the defect becomes critical.

With the growing interest in using FPP structural components in automobiles to save weight, an urgent need is developing for 100% non-destructive inspection to insure the reliability of these parts. Monitoring AE during proof testing has great potential of providing this capability. Assuming the component can be loaded in a fashion analogous to the way it would be used in service, critically stressed regions will identify themselves via AE. Further, defects which will permit crack initiation and growth should generate more noise than would be detected in a sound part. In addition to being directly related to a structural test, AE has the advantage of being quantitative and therefore, easily analyzed for decision making.

Developing an on-line quality control system is a substantial task. AE instrumentation is rapidly evolving and new hardware and software continually make new techniques possible and old ones obsolete. Previous development of AE instrumentation has been primarily devoted to metals and considerable adjustment is needed to optimize monitoring of FRP since the attenuation in FRP greatly affects signal dispersion, range, and reflections. In addition, there is a great deal of fatigue-testing to do in parallel with the proof-testing to develop the required correlations.

EQUIPMENT AND TEST METHODS

A Dunegan/Endevco Model 1302D computerized acoustic emission monitoring system was used in this study. The hardware configuration of this system is depicted in a block diagram shown in Figure 1. When a test part is loaded, acoustic emissions are detected by pickup transducers. The signals are amplified and processed by signal processors. A mini-computer provides data acquisition, handling and analysis functions. Test data can be analysed on-line or off-line and the results are displayed on a graphic terminal.

Generally, the acoustic emission signal obtained can be characterized by the following six parameters (Figure 2): 1) Event count; 2) Ring down count; 3) Peak amplitude; 4) Rise time; 5) Duration; 6) Energy. Except for energy, the parameters are independent. The event count, ring down count, peak amplitude and energy together with occurence location, are particularly useful parameters for data analysis. Acoustic emission obtained by deforming an FRP test part possess distinct characteristics, and presumably these may be related to various failure processes. However, the magnitude of various signal parameters measured is affected by the threshold, amplifier gain, and transducer characteristics as well as the filtering circuitry. To acquire significant and consistent acoustic emission signals for analysis, the equipment operating conditions should be adjusted and optimized. Following the terminology given by the equipment manufacturer, Table I is a list of equipment operating conditions that had to be optimized for this study.

Since the stress wave of an acoustic emission possesses a finite wave propagation velocity, the signal takes time to reach various transducers placed on the test part. Time delay then allows the calculation of the location of the source of the acoustic emission. Depending on the transducer array configurations, one dimensional linear source location or two dimensional planar source location methods are available. A significant advantage of a computerized source location system is its ability to set up data discrimination schemes which will reject noises generated from the test fixture or from areas outside the detecting bounds. The selection of transducer array configurations is dictated by the geometry of the test part and the signal dispersion and attenuation characteristics of the material. For unidirectional fiber glass reinforced polyster, the typical signal attenuation is about 40db/m. Because of this high attenuation, an acoustic emission signal may fall below the threshold before reaching the transducers. One way to circumvent this difficulty is to place the transducers close to the high stress regions and properly adjust the gain and threshold. In our study, a 40 db threshold was used for two two-transducer linear arrays. Since the spacing between the transducer in each array is about 50 cm., a worst case acoustic emission signal must be higher than 60 db to be detected and located. Further, only the transducer located at the center of the part for each array measures amplitude while the other functions simply as an event detector and timing gate.

The high attenuation of signals causes the signal amplitude measured to be significantly reduced if it is emitted far away from the measuring transducer. Therefore, when analysing AE data using the intensity as a parameter, the intensity should be corrected for attenuation. This correction is carried out by a computer routine. Other parameters such as time of arrival measurements and ring down count are affected in a more subtle manner, but these will not be discussed here.

COMPONENT TESTING

Test parts used in this study are structural beams made out of directional fiber glass reinforced polyester (XMC). The part is a hat section beam structure 150 cm. long and 13 cm. wide. The part is loaded at the center with the two ends fixed providing a simple structural test. A downward peak load of L and upward peak load of .625L simulate actual maximum vehicle loadings. As mentioned before, two linear source location transducer arrays each consisting of two transducers were used. The use of a single linear source location array with two transducers located at the ends of the beam was rejected because of the high attenuation characteristics of the material. Improved instrumentation and more understanding of acoustic emissions may later permit the use of this array with its inherent simplicity.

SIGNAL ATTENUATION AND PROPAGATION VELOCITY

Figure 3 shows the variation of the AE signal amplitude measured at various locations along the part (in the fiber orientation direction) with various signal gains. The intensity is measured on a db scale, and it forms a linear relationship with the distance between the signal source and the measuring transducer. The signal attenuation coefficient of 40 db/m is obtained from the slope of the lines. The signal attenuation is not affected

by the transducer amplifier gains. A higher signal attenuation (about 55 db/m) is observed in the direction perpendicular to the fiber orientation direction.

Accurate measurements of acoustic emission wave propagation velocity in the unidirectional fiber glass reinforced polyesters are difficult, as has been reported by other AE investigators in Kevlar fiber reinforced composites.[1] This is mainly due to signal dispersion and the ambiguity of the wave form timing due to attenuation effects. However, maintaining a fixed signal threshold and using a linear array for this determination helps to minimize the problem. An average wave propagation velocity of 227000 cm/sec was measured along the principal fiber orientation direction and 125000 cm/sec in the perpendicular direction.

The uncertainty of AE waveform timing affects the accuracy of source location. Using a known signal source to map the actual location and comparing this with the location calculated by the source location method, it was found that the discrepancy may be as much as 5 cm. in the 50 cm. spans of the arrays used here.

MONITORING ACOUSTIC EMISSION DURING PROOF TESTING

A 4-stroke static loading was applied to the structural beams as a means of proof testing. Acoustic emission was monitored simultaneously. Figure 4 represents a typical result of acoustic emission event count accumulated during the proof loadings. The acoustic emission generated in the first loading (downward force of 0 - 0.5 L) and the third loading (upward force of 0 - 0.25 L) are much less than those obtained during the second loading (downward force, 0 - L) and the fourth loading (upward force 0 - .625L).

It is noted that the Kaiser effect (i.e., acoustic emissions are not generated on a second loading until the first load is exceeded) appears to hold true under these loading conditions.

Figure 5 is a plot of acoustic emission cumulative event count obtained during the second proof loading for a number of test parts. The test parts in this sample batch generated a wide variation of acoustic emission signatures. Subsequently, several of these test parts were subjected to fatigue tests for studying the correlation between the acoustic emission signature and the part performance. There is no visible damage observed in the parts after the proof testing except for parts No. 1 and 2. These two parts showed visible damage when loaded to 0.6 - 0.7 L. In addition, they emitted substantially higher acoustic emissions during all proof loading sequences. The study indicates that acoustic emission event counts accumulated during the second proof loading sequence can be very well related to the load which causes the initial visible damage. Thus, the cumulative AE event count obtained during the second proof loading may reflect the degree of structural weakness or defects in the test part. However, the load at which initial visible damage occurs may exceed the proof load or even lie close to the ultimate failure load (about 2.3L) and thus no damage would be seen by simply proof testing. Also, the acoustic emission event counts accumulated during proof testing do not correlate well with the ultimate failure load of the test part. This is postulated to be due to the high degree of stress transfer that can occur in composites during static failure and the fact that the defects may not be located in the critical high stress regions.

Monitoring acoustic emission during component proof testing is also a useful design analysis tool. Distributions of acoustic emission signatures generated during the proof testing of various component designs reveal orientation problems or the high stress regions associated with a design. Figure 6 compares the acoustic signatures of parts of a phase II design to those of a phase I design which contained sharper radii in a high stress region. Consequently, when the test parts are proof tested, the phase I components generated more acoustic emission bursts than the phase II components due to the stress concentrations and the fatigue life of the phase I components was about 50% lower than the phase II components.

ACOUSTIC EMISSION MONITORING DURING FATIGUE

Parts were cycled sinusoidally in load control between L down and 0.625L up at 4Hz. The fatigue life of the test part is defined as the point at which the center loading point of the test part deflects to 2.5 cm in either loading direction (initial deflection is about 1.2 cm) This deflection provides a measure of the extent of damage while still maintaining its load carrying capability. Acoustic emission was monitored during the fatigue test at a reduced sensitivity (60 db instead of 80 db amplifier gain). A load controlled gate was used for limiting acoustic emission data measurement in a load range of 0.9L to L downward. This arrangement avoids the acquisition of much spurious noise generated in the test fixture and reduces the amount of data to be processed.

Figure 6 is a plot of cumulative acoustic emission event count accumulated during the fatigue loading for five of the parts shown in Figure 5. The acoustic emission activity is relatively low during the fatigue cycles until the test part approaches its fatigue life. Under these conditions, acoustic emission monitoring during fatigue testing may not provide adequate early indication of failure. This is particularly so for the parts which exhibit lower fatigue lives because these parts possess a rapid rate of crack growth apparently due to serious flaws in critical regions.

CORRELATION BETWEEN PROOF TEST DATA AND FATIGUE PERFORMANCE

Figure 7 shows the relationship between the total acoustic emission event count obtained during the proof testing (from the 0 - L down stroke loading) and the fatigue life of the component. The total event count is the simplest representation of the acoustic emission and does not even take into account the amplitude or intensity of the contributing events for which an attenuation correction is required.

The plot clearly indicates that fatigue life tends to decrease as the event count increases, although one point at a relatively short lifetime lies outside the trend. This point represents a part which failed along a fold line in the oriented material between the two linear arrays, and further analysis may yet be able to account for it. Establishing a correlation requires the use of more parameters and more sophisticated analysis. This is expected because (1) there are several failure modes possible, usually related to different types of defects; (2) multiple defects probably exist which will complicate the AE Picture; and (3) the two factors of crack initiation due to a defect and propagation through either sound or defective material may affect fatigue life in different ways.

Our AE program is in an early stage and this analysis is not complete; thus, more results will be reported at a later date. There are; however, several comments that can be made now based on accumulated experience. Obviously, location and possible concentrations of AE events are important parameters that have not been incorporated in Figure 7. The simplest approach to this is to divide the AE data into that generated in the left and right hand sides for the symmetric beam and just plot the higher number. However, much finer resolution to give effectively the acoustic emission "density" along the part will be examined in the near future. Subtracting the noise profile of a "best" beam before analysis may also enhance the contribution due to defects and permit better discrimination.

In addition to the event parameter, this program also found that a derived energy parameter, U, may be a strong indicator of fatigue life. The energy parameter U is defined by:

$$U = \sum_{i=1}^{N} n_i \, v_i^2$$

Where n_i is the ring down count of the AE signal, and v_i is the peak amplitude of the AE signal corrected for attenuation. U heavily weights the intensity of each acoustic emission event. Figure 8 shows a relationship between this energy signature and the fatigue performance of a structural beam of a bonded two-piece design. These components exhibit more complex modes of failure particularly when the fatigue crack propagates along the adhesive bond. The correlation between AE event count and fatigue performance was poor. However, the correlation was improved with the use of the U parameter and treating the data from the four quadrants (upper right, upper left, lower right, lower left) separately.

The actual proof load also appears to be an important factor and those emissions occuring as the part is proof tested near the peak fatigue load seem to relate best to the fatigue life. AE data gathered by going to 1.1L gave poorer correlation to fatigue life than those data obtained in the vicinity of L This aspect will require further investigation to verify the relationship.

SUMMARY

Although non-destructive evaluation of FRP components by monitoring AE during proof testing is still in a primitive stage, there are str indications that it can be used to assess the structural integrity of a composite part and predict the fatigue life. With this development, one can easily envision a black box that would process AE data during an on-line proof test of a newly fabricated component and would then generate an accept/reject decision. The whole test may take only a few seconds.

However, the technology behind AE analysis is far from simple. Predicting fatigue life by NDT has never been accomplished before for any material. The instrumentation and computer techniques are advanced and are evolving at a rapid rate (remarkably advanced considering the size of the AE instumentation industry). The equipment has to be especially tailored to FRP and multiple parameters describing the AE data will have to be combined to derive useful correlations. Although micromechanical mechanisms have been postulated for the generation of AE[2], it will probably be many years before the phenomenon is well understood. Further, the structural beam cited here is a relatively simple structure with a simple loading pattern and a fairly homogeneous composition. Most candidates for FRP substitution are much more complex. However, the advantages inherent in having this NDT capability are enormous such as increasing engineering confidence for faster product release, improving product safety, and reducing manufacturing costs by identifying defects and speeding up the Q. C. feedback loop.

ACKNOWLEDGEMENT

The authors wish to thank the personnel of Dunegan/Endevco for their cooperation, support, and always rapid response in applying the AE monitoring equipment to our problem.

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2. T. J. FOWLER. ASCE Preprint, No. 3092, October 1977.

TABLE I

EQUIPMENT OPERATING PARAMETERS USED IN THIS STUDY

PRE-AMPLIFIER GAIN (Dunegan/Endevco Model 1801)
MAIN SIGNAL AMPLIFIER GAIN (Dunegan/Endevco Model 1302D)
TOTAL GAIN
THRESHOLD
HOLD TIME
CORRELATION TIME (DURATION)
BAND-PASSED FILTER
RISE TIME DELAY

NOTE: Dunegan/Endevco Model S-140 transducers were used

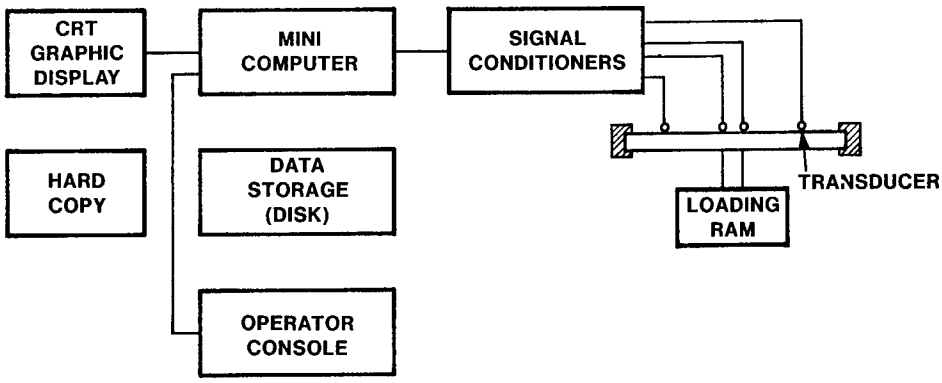

Fig. 1 — Multi-Sensor Monitoring of Acoustic Emissions

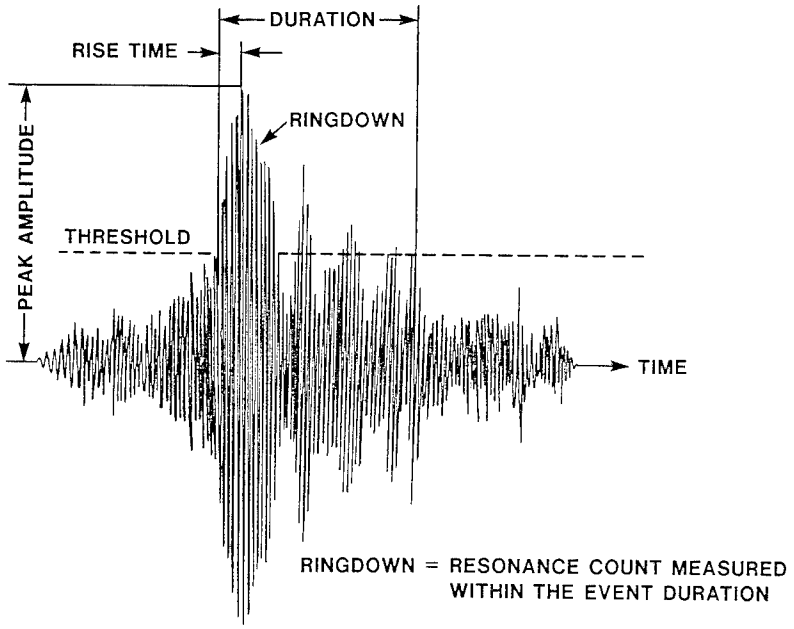

Fig. 2 — An Acoustic Event Showing Measured Parameters

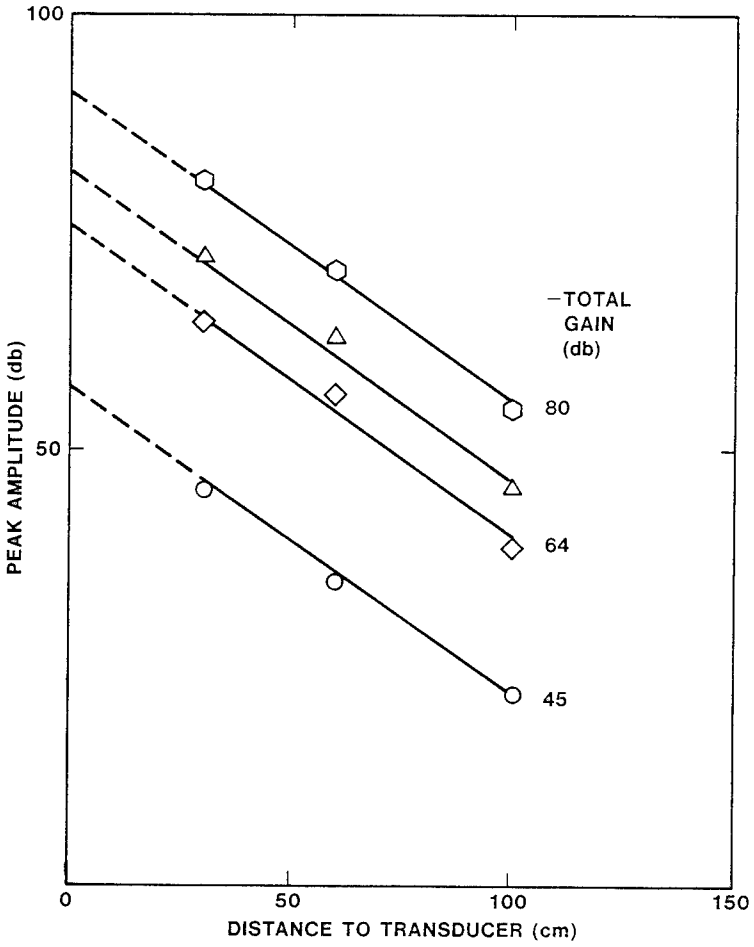

Fig. 3 — Measured Amplitude vs. Distance from Transducer of Artificial Signals Traveling Along the Principal fiber Orientation Direction of XMC.

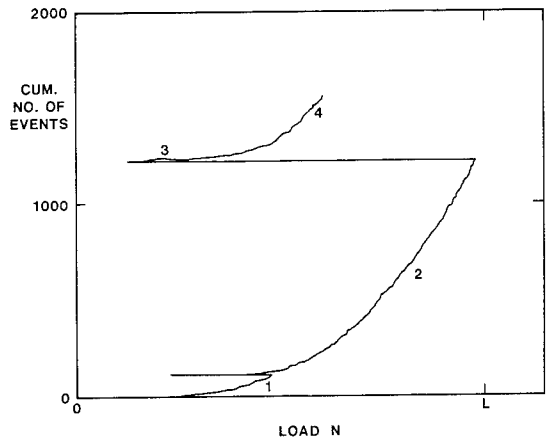

Fig. 4 — Typical AE Activity (Cumulative Event Count) During Proof Loading. No.'s 1-4 Indicate Test Strokes: (1) 0–0.5L Down, (2) 0–L Down, (3) 0–.25L Up, (4) 0–.625L Up.

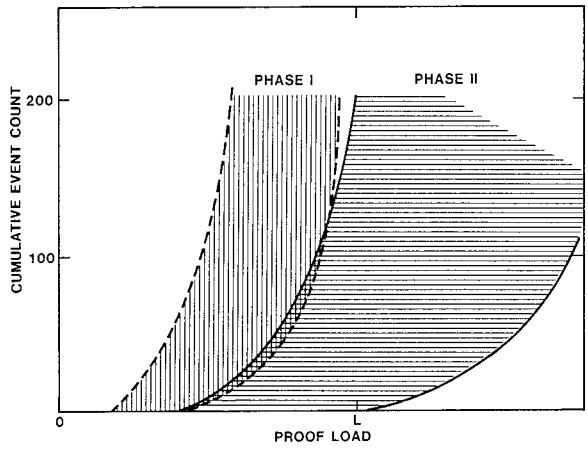

Fig. 5 — Distributions of AE Activity of Two Different Structural Beam Designs. Phase II Parts had Softened Radii in a Critical Stress Region and Twice the Fatigue Life of Phase I Parts.

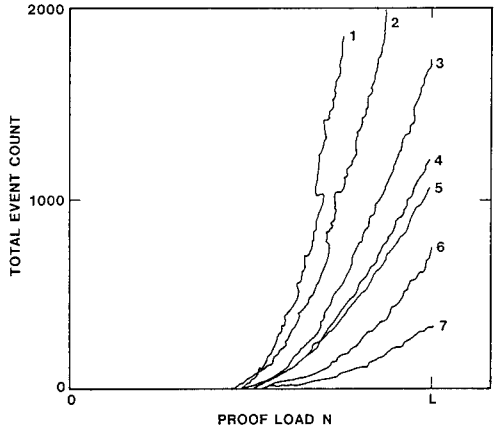

Fig. 6 — Total AE Event Count vs. Load History (0–L Downstroke) of Seven FRP Structural Beams.

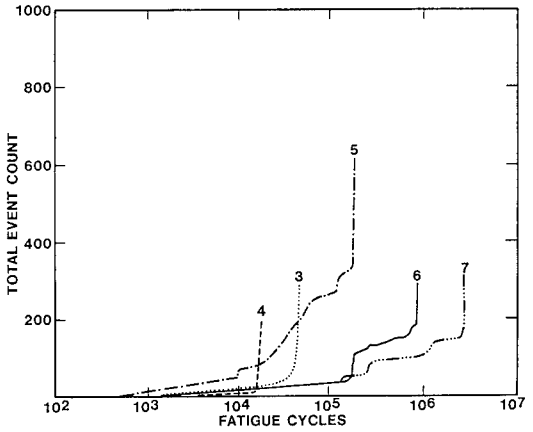

Fig. 7 — Cumulative AE Event Count vs. Fatigue History for Five of the Structural Beams shown in Fig. 5.

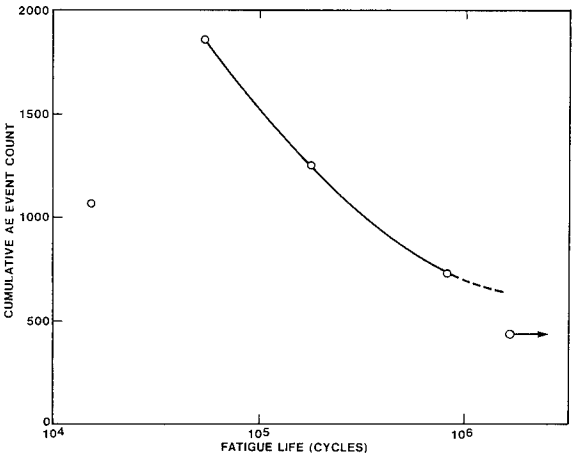

Fig. 8 — Total AE Event Count Obtained During Proof Testing vs. Fatigue Life for Five of the Structural Beams Shown in Fig. 5.

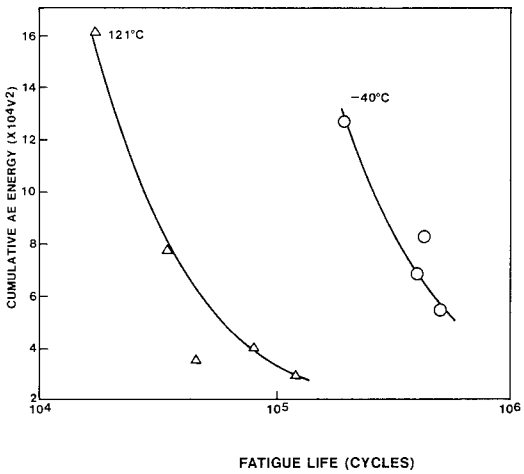

Fig. 9 — Cumulative AE Energy Release During Proof Testing vs. Fatigue Performance for Bonded Two-piece Structural Beams at 121°C and −49°C.

A CHARACTERIZATION STUDY OF AUTOMOTIVE CONTINUOUS AND RANDOM GLASS FIBER COMPOSITES

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INTRODUCTION

As the automotive industry moves into the 1980's, the federally mandated fuel economy requirements become eminent (1). The first, and easiest step toward meeting these requirements has already been taken by resizing vehicles. Such redesign efforts yielded a Corporate Average Fuel Economy (CAFE) of 19 mpg in 1979. Methods to further increase mileage while maintaining customer desired two to six passenger vehicles, will include improvements in vehicle engine and drive train efficiency, more efficient structural design, improved vehicle aerodynamics and lightweight material utilization. The discussion in this paper will concentrate on material properties needed to design with, and to understand fiber reinforced plastics (FRP) as one class of candidate lightweight materials for vehicle weight reduction.

FRP material weight reduction potential is due primarily to its low specific gravity. It also offers design freedom in the compression molding process that allows part thickness and shape variations that are not readily obtainable with sheet metal processes. Properties in a given part can be tailored for specific applications by controlling flow or fiber orientation during molding. These composite materials offer other potential advantages such as reduced production cost due to parts consolidation, reduced assembly costs, corrosion resistance, and good vibration damping properties.

Primary applications of FRP in the automobile have been in appearance parts such as front end header panels. However, if FRP materials are to make a significant contribution to vehicle weight reduction, applications will have to become more structural in nature. Meanwhile, there are some areas that require continuing investigation before these materials can replace steels in load bearing applications. Among these are: (1) the development of an extensive design data base and the broadening of automotive design experience with FRP materials; (2) the source of the mechanical property scatter existent in FRP; (3) the time and temperature dependency of the mechanical properties; and (4) the low through-the-thickness properties of compression molded FRP.

Work done by Heimbuch and Sanders (2), Denton (3), Enos, et al. (4), and others has identified and characterized the behavior of several types of short, glass fiber reinforced sheet molding compound (SMC) materials. The purpose of this paper is to characterize recently developed structural SMC materials by determining their engineering properties and the effect of the automotive service environment on these properties. Previous work in this area includes that of Ackley (5) and Jutte (6). Material properties determined are compared to those for random fiber SMC. Details of the test methods used are documented in an automotive Fiber Reinforced Plastics Test Specification by Riegner and Sanders (7).

The structural SMC materials investigated (SMC-C20/R30 and XMC®-3) are reinforced by a combination of continuous and random glass fibers, Figure 1. These materials may be used in more demanding structural applications by aligning the continuous fibers in the direction of maximum stiffness and strength requirements. The random fibers are included to increase the properties perpendicular to the continuous fiber direction, and to allow some flow of material during the molding process. These materials fill in the property range between random fiber SMC and continuous glass fiber composite materials. This is shown graphically in Figure 2, which illustrates approximate tensile modulus ranges for various reinforced plastic materials. These new structural SMC materials also offer the advantage that they can be processed in the high volume required by the automotive industry more easily than continuous fiber aerospace type composites.

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MATERIALS AND PROCESSING

Table I specified the formulations of the two continuous and random glass fiber SMC materials investigated in this report, and the random fiber materials to which they are compared. All property data for SMC-R50 was taken from Denton (2); SMC-R25 and SMC-R65 data was taken from Heimbuch and Sanders (1).

SMC material properties are dependent on processing techniques. A brief review of the processing of SMC is appropriate to help interpret the property results which follows. All the materials discussed in this report, except for XMC-3, are compounded on a machine shown schematically in Figure 3. To produce SMC-C20/R30, continuous fiber rovings are added before the upper and lower carrier films are brought together and compacted. The XMC-3 sheets are produced by filament winding glass strands on a mandrel at a 7.5° wind angle while depositing chopped strands on the mandrel throughout the process, Figure 4. The compounded SMC is then allowed to thicken to molding viscosity for five to ten days.

For automotive applications, the material is then compression molded in matched metal dies, Figure 5. Molding conditions range from 130°C to 165°C in temperature and 3 to 14 MPa in pressure for 60 to 180 seconds. Exact molding conditions depend on the particular part and mold design. New developments in sheet molding compound processes are discussed in detail by Yee (8).

The SMC-C20/R30 material was molded with 20 percent by weight continuous strand roving E-glass fibers and 30 percent by weight random chopped fiber. The continuous fibers were aligned in one direction on both surfaces of the molded material. This direction will be referred to as the longitudinal (L) or 0° direction of the material. The transverse (T) direction is 90° rotated from the 0° direction. The continuous fibers were molded on the surfaces to maximize the flexural properties. The 30 percent by weight 2.54 cm random fibers are sandwiched between the surface layers of continuous fibers to increase the transverse properties and to allow some material flow during molding. The matrix of the SMC-R and SMC-C/R material is a paste consisting primarily of polyester resin and calcium carbonate filler.

The XMC-3 material uses both continuous and random glass fibers in roving form. The continuous fibers are filament wound in an X-pattern which is ±7.5° from the longitudinal or 0° direction of the material. The composite is 50 percent by weight continuous X-pattern fibers, with 25 percent by weight chopped fibers interspersed throughout the thickness. A polyester matrix with no filler is used in this material.

SMC-R25, R50, and R65 are all random 2.54 cm chopped fiber reinforced polyesters with varying amounts of filler, resin, and glass. Filler content ranges from 0 percent in SMC-R65 to 41 percent by weight in SMC-R25. SMC-R25 is a typical material used for non-structural body panel applications. SMC-R50 and R65 are intended for more demanding structural applications such as radiator supports and wheels.

Control of the SMC compounding and molding processes is critical in production of high quality parts with consistent performance properties. Formulation, mold charge pattern, material flow in the mold, molding temperature, molding pressure, and velocity of mold closure are all variables which may have a significant effect on the properties of the molded part.

The materials used in this program were produced on SMC machines and molded in presses in developmental laboratories. The molds were charged to 100 percent of the mold surface area with the SMC-C20/R30 and the XMC-3 materials to eliminate flow effects. Flat plaque molds were used. The test panels produced are considered to be representative of controlled production conditions, even though they were produced under laboratory conditions. Since flat plaques are used, there is no attempt to address the influence of flow into complex geometries on material properties.

AUTOMOTIVE SERVICE ENVIRONMENT

Table II indicates the general service environment for an automotive component. Few components would be subject to the most severe of these conditions, but the list provides a guideline for developing a general data base of environmental influence on material properties.

MATERIAL PROPERTIES

Static Properties

Table III summarizes the room temperature static properties of SMC-C20/R30 and XMC-3, and compares them to random fiber SMC systems. The number of observations, average, and the coefficient of variation (COV = standard deviation x 100%/mean) are noted. The properties of SMC-C20/R30 and XMC-3 are reported in both the longitudinal (L) and transverse (T) directions where the two values differ significantly.

Typical tensile stress vs. strain curves for longitudinal and transverse SMC-C20/R30 and XMC-3 are shown in Figures 6 and 7. All four curves show a bilinearity which is probably indicative of matrix damage. This effect is minimal in the XMC-3 in the longitudinal direction. The transverse curves are very similar to those reported by Heimbuch and Sanders (1) for SMC-R25 with two very distinct linear regions separated by a nonlinear region. This nonlinearity and change of modulus should be considered in design with these materials. It can be seen that the secondary transverse moduli are approximately one third of the initial transverse moduli for both materials. The longitudinal secondary moduli are 95 and 81 percent of the initial moduli values for XMC-3 and SMC-C20/R30, respectively. The failure strain of SMC-C20/R30 has a high coefficient of variation in both the longitudinal and transverse directions. In observing individual stress-strain curves it can be seen that some have a third "ductile" region of almost no slope immediately before failure while others fail while still in the second linear regions. This behavior must be accounted for in strength critical designs.

Tensile strength (σ_T) and modulus (E_T) are considerably higher in the longitudinal directions of XMC-3 and SMC-C20/R30 than for the random fiber SMC materials. However, Figures 8 and 9 show that these values decrease rapidly as the loading axis is rotated from the longitudinal (0°) direction to the transverse (90°) direction. Tensile strength becomes lower than that of SMC-R65 when XMC-3 is loaded at angles greater than 19° and when SMC-C20/R30 is loaded at angles greater than 6°. Tensile modulus values for XMC-3 and SMC-C20/R30 remain higher than random fiber SMC materials up to loading angles of 51° and 28°, respectively. XMC-3 retains its high properties to higher loading angles because the continuous fibers are oriented in the ±7.5° X - pattern rather than the 0° unidirectional pattern of the SMC-C20/R30. Also, the XMC-3 composite contains 50 percent by weight continuous fibers. This provides much higher properties than the 20 percent continuous fibers in the SMC-C20/R30. The transverse tensile properties of XMC-3 and SMC-C20/R30 are in the same range as SMC-R25. The error bars shown in Figures 8 and 9 and in the following graphs are the 95 percent confidence interval for the mean.

Typical failed tensile specimens are shown in Figures 10 and 11. The longitudinal SMC-C20/R30 and XMC-3 exhibit brooming type failures. It can be seen that these failures in the longitudinal direction often extend into the gripping area of the ASTM D638 Type I tensile (dogbone) specimen. This may result in conservative values for tensile strength in the longitudinal direction.

In order to assess this effect, tests were also run using straight sided test coupons with bonded beveled end tabs. This is a standard test method for high modulus fiber reinforced materials. Table IV shows the results of this comparative testing. The straight coupon test resulted in a longitudinal tensile strength that was 30 percent higher than the dogbone test specimen results for SMC-C20/R30; only a 4 percent difference in tensile strength of the specimen types is seen for XMC-3. Tensile strain to failure was 23 percent higher for SMC-C20/R30 and 7 percent higher for XMC-3 using the straight coupon specimens. As expected, tensile modulus and Poisson's ratio values were similar for the two specimen types. Transverse tensile results were similar for both test methods. These results seem to indicate that ASTM D638 dog bone specimens are not adequate for testing composites with unidirectional continuous fibers in the fiber direction for tensile strength and failure strain. But, for composites with angled unidirectional fibers the dog bone specimen is probably acceptable.

Tensile strain to failure (ϵ_T) is less than 2 percent for all the materials listed in Table III. This indicates the SMC materials are not very ductile compared to the metals they are intended to replace. This difference in ductility must be considered in design.

Poisson's ratios (ν) are considerably lower in the transverse direction of SMC-C20/R30 and XMC-3 due to the anisotropy of these materials.

Strain to surface matrix crazing (ϵ_{mc}) was measured by bending flat coupons over an elliptical mandrel. The radius of curvature at the point where surface crazing begins on the test sample is converted to surface strain (ϵ_{mc}). The resulting surface crazing strains were higher than the strains where the stress-strain plots changed slope. This indicates that the damage mechanism which causes slope change may not be matrix crazing, or that the crazing strain may be different for the two loading modes. Further work is necessary to determine the exact nature of the mechanism causing the change in tensile modulus. Matrix crazing strain could be an important consideration in SMC design because crazes can grow into cracks leading to failure, and crazes may degrade coatings and open the material to chemical attack. Crazing strain appears to be a function of fiber orientation and matrix type and percent. The highest values are seen in the longitudinal SMC-C20/R30 and XMC-3.

In-plane shear strength (τ_{LT}) and modulus (G_{LT}) do not vary greatly among the different SMC materials. The random fiber materials give a higher shear modulus than the materials with both continuous and random fibers.

Compressive properties followed trends similar to those seen in tensile properties of the SMC-C20/R30 and XMC-3: properties in the longitudinal direction tend to be greater than those in the transverse direction. In comparing strengths in the two loading modes, the compressive strength of the SMC-C20/R30 and XMC-3 are comparable to the tensile strengths in the longitudinal direction. However, in the transverse direction, compressive strength (σ_c) is approximately twice as high as tensile results. As expected, modulus values were similar between tensile and compressive loading modes. Typical compression failures are shown in Figure 12.

The compression specimens tested were straight sided with no end tabs. To assess the effect of end tabs on compression test results, comparative tests were run with bonded end tab specimens. Both types of samples were run in an IITRI compression test fixture (9). Table V shows the results of this testing. Longitudinal compression strength values are shown to be 33 percent higher using end-tabbed specimens for SMC-C20/R30 and 20 percent higher for XMC-3. Compression failure strains are 12 and 25 percent higher for tabbed SMC-C20/R30 and XMC-3, respectively. Modulus values are similar, as expected. Transverse compression results were similar for both test methods. This indicates that tabbed test specimens should be used for compression tests of continuous glass fiber SMC materials in the longitudinal direction, if accurate strength values are required.

Flexural strength (σ_F) values are typically twice as high as tensile strength values for all the SMC materials in Table III. Flexural modulus (E_F) values are similar to tensile modulus values for longitudinal SMC-C20/R30 and XMC-3, but are considerably lower for transverse SMC-C20/R30, transverse XMC-3, SMC-R25 and SMC-R65. Typical flexural test failures are shown in Figure 13 in a through-the-thickness view. The transverse specimens exhibit a matrix failure. The longitudinal SMC-C20/R30 sample appears to fail in a combination of surface fiber failure and interlaminar shear failure, and the longitudinal XMC-3 sample appears to fail by surface fiber breakage only.

The through-the-thickness or "interlaminar" shear strength (τ_I) ranged from 25 to 55 MPa for these SMC materials. This is about one third to one half of the in-plane shear strength values. These values indicate a lower limit of (τ_I) because of questionable failure modes of the test samples.

Thermal expansion coefficients (α) were found to decrease with increasing weight percent of glass in the random fiber materials. In the continuous fiber directions of XMC-3 and SMC-C20/R30, the thermal expansion coefficients were found to be much lower than that of the transverse direction, as expected.

Figures 14, 15 and 16 and Table VI illustrate the effect of temperature on tensile, compression, flexural and shear strength for SMC-C20/R30, XMC-3, and SMC-R50. Relative to room temperature strength values, temperature affects tensile strength much less severely than compression, flexural, or shear strength. Tensile strength vs. temperature data for transverse SMC-C20/R30 and XMC-3 shows trends similar to SMC-R25 data published by Heimbuch and Sanders (1).

Figures 17, 18 and 19 and Table VI show the affect of temperature on the tensile, compressive, flexural, and shear moduli of SMC-C20/R30, XMC-3 and SMC-R50. These affects could be extremely important in many automotive designs where part modulus is critical. The affect of temperature on modulus appears to be somewhat less severe than its affect on strength. However, the percentage decrease in shear modulus with increasing temperature is comparable to that seen in shear strength.

Fatigue Properties

Tension-tension S-N fatigue data is shown in Figures 20-23. Data plotted at 0.5 cycles is the average static ultimate strength of the material at the fatigue test temperature. Arrows indicate that the fatigue test was stopped due to time limitations. Arrows pointing upward indicate the residual strengths of the test specimens after the fatigue test was stopped.

The longitudinal S-N curves have considerably more slope than the transverse curves. This indicates a higher absolute degradation with fatigue cycles in the longitudinal direction. However, relative to the static ultimate strength of the materials, the S-N fatigue performance is similar in the longitudinal and transverse directions. Considerable scatter is evident in the fatigue data, indicating that a large data base and statistical methods would be required for design with these materials.

One indication of fatigue performance is the maximum fatigue stress for survival to 10^6 fatigue cycles. This does not indicate an endurance limit, but is simply a convenient measure of fatigue performance at high cycles. Table VII summarizes this data. Note that fatigue performance at 90°C is very similar to that at room temperature relative to the static ultimate strength at the test temperature. Only the transverse SMC-C20/R30 has considerably different relative survival stress at the two test temperatures. This indicates that fatigue performance at various temperatures could be predicted by tensile strength data at the same temperatures. Further verification of this result is needed.

XMC-3 fatigue stress for survival to 10^6 cycles and S-N performance may be low due to the smaller test sample size used in the fatigue tests. These tests were run with half inch wide test specimens. All other results were from two inch wide test specimens. This possible sample size effect is presently being investigated. Also, dog bone test samples were shown to result in lower tensile strengths due to stress concentrations for longitudinal XMC-3 and SMC-C20/R30. This effect should also be seen in S-N fatigue data for these materials. This indicates that the fatigue S-N data presented here is probably conservative for longitudinal XMC-3 and SMC-C20/R30.

Figures 24A and 24B are typical fatigue test records for SMC-C20/R30 material. Note that load and elongation have been converted to stress and strain. In addition to documenting load and cycles to failure, fatigue hysteresis loops were recorded periodically during the test. This allowed monitoring of creep during fatigue (or cyclic creep) and modulus decay. Secant modulus decay was normalized with respect to initial tangent modulus to eliminate scatter in the data. Initial tangent modulus was used as the normalizing factor because of the fatigue behaviour of the transverse material. Due to the large amount of nonlinear deformation in the first fatigue cycle, the initial secant modulus was much lower than succeeding secant modulus values. Using the initial secant modulus as the normalizing factor would result in misleading modulus decay data. To reduce data scatter, cyclic creep was reported as the maximum strain minus the maximum strain of the first cycle.

Figure 24 indicates that neither initial tangent or secant modulus values are accurate indicators of FRP modulus under fatigue loading. Thus, modulus values for design should be chosen by also evaluating high cycle fatigue stress-strain data.

Figures 25 and 26 show average curves for SMC-C20/R30 modulus decay. Modulus decay in the transverse direction is considerably larger than that in the longitudinal direction. At low stress levels, longitudinal modulus decay may not be significant in design. However, transverse modulus decay is large even at low levels of fatigue stress. For example, at a stress level of 40 percent of static ultimate an average of 93 percent of initial modulus was retained at 10^6 cycles in the longitudinal direction and 50% in the transverse direction. This characteristic must be considered in design of fatigue loaded components. Due to the high scatter in this data, a larger fatigue data base is needed to effectively use this information in design.

Average cyclic creep data for SMC-C20/R30 at room temperature is presented in Figures 27 and 28. Note again the considerable difference between longitudinal and transverse behavior. At a stress level of 40 percent of static ultimate, the longitudinal strain is 0.068 percent at 10^6 cycles compared to 0.25 percent strain for the transverse direction. Again, a larger statistical data base is required to fully characterize and design for cyclic creep with these types of materials.

Room temperature data for XMC-3 material suggests that this material behaves similarly to SMC-C20/R30 material in modulus decay and creep during fatigue. Tests run at 90°C show that increased temperature increases both the modulus decay and cyclic creep of both these materials.

Creep Properties

Typical creep curves are shown in Figures 29, 30, 31, and 32. These curves show considerable scatter in creep data for these materials. This scatter tends to increase with increasing temperature, stress, and humidity. Also, random jumps in strain appear more frequently with increased temperature, stress, and humidity. This behavior was also reported by Heimbuch and Sanders (1) for chopped glass fiber SMC systems. The strain vs. log time curves for XMC-3 transverse and SMC-C20/R30 longitudinal and transverse exhibit similar scatter and random strain jump behavior. The arrows at 1000 hours indicate that the test was stopped due to time limitations. Sample failure is indicated by an X.

Typical creep curves as a function of test environment and test stress level are shown in Figures 33–44. The data shows that an increased humidity environment has a much more serious effect on static creep properties than does increasing temperature or stress level in the range of environments and stress levels investigated. This effect is more pronounced in the transverse directions of both materials because this direction is dominated by the matrix properties more than the longitudinal direction, which is dominated by the fiber properties. Increased stress level, temperature, and humidity increase both the initial creep strain and the creep rate, and decrease the life of the test specimen.

Creep in the longitudinal direction of both XMC-3 and SMC-C20/R30 at 23°C, 50% RH is small compared to the initial strain on loading at stress levels of 30 and 50 percent of room temperature static ultimate strength. This is not the case for other environmental conditions and stress levels, where creep is increased. In the transverse direction, creep is significant at even the least severe condition of 23°C, 50% RH at 30 percent of static ultimate strength. The creep properties of these materials should be considered in structural applications.

Vibration Damping Properties

Vibration damping properties of various SMC materials were measured. Complex modulus (E^*) and loss coefficient (η) were determined as a function of vibration frequency for SMC-C20/R30, XMC-3, SMC-R65, and SMC-R25.

When a viscoelastic material, such as a polymeric resin or a polymeric matrix composite, is excited by forced sinusoidal oscillations, the stress and strain are out of phase with each other. This phase lag between modulus, E^*, is defined as the ratio of input stress to output strain for a material excited by a forced sinusoidal input, and is composed of an in-phase and an out-of-phase component. The storage modulus, E', is the in-phase, elastic contribution to the complex modulus. The loss modulus, E'', is the out-of-phase, viscous contribution. The tangent of the phase angle between stress and strain, $\tan\delta = \eta$, is the loss coefficient, and is the ratio between energy dissipated and energy stored in the material. These values are related as follows:

$$E^*(i\omega) = E'(\omega) + iE''(\omega)$$

$$E^* = \sqrt{(E')^2 + (E'')^2}$$

$$E''/E' = \tan\delta = \eta$$

If any two of the four components E^*, E'', E', and η are known the other two can be calculated.

Results of forced, steady state, three-point vibration damping tests are shown in Figures 45-56. The complex modulus is fairly constant throughout the range of test frequencies for all the materials tested. Values for the loss coefficients of each material also do not vary significantly with test frequency. Table VIII summarizes these results. Values of loss coefficient are listed at both 0.1 Hz and 10 Hz. The loss coefficients of these materials are much greater than those of steel and aluminum materials which typically have loss coefficient values of approximately 0.001. This indicates that noise and vibrations in automotive structures would be damped out much more effectively with FRP materials than with steel or aluminum.

Notch Sensitivity Properties

For high modulus composite materials, laminate strength has been found to be a strong function of the absolute dimension of a cutout in the laminate. Design by the classical stress concentration factor is unnecessarily conservative for materials which exhibit this behavior. Tests were run on samples with circular holes or "notches" of several radii to determine this effect on automotive composites (low modulus). The experimental results were used in conjunction with a three-parameter model from pipes, et al (10) to predict notch strength. The strength model identifies two parameters m and c, which fully characterize the material's notch behavior. The notched tensile strength is expressed as a function of notch radius.

$$\frac{\sigma_n}{\sigma_o} = 2\{2 + (\lambda)^2 + 3(\lambda)^4 - (K_T^\infty - 3)[5(\lambda)^6 - 7(\lambda)^8]\}^{-1}$$

where,

σ_n = notched tensile strength

σ_o = unnotched tensile strength

$$\lambda = (1 + R^{m-1}R_o^{-m}c^{-1})^{-1}$$

R = the notch radius

R_o = 25.4 mm

$$K_T^\infty = 1 + \sqrt{2\left(\sqrt{\frac{E_y}{E_x}} - \nu_{xy}\right) + \frac{E_y}{G_{yx}}}$$

K_T^∞ is the stress concentration factor for the material, expressed as a function of the effective orthotropic engineering elastic constants, and y is the loading axis.

The m and c parameters for a particular material are determined by fitting the experimental data to the strength prediction.

The effect of varying m and c are shown in Figures 57 and 58. The factor "c" is seen to shift the strength curves along the radius axis (either left or right) without distorting the shape of the curve. A higher value of "c" indicates a more notch sensitive material by shifting the curve to the left. The parameter "m" acts to change the slope of the notch sensitivity curve. A lower "m" results in a higher slope. The influence of the stress concentration factor, K_T^∞, is important for large notch radii. As the notch radius approaches infinity, the notch strength approaches σ_o/K_T^∞.

It is possible to shift the notch strength relation to a master curve for all materials. The magnitude of this shift is a measure of the relative notch sensitivity for a particular material. The reference system is chosen as $m^* = 0.0$, $c^* = 25.4$ mm and $R^* = 2.54$ mm. The relative notch sensitivity (R_{ns}) is then

$$R_{ns} = m + \log_{10} c$$

The relative notch sensitivity for two materials can be compared if both systems have the same K_T^∞.

The notched strengths of SMC-C20/R30, XMC-3, and SMC-R65 are plotted in Figures 59, 60, and 61. In these figures, the error bars indicate maximum and minimum strength values obtained. SMC-R25 material was also tested, but found to be apparently insensitive to notches up to 12.7 mm in diameter and was not fit to the model. Most of the failures for SMC-R25 did not occur through the circular holes. This implies that internal material structure had a greater effect on the strength properties than the notches did. The notch sensitivity curves and average data points for all materials tested are shown in Figure 62. It can be seen that XMC-3 is more sensitive to smaller holes. Table X gives the "m" and "c" parameters for each material, plus K_T^∞ and R_{ns}. The "m" and "c" parameters enable the designer to predict notch strength as a function of notch radii for these material systems. K_T^∞ is the theoretical stress concentration at the hole edge, and R_{ns} is the relative notch sensitivity factor.

Many of the notch sensitivity specimens for the SMC-C20/R30 were fabricated from a panel which was found to have an incorrect stacking of the continuous and random plies. However, the results from specimens fabricated from this panel seem to agree with the results from specimens with the correct stacking sequence.

Impact Properties

Impact tests were run on a Rheometrics impact test machine (11). In this unit, a horizontal hydraulic driven ram impacts a 76 mm diameter clamped plate of test material. Typical output of load vs. displacement for the impact tests are shown in Figure 63. These tests were run to establish trends only. Many more tests must be run to establish confidence in this data. Quantitative results, and the implications of such results have not yet been established. This type of test does supply comparative impact data in this type of loading mode.

From the output data, several parameters can be calculated. Apparent impact modulus, yield load, yield displacement, yield energy, ultimate load, ultimate displacement, and ultimate energy are plotted as a function of impact speed in Figures 64-67 on log-log scales.

Apparent modulus vs. impact speed data is shown in Figure 64. For XMC-3 the lower test temperature decreases the impact modulus of the material. These trends are not seen for SMC-C20/R30. No strong trends of increased impact modulus with increasing impact speed are seen except with the SMC-R25.

Force vs. impact speed results shown on Figure 65 indicate a general trend of increased yield and ultimate force with increased velocity, XMC-3 shows decreased yield and ultimate loads at -35°C. This trend is not seen in the SMC-C20/R30.

Ram displacement vs. impact speed results are shown in Figure 66. Yield displacement shows a general increase with increased impact velocity. Ultimate displacement does not show these trends.

Yield energy tends to increase with increased impact velocity, as shown in Figure 67. Ultimate energy does not seem to be a strong function of impact velocity for these materials.

Environmental Effects

Unloaded ASTM D638 Type I tensile samples with uncoated edges, were soaked in various automotive fluids for 28 days. The soak solutions were plain tap water, 5% by weight salt water, anti-freeze, motor oil, transmission fluid, brake fluid, and gasoline. The specimens were then tensile tested for strength and modulus. Results are shown in Tables XI and XII in percentage of original property values. Due to the coefficient of variation of tensile strength and modulus for SMC materials (5-20%), results of this testing are not conclusive. Strength and modulus of XMC-3 material was not reduced more than 11 percent after a 28 day soak in any of the solutions in both the longitudinal and transverse directions. Longitudinal modulus of SMC-C20/R30 was not reduced by more than 10 percent in any of the test solutions. However, transverse modulus was reduced significantly for tap water (20% reduction), transmission fluid (30% reduction), brake fluid (44% reduction), and gasoline (31% reduction). These transverse reductions in modulus are similar to those reported by Heimbuch and Sanders (1) for SMC-R25. Moderate reductions in tensile strength were seen for longitudinal SMC-C20/R30 in anti-freeze (22% reduction) and transmission fluid (18% reduction) and, for transverse SMC-C20/R30 in tap water (27% reduction). These strength reductions are somewhat less than those reported for SMC-R25.

Figure 68 shows the rate of water absorption for XMC-3 and SMC-C20/R30. Due to time limitations the environmental test samples were tested long before they reached moisture equilibrium. However, relative effects of fluid soaking could still be assessed. The SMC-C20/R30 absorbed moisture at a higher rate than the XMC-3. This is probably due to the higher percentage of resin in SMC-C20/R30.

EXPERIMENTAL METHODS

Static Tests

ASTM D638 Type I dog bone specimens were rough cut and routered from flat plaques for tensile tests. Crosshead speed was 1.27 mm/min. High and low temperature tensile test specimens were allowed to "soak" for 10 minutes after reaching the test temperature. Tensile strains were measured with a 50 mm gage length extensometer in all tests except for Poisson's ratio measurements. For these measurements, bonded electrical resistance strain gages were used to measure strain in the loading direction and transverse to the loading direction.

Straight sided specimens were tested to assess the effect of specimen geometry on tensile test results. These specimens were 228 mm in length and 25 mm in width. End tabs beveled at 30 were bonded to the specimen to reduce stress concentrations near the gripping region. The specimens had a resultant gage length of 152 mm. They were cut from flat plaques using a diamond saw. These samples were tested at .51 mm/min., and strain was measured with bonded electrical resistance strain gages.

Matrix crazing strain was measured by bending flat test coupons, 22 mm wide by 250 mm long, over an elliptical mandrel. The mandrel used had a major axis of 254 mm and a minor axis of 127 mm. The test specimens were clamped to conform to the elliptical shape of the mandrel. Dye was then wiped on the test specimens and the maximum radius of curvature where surface crazing occurred was noted. Strain at the point of craze initiation may be calculated knowing the radius of curvature at that point. This test method is discussed in detail by Riegner and Sanders (7).

In the two-rail shear test, the actual test area was 19 mm wide by 152 mm long. The rails are attached to the test specimen by clamping with high strength fasteners. Specimens were instrumented with 0°, 45°, 90° strain gage rosettes so that shear strain could be calculated.

Compression tests were run in an IITRI compression test fixture. The specimens were 13 mm wide by 120 mm long. An unsupported gage length of 13 mm was used in all tests. Initial testing was done with one longitudinal strain gage on both sides of the specimen to determine if specimen buckling was occurring. No buckling was detected, and the remainder of the tests were run with only one strain gage to determine modulus. Crosshead speed was 1.27 mm/min.

IITRI compression tests were also run to determine the effect of end tabs on compression test results. The overall specimen dimensions were 152.4 mm long by 12.7 mm wide. Unbeveled end tabs were bonded to the specimen, leaving a 12.7 mm gage length for SMC-C20/R30 and a 15.9 mm gage length for XMC-3. Longitudinal strain gages were bonded to both sides of the specimens to determine Young's modulus in compression and to indicate the onset of specimen instability. The specimens were tested at .51 mm/min.

Flex tests were run on ASTM D790 test specimens in three point flexure loading. Specimens were 13 mm wide by 75 mm long and a 50 mm support span was used. Test rate was 1.27 mm/min. Crosshead deflection was used to determine flexural modulus.

Through-the-thickness or "interlaminar" shear strength tests were run using short beam shear tests conducted according to ASTM D2344. Specimens were cut to 15.2 mm long and 6.4 mm wide, and tested on a 10.2 mm span.

The coefficient of thermal expansion was measured per ASTM D696 using Anter Laboratory "Unitherm" equipment. Density measurements were made according to ASTM D792.

Fatigue Test

Tension-tension fatigue tests were run at 5 Hz with a load ratio of 0.05. Testing was done on closed-loop servohydraulic testing equipment in load control. Clip gage extensometers were used to measure strain. Maximum and minimum stress and strain were recorded throughout each test. Temperature was monitored on several tests and found to not increase over 5°C above the test temperature during the bulk of the fatigue tests. However, test sample temperature rose significantly near failure. Test samples which had not failed at 10^6 cycles were tested statically to determine residual properties using standard tensile test procedures. Figure 69 shows the dimensions of the two types of test specimens used. Different test specimens were used due to test machine limitations. Tests were run at room temperature and 90°C for both XMC-3 and SMC-C20/R30 in both the longitudinal and transverse directions.

Creep Tests

Static creep tests were carried out at 23°C and 90°C for 1,000 hours on SMC-C20/R30 and XMC-3. Testing was done on dead load machines. Temperature was controlled using heated forced air, with relative humidity controlled at about 50 percent for the 23°C and 90°C tests. Tests were also run at 90°C plus 100% relative humidity. This condition was simulated by immersing the test samples in water. Test samples were placed in the 90°C water for 48 hours prior to testing and remained in the water bath throughout the test. The test samples were standard ASTM D638 Type I tensile samples held in friction grips. Typically five replicates of each test condition were made. Tests were run at 30, 50, and 70 percent of room temperature static ultimate in both the longitudinal and transverse directions for the 23°C and 90°C tests. Stress levels for the 90°C, 100 percent relative humidity tests were 20, 30 and 50 percent of room temperature static ultimate tensile strength, respectively.

Strain during loading, and for the first half hour of creep was measured with an LVDT and recorded continuously on an X-T recorder. An optical-beam extensometer was used for strain measurement for the remainder of the test. Load was applied by releasing dead weights held up with a hydraulic jack.

Vibration Damping Test

A rectangular cross section three point bending test sample geometry was used. The beams were 5.08 cm long by 1.3 cm wide. A Dynastat dynamic viscoelastic analyzer, together with a Dynalyzer auto-correlator/analyzer were used to perform the tests. The beams were loaded sinusoidally at 0.10 to 40 Hz, and the resultant deflections and phase shifts were recorded and analyzed to produce the dynamic material properties.

Notch Sensitivity Test

Notch sensitivity tests were run using test specimens fabricated in the same manner as the tensile straight sided test samples with bonded beveled end tabs described previously. The only difference was that the overall specimen dimensions were 305 mm long by 38.1 mm wide. Circular holes were machined into the specimens using a diamond core drill. The hole sizes for the SMC-R25 and SMC-R65 were 1.60 mm, 3.18 mm, 4.78 mm, 6.35 mm, 7.94 mm, 9.53 mm and 12.7 mm. Only longitudinal SMC-C20/R30 and XMC-3 samples were tested. The hold sizes for these materials were 3.18 mm, 4.78 mm, 6.35 mm, 7.94 mm, 9.53 mm, 11.1 mm, and 12.7 mm. Five samples of each hole size were tested. In addition, 5 samples of each material were tested unnotched. Tests were run at a crosshead speed of .51 mm/min.

Impact Test

Impact testing for SMC-C20/R30 and XMC-3 was done on a Rheometrics hydraulic ram test system. Figure 70 shows a simplified schematic of the test set up. Samples were clamped in place over a 76 mm diameter opening and impacted with a controlled velocity 12.7 mm ram with a 6.35 mm radius impact nose. Ram displacement and loading was monitored throughout the test and plotted on an x-y plotter. Tests were run at both room temperature and -35°C. Impact rates were varied from .42 m/s to 12.7 m/s. One to three test samples were run per test condition in this study.

Environmental Test

Unloaded ASTM D638 Type I tensile sample with uncoated edges were soaked in various automotive fluids for 28 days. The soak solutions were plain tap water, 5% by weight salt water, anti-freeze, motor oil, transmission fluid, brake fluid, and gasoline. Five longitudinal and five transverse specimens were soaked in each fluid. Percent water weight gain was measured for 10 samples each of XMC-3 and SMC-C20/R30 and averaged at several intervals during the 30 day soak period. All samples were tested per ASTM D638 for both residual strength and modulus.

CONCLUSIONS

The work reviewed here indicates that combination continuous and random fiber and reinforced plastic materials could be viable candidates for structural automotive applications. However, designers must be made aware of the differences in material property behavior of these materials compared to conventional automotive steel and aluminum alloys. Additional work is necessary to develop analytical models and design methodologies to be used when designing for combined loading conditions and varying environmental conditions. In addition, the effects of processing variables and geometric effects must also be assessed and incorporated into design methods. The work presented in this report serves as baseline data on combination continuous and random FRP material systems. A more extensive study of these materials is necessary if the statistical data base, needed for efficient design, is to be generated.

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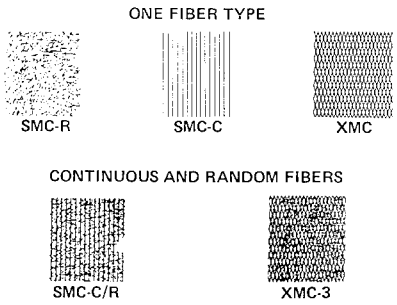

FIGURE 1
TYPES OF GLASS FIBER REINFORCED SHEET MOLDING COMPOUND

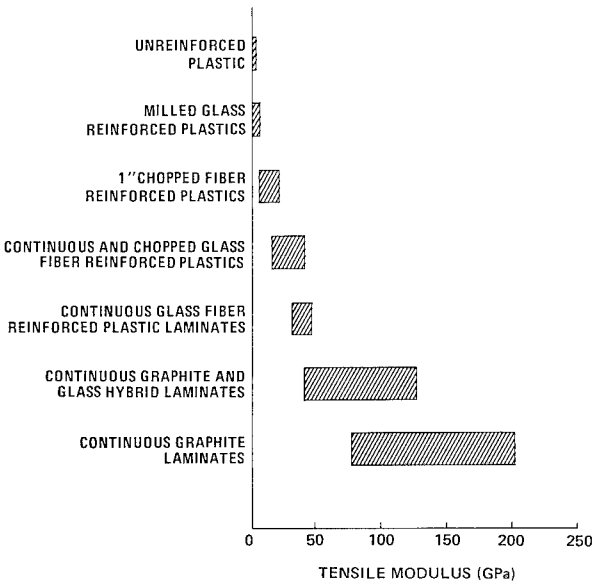

FIGURE 2
APPROXIMATE MODULUS RANGES FOR REINFORCED PLASTIC MATERIALS

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NOTICE: Remaining figures 3-70 are included in the complete report (MD-79-023), available on request from:

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TOUGHNESS EVALUATION WITH SMALL QUANTITIES OF MATERIAL

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INTRODUCTION

The evaluation of experimental polymers is often complicated by the small quantities of material available. Although many tests of physical properties have been designed to reduce sample requirements, traditional impact testing requires a much larger quantity of polymer than is produced in a laboratory reaction.

In our research, for example, exploratory synthesis begins with 20g reactions in glassware before "scale-up" to a 200g batch reactor. But, a normal Izod bar takes 10g (10 specimens preferred), and a falling dart impact chip takes 4g (20 specimens preferred). Thus, the large material requirement is the result of two factors: the size of the specimen to be impacted, and the number of specimens which must be tested in order to build up reasonable statistical confidence.

Because of the importance of toughness evaluation in the screening of polymer systems, we have developed a small-scale instrumented dart impact test. The instrument records the force-time response during the high speed puncture of a thin (0.2-0.5mm) plastic film. Instrumented impact tests offer many advantages (1-3). In particular, the mean energy-to-fail can be reliably determined from relatively few specimens. The dart-type test appears to be the most suitable configuration for reducing the size of the individual impact specimen.

The dart and clamping rings can be scaled down proportionately, and the specimen thickness can be reduced. In addition, the "edgeless" testing mode avoids the common difficulty of micro-tensile specimens in which edge flaws dominate the deformation and fracture behavior.

THE IMPACT TEST

A photograph of the complete impact test apparatus is shown in Figure 1; Figures 2 and 3 give close-up views of the impact area and the oscilloscope display.

A thin plastic film, typically 25mm square and 0.4mm thick, is clamped over a 22mm diameter hole in the falling plate. The plate, guided by three rods and bushings, falls 0.91 m; the plastic film is punctured by a 6.4mm diameter hemispherical dart at a rate of 3.6 m/sec; and the plate is stopped by a shock absorber.

The force applied to the plastic film during the impact is coupled to a Kistler quartz crystal transducer mounted beneath the dart. The charge signal from the transducer is converted to a voltage and amplified by the charge amplifier. Maximum sensitivity is 10 N/v, and frequency response is up to 180 kHz.

A Nicolet digital storage oscilloscope records the force on the dart during the impact. The oscilloscope display in Figure 3 has a total width of 5.12 msec. Four quadrants of memory, each containing a force-time curve of 1024 points sampled at 5 μs/point, are displayed simultaneously for visual comparison. The transducer ringing after failure has been erased from the digital memory.

An analog integrator with a digital display electronically integrates the force-time curve to obtain the Energy-to-Fail. A system calibration factor converts the number on the indicator to "Joules."

The design of the impact test produces a constant velocity impact. The mass of the falling plate is chosen so that the energy absorbed by the toughest polymer film is 2% of the kinetic energy of the plate at impact. Then, the velocity of the falling plate would be reduced 1% during the film puncture. But the gravitational acceleration during a 2 msec puncture would increase the plate velocity 0.5%. Therefore, the impact velocity is constant to ± 0.5% during the puncture of any film tested.

Thin film specimens are compression molded from polymer pellets or powder. The use of temperatures well above the Tg or Tm of the polymer and four-minute molding cycles usually insures film properties representative of the unoriented polymer. Thin extruded sheet or thin injection molded film has been used on occasion.

RESULTS

For initial calibration of the small-scale impact test, the mean Energy-to-Fail of 0.38mm film was compared to ASTM D256 notched Izod impact. Figure 4 shows this correlation for a variety of commercial thermoplastics -- brittle, ductile, amorphous, rubber-modified, and crystalline. Relative ranking is very good if unnotched Izod is used for polysulfone, a notch-sensitive material. The error bars represent the standard deviation obtained with six specimens cut from a single compression molded film: 2 g polymer! Force-time curves from four specimens of polycarbonate are shown in Figure 3 to illustrate the excellent test reproducibility.

The effect of specimen thickness on the test results is an area of great concern (see DISCUSSION). Each family of polymers has been tested at various thickness in the range 0.2-0.5 mm. As the examples in Figure 5 demonstrate, the mean Energy-to-Fail shows a linear dependence on film thickness and extrapolates to the origin .

If tough plastics are tested at thicknesses approaching 1 mm, the force-time curves do not usually exhibit sharp failure points. Instead, the force shows a broad maximum before falling to a low level. This force-time curve includes, in addition to the force leading to failure, the force necessary to push the dart through the puncture area in a thick, ductile specimen. Therefore, the Energy-to-Fail must be measured only to the point of maximum force. The Nylon 66 curve in Figure 5 uses this method of analysis.

The small-scale impact test has been extremely useful in the evaluation of experimental polymer systems. In one project, summarized in Figure 6, over 70 experimental ABS polymers were tested using 2 g of material. Thin film impact provided rapid and reliable characterization of the polymers as numerous polymerization variables were explored. The trends from the small-scale test, which indent-

ified "success" in attaining toughness, show a surprisingly good relation to Izod values. The advantage of a small-scale impact test is illustrated well in this example: exploratory work could proceed on a small scale and cover a great deal of territory in a short time.

DISCUSSION

The most troublesome variable in the scale-down of the impact test is the specimen thickness. For example, Morris (4) showns two materials A and B: at thicknesses of 2.5 mm A is clearly superior to B in impact resistance, but at thicknesses of 0.5 mm the two material have very similar impact resistance.

The failure mechanism for materials that deform plastically depends on the thickness. In thin specimens deformation can occur at nearly constant volume because of lateral contraction. In thicker specimens, where bulk constraints inhibit lateral contraction, the deformation boundary conditions change from plane stress to plane strain, and a transition from ductile to brittle fracture takes place.

In polymers tested to date, however, the small-scale dart test has generated a mode of failure (determined by visual examination of the broken specimen) and a relative energy-to-fail consistent with conventional impact testing on thicker specimens -- with one exception. Unlike the situation for thick samples (5), annealing has only a small effect on the toughness of thin polycarbonate films.

SUMMARY

We have developed a small-scale instrumented dart impact test for use in evaluating experimental polymers. The instrument records the force-time response during the high speed puncture of a thin plastic film. The Energy-to-Fail is a linear function of film thickness in the 0.2-0.5 mm range and correlates with accepted values of impact resistance for a variety of plastics. Toughness evaluation can be made with as little as 2 g of material.

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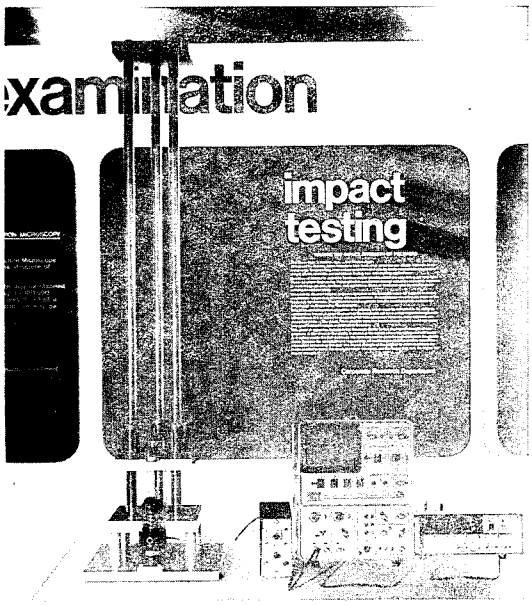

Figure 1. The impact apparatus: the tester, the charge amplifier for the quartz transducer, the digital storage oscilloscope, and the integrator with digital display.

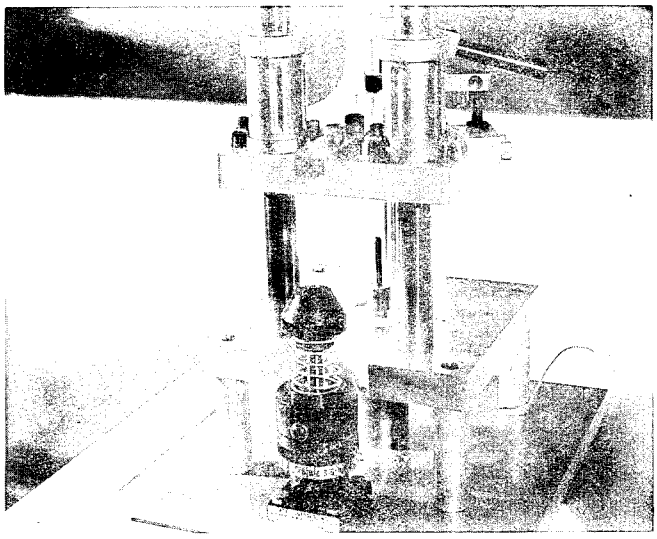

Figure 2. A close-up view of the impact area showing the falling plate which holds the plastic film, the dart which punctures the film, and the shock absorber. The force transducer is mounted beneath the dart.

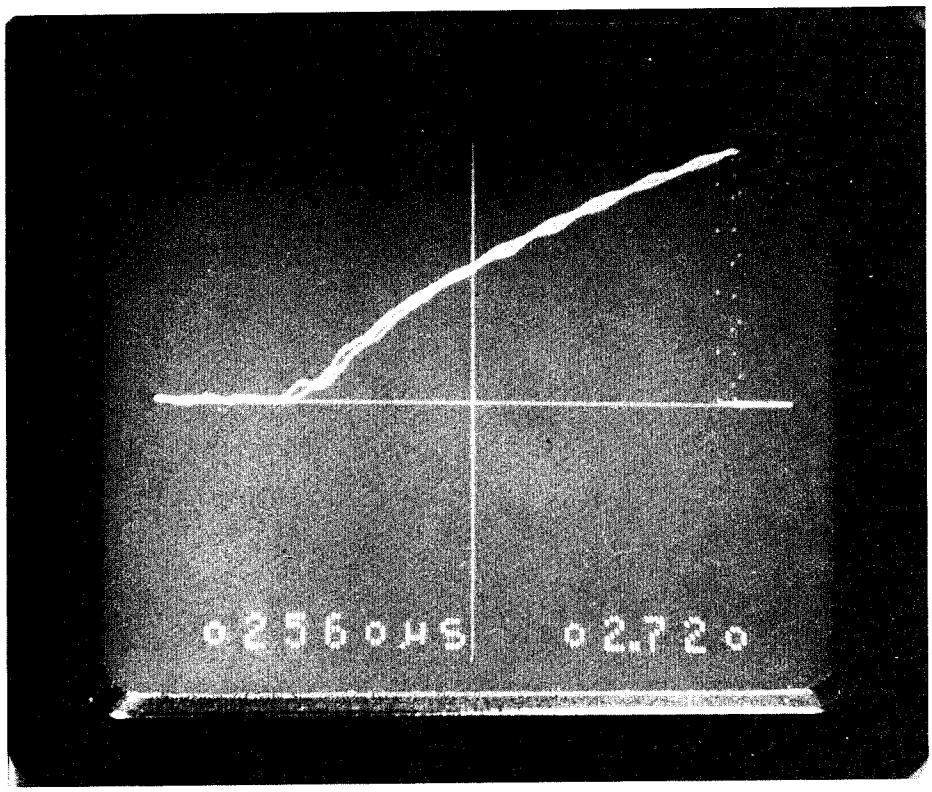

Figure 3. A close-up view of the oscilloscope display. The force (vertical) vs time (horizontal) curve is stored in a digital memory. Four curves are displayed simultaneously for comparison. The width is 5.12 msec (1024 points at 5 μsec intervals).

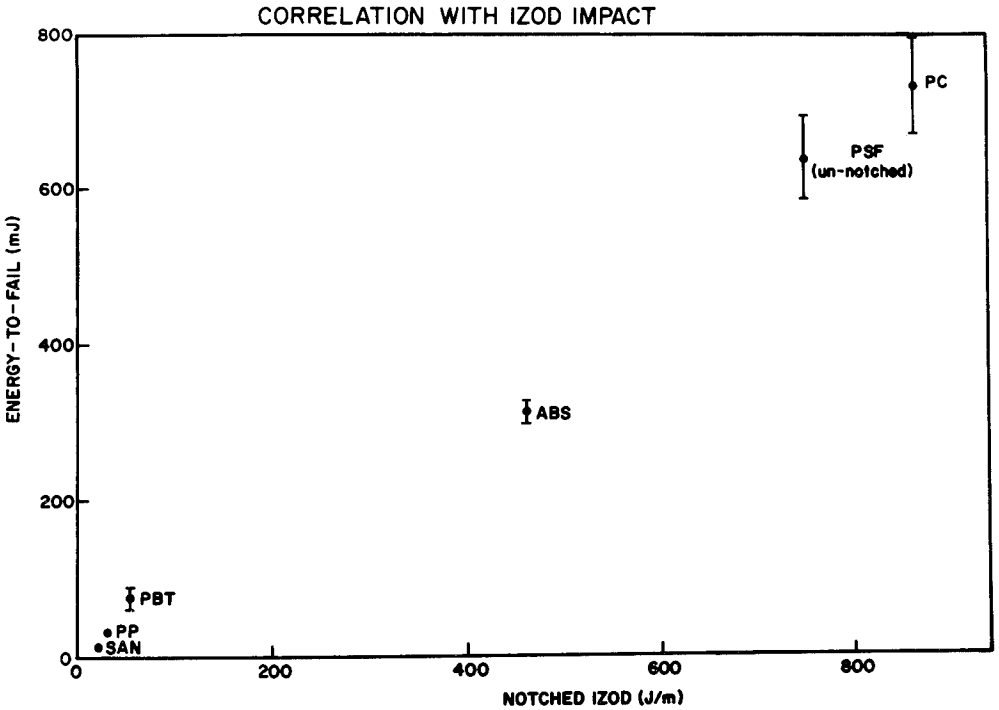

Figure 4. Thin film Energy-to-Fail vs notched Izod impact for commercial thermoplastics: SAN (styrene-acrylonitrile), PP (polypropylene), PBT (polybutylene terephthalate), ABS (rubber-modified SAN), PSF (polysulfone), PC (polycarbonate).

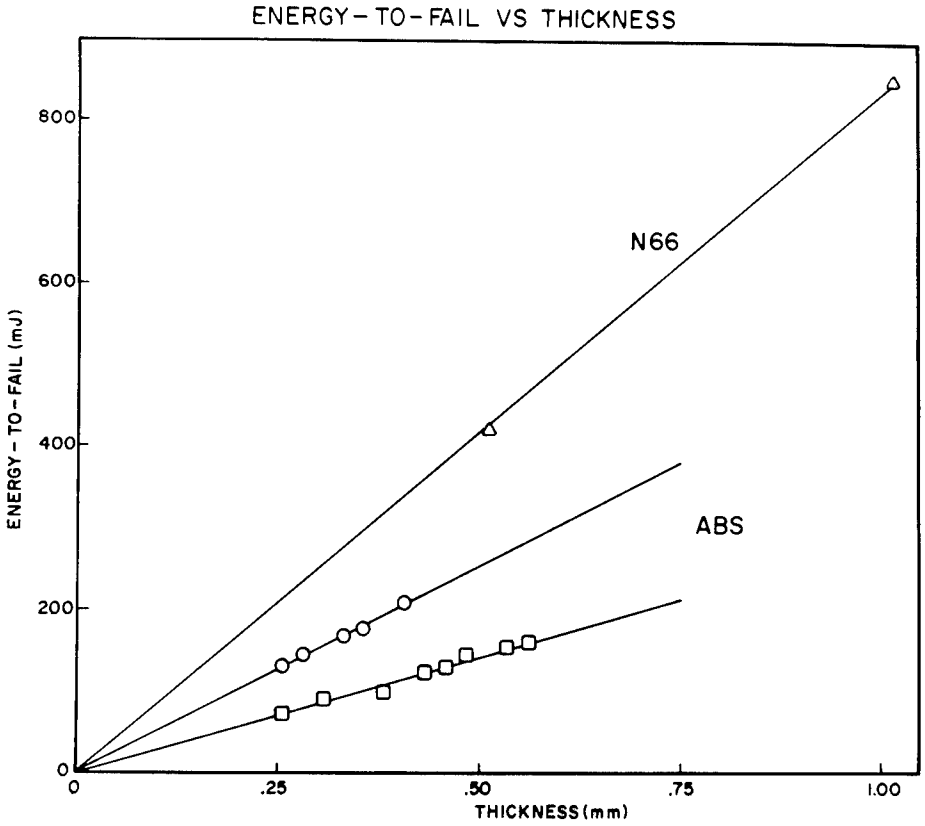

Figure 5. Thin film Energy-to-Fail vs film thickness.

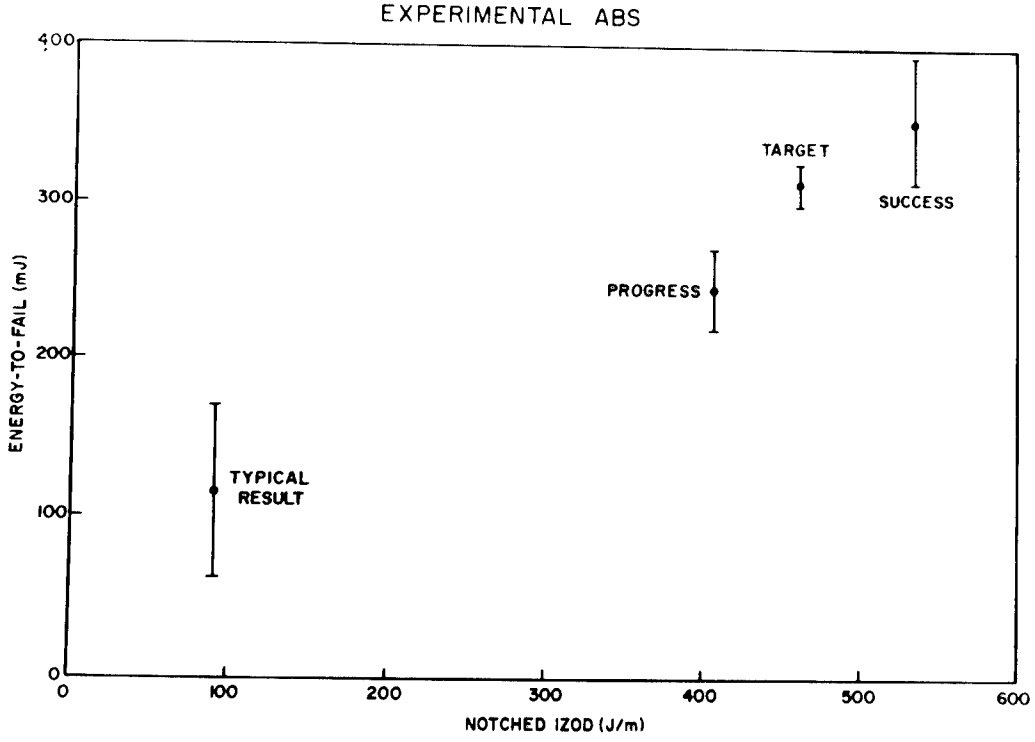

Figure 6. Results from an experimental program on ABS polymers. Thin film Energy-to-Fail determined using 2g material shows a good correlation with Izod values.

PHYSICAL PROPERTIES OF STYRENIC STRUCTURAL FOAMS

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INTRODUCTION

There is a great need for accurate physical property data in designing structural foam parts. Without such data, designers have been forced to select a large number of candidate materials and mold and test them in the actual part to determine suitability. The present experimental work was undertaken to identify the primary variables affecting physical properties of styrenic structural foam and to develop design equations which would predict foam properties based on solid resin data and a few controlling structural variables. Such design equations will allow the selection of proper candidate materials from the multitude of styrenics available based on well known solid resin data. The design equations might also prove useful for other resin types and give insight into the efficiency of SF.

EXPERIMENTAL PROCEDURES

A range of ABS, HIPS, and glass reinforced ABS and HIPS materials were tested using chemical blowing agents (azodicarbonamide and 5 phenyl tetrazole) and conventional injection molding machines to produce molded structural foam test specimens (the single component short shot technique). To study orientation effects, structural foam plaques were molded and test bars cut out in the flow and transverse directions.

A series of experiments were performed on an Ex-Cell-O 220 ton SF machine using a seat frame mold to compare nitrogen and chemical blowing agents and to compare physical properties of the lab moldings with those of commercial moldings. No differences in any properties of these moldings were observed versus the lab moldings which were attributable to the different blowing agents or machine conditions.

RESULTS AND DISCUSSION

Cell size is a function of the type and number of nucleation sites present, the pressure drop during injection, the gas concentration in the melt, and the polymer type. For most SF parts, these factors combine to form macroscopic cells (> 100 μ) (1). For cells of this size, there seems to be no effect of varying cell size, either from this work or in the literature, except for the case of random, very large cells which effectively reduce the local density and, hence, create a relatively weak spot. In making the transition from macroscopic to microscopic cells, there may be a substantial increase in impact properties (2). However, this point has not been well demonstrated as yet.

All physical properties are rapidly decreased with density reduction. To quantify the effects of density, the following equation was chosen to fit the data:

$$Y_f/Y_s = (d_f/d_s)^n \quad \text{Equation 1}$$

where Y is the property of interest, d the average density, f and s denote foam and solid, and n is an empirical exponent. The styrenic data were plotted in the form log (Y_f/Y_s) vs. log (d_f/d_s) and ranges of n were selected to envelope the data, as shown in figures 1-4.

Figure 1 shows a different density dependence for stiffness of filled and unfilled systems. A simple model for stiffness is shown in Figure 5 which predicts values in very good agreement with the data, n = 1 for unfilled and n = 2 for filled systems. The higher density dependence for filled systems is due to the nucleating effects of fillers which reduce the skin thickness to almost nothing giving the behavior of a uniform foam.

Multiaxial and uniaxial impact have different density dependencies. Figure 2 shows a variation in n from 3 to 5 for driven dart impact while figure 3 shows n varying from 1.6 to 3 for Charpy impact. Throne (3) suggests that n = 4 fits most of the data from both types of test. However, due to orientation effects which decrease the density dependence in the flow direction but increase the dependence in the transverse direction, it is expected that uniaxial impact in the flow direction will be less dependent on density than multiaxial impact which tests the weaker transverse direction.

Figure 4 shows that DTUL has a low dependence on density. This stems mostly from the nature of the test. A constant temperature creep test would no doubt show a higher dependence of heat resistance on density.

While density profile (skin/core ratio) was found to have a strong effect on stiffness, it does not affect impact or strength properties. Density profile also is relatively constant for unfilled materials and a given density. Our experiments show that random variation of skin thickness gives rise to at most a 5% variation in stiffness, see Figure 6.

The density limit, or maximum expansion that can be achieved, is controlled largely by the polymer viscosity for two different situations. For a large seat frame mold the viscosity correlated at a shear rate of 1000 $sec.^{-1}$ showing that the initial rapid portion of the injection is controlling maximum expansion. For a small test specimen the correleation was obtained at 1 $sec.^{-1}$ showing the initial injection to have less control over maximum expansion.

In any of the processes where foaming occurs during injection, cell orientation results. The cells become elongated in the flow direction increasing properties in this direction and decreasing properties in the transverse direction. Orientation effects on stiffness are shown in Figure 8. Meta and Colombo (4) have developed a model to represent the orientation of the core which when used with the model in Figure 5 predicts values in excellent agreement with the data. Figure 9 shows orientation effects on impact.

The effects of changes in orientation due to changes in density or part thickness for a given part geometry are small compared to the effects of density and thickness themselves. This allows the development of design equations for SF properties as a function of density and thickness only, and orientation effects for different geometries can be accounted for separately. Expanding Equation 1 to account for thickness we get:

$$Y_f/Y_s = (d_f/d_s)^n (t_f/t_s)^m \quad \text{Equation 2}$$

where t is the part thickness and m a new empirical

exponent. Figures 10 and 11 show the ranges of m found by enveloping the data obtained at a constant density and assuming a constant density dependence. There is a small interdependence of the effects of density and thickness which is not accounted for in Figures 10 and 11. The various theories for SF stiffness (5) predict a value of m = 3 in agreement with the data. Figure 11 shows roughly the same dependence on thickness for multiaxial and uniaxial impact. Using the values of n and m found empirically and Equation 2, the properties of Styrenic SF can be predicted from solid resin properties.

The efficiency of SF in meeting properties at a given weight (or resin cost) can be derived from the design equation. For constant weight per unit area, W, equal to density times thickness, we can substitute for d_f in Equation 2 and obtain:

$$Y_f/Y_s = (t_f/t_s)^{m-n} \qquad \text{Equation 3}$$

Using average values of n and m this equation is plotted in Figure 12 for stiffness, Charpy impact, and Driven Dart impact. It is apparent that as the thickness is increased and density reduced the efficiency relative to solid increases for stiffness but decreases for impact.

CONCLUSIONS

1. Properties of large SF moldings can be predicted by testing small lab specimens within experimental error.
2. SF property predictions can further be based on solid resin data using the design equations empirically derived.
3. The major structural variables affecting physical properties of SF are density, thickness, and cell orientation.
4. SF is very efficient in achieving high stiffness but is very inefficient in achieving impact resistance. SF is therefore not suited to applications requiring both high stiffness and high impact.
5. Orientation can only help performance if a part is designed so that the orientation is in the direction of highest stress. Otherwise, orientation can significantly reduce the part performance, particularly impact.

ACKNOWLEDGEMENT

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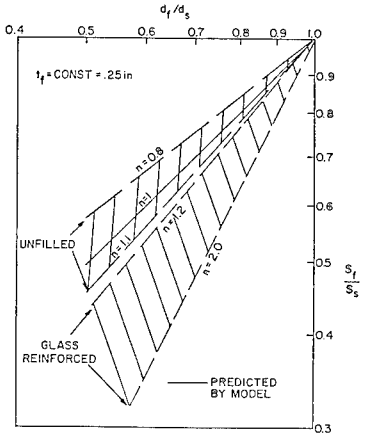


FIG. 1 STIFFNESS VS DENSITY

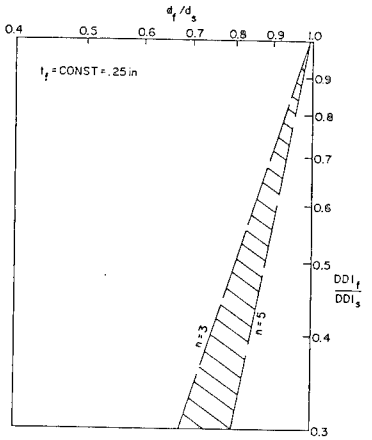


FIG. 2 DRIVEN DART IMPACT VS DENSITY

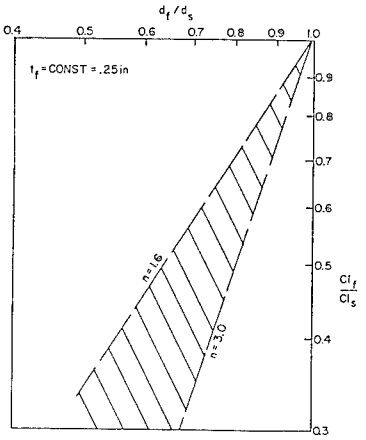


FIG. 3 CHARPY IMPACT VS DENSITY

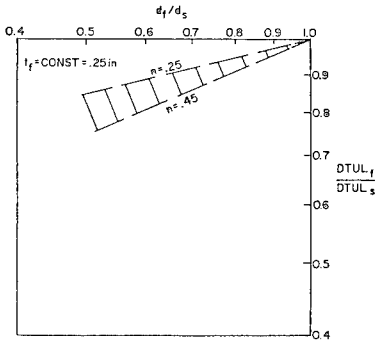
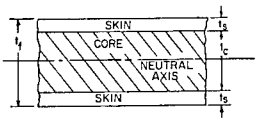


FIG. 4 DTUL(264PSI) VS DENSITY



$$\frac{S_f}{S_p} = \frac{I_s + (d_c/d_s)^2 I_c}{I_p}$$

$$I_s = b\left[\frac{t_s}{6} + \frac{t_s(t_f - t_s)^2}{2}\right]$$

$$I_c = b\,(t_f - 2t_s)^3/12$$

$$I_p = b\,t_f^3/12$$

FIG. 5 SIMPLIFIED MODEL FOR STIFFNESS

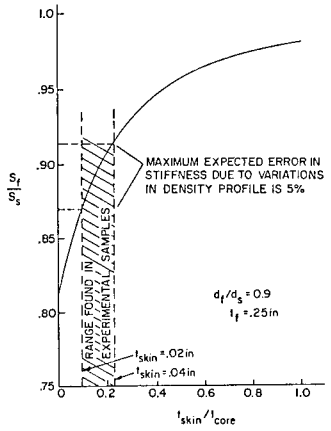


FIG. 6 STIFFNESS VS DENSITY PROFILE FROM MODEL

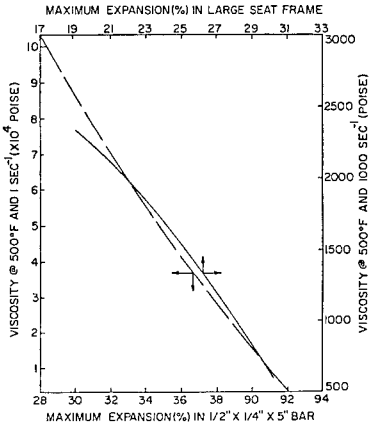


FIG. 7 CORRELATION OF MAXIMUM EXPANSION WITH VISCOSITY

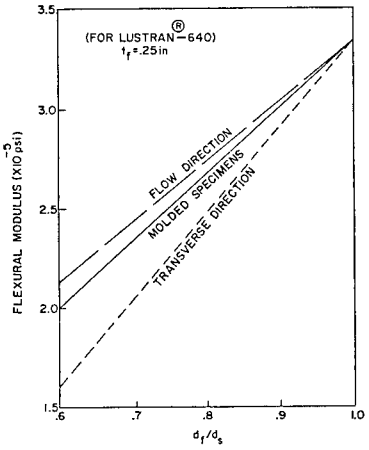


FIG. 8 ORIENTATION EFFECTS ON MODULUS

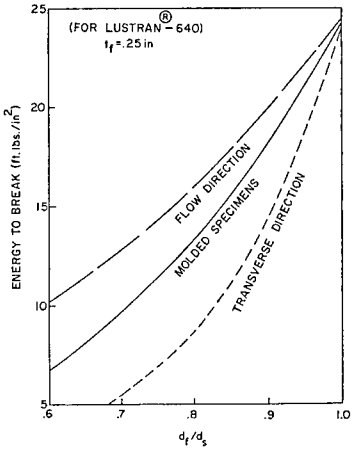


FIG. 9 ORIENTATION EFFECTS ON CHARPY IMPACT

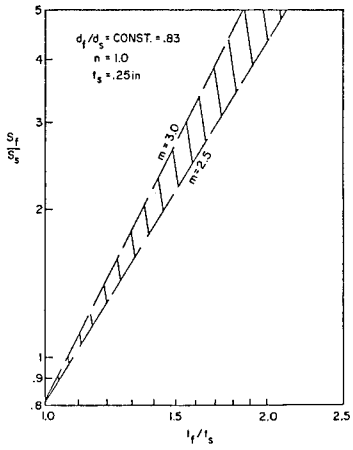


FIG. 10 STIFFNESS VS PART THICKNESS

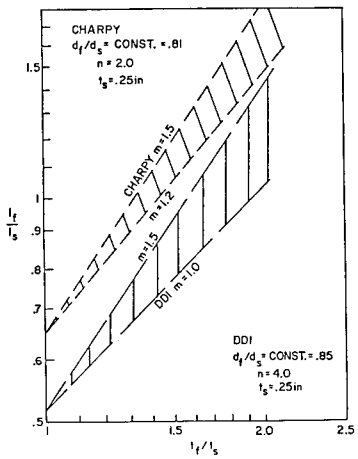


FIG. 11 IMPACT VS PART THICKNESS

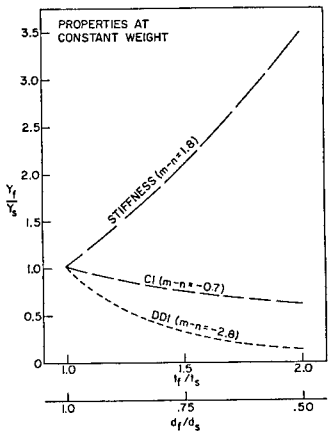


FIG. 12 EFFICIENCY OF STRUCTURAL FOAM

EVALUATION OF THE VISCOSITY EFFECTS OF METALLIC STEARATES IN POLYESTER RESINS

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Mallinckrodt, Inc.

INTRODUCTION

It has been known for some time, that alkaline earth oxides and hydroxides can be used to thicken SMC materials and they have been used for this purpose for many years. In general, a typical SMC compound, filled or unfilled is thickened by the addition of magnesium or calcium oxide to the styrene-polyester solution. The chemistry of metal oxide thickening (1) appears to involve two steps: first, the reaction between the metal oxide (or hydroxide) and the pendant carboxyl groups of the unsaturated polyester resin, and second, a coordinate bond between the metal ion and the carbonyl groups of the polyester molecule.

Metallic stearates (particularly zinc stearate) are generally added to SMC materials to promote good mold release properties to molded parts. However, metallic stearates also play a role in the thickening process, particularly during initial stages of thickening.

Some factors inherent to the metal stearates are considered important in the thickening process:

1. Type of metal cation (e.g., zinc, calcium, magnesium).
2. Percent ash (high ash contents would indicate an excess of metallic oxide or hydroxide).
3. Free fatty acid.
4. Particle size distribution.
5. pH (pH is defined here as the pH of a 1 gram dispersion of the metallic stearate in 100 grams of distilled water containing 2 drops of Igepal CO-639 surfactant).

Table I illustrates some chemical and physical properties of metallic stearates. Five zinc stearates, three calcium stearates and two magnesium stearates were chosen for this study. The percent free fatty acid is the amount of unreacted stearic acid present in the metallic stearate. The percent free fatty acid in the zinc stearate series varies from 0.47% for C to 4.40% for Zinc Stearate A. Free fatty acid for the calcium stearate series varies from 0.10 to 1.09% and the magnesium stearate series also has a narrow range of 0.24 to 1.40 percent.

Percent metallic oxide was determined analytically by ashing the metallic stearate. The theoretical percent zinc oxide for zinc stearate is 13.2%.

The percent zinc oxide in this series of zinc stearates ranges from a low of 12.8% for Zinc Stearate A to a high of 14.3% for D. It is well known (2 and 3) that zinc oxides and hydroxides can be used as thickening agents. It is for this reason that the % excess zinc oxide was considered an important factor. The theoretical percent calcium oxide for calcium stearate is 9.5%. Note that all the calcium stearates are below the theoretical amount.

For magnesium stearate, the theoretical % metallic oxide is 7.01%. Both Magnesium Stearate I and Magnesium Stearate K have ash contents which are about a 0.50% higher than theoretical.

The particle size distribution of the metallic stearates was determined utilizing a Coulter Counter.

Zinc Stearate D has an average particle size of 7.39μ. D has the largest average particle size of the zinc stearates studied. Zinc Stearate B has the smallest average particle size 2.62μ.

The three calcium stearates have almost identical average particle sizes ranging from 2.03 to 2.26 microns.

Magnesium Stearate K has the largest average particle size (9.05μ) of all the stearates evaluated.

The pH of the metallic stearates is determined by reaction stoichiometry. If excess tallow is used, the metallic stearate is said to be on the acid side. Zinc Stearate A is on the acid side with 4.40% free fatty acid and a pH of 5.8.

The metallic stearate is said to be on the basic side if excess caustic (usually present as sodium stearate), is used in its preparation. Zinc Stearate B is an example of a stearate prepared on the basic side and has a pH of 9.1.

The calcium stearates have a pH range of 6.4 to 9.2, while the magnesium stearates have the highest pH of all in this group, 10.2 to 10.4.

The next two slides show the viscosity-thickening characteristics of metallic stearates in a commercial resin system with the following formulation:

Paraplex 340	60.0
Paraplex 701	40.0
Camel Wite	150.0
Marinco H-1241 $Mg(OH)_2$	2.5
Metallic Stearate	3.0 - 5.0

Here Zinc Stearate C gives the lowest initial viscosity. Zinc Stearate E, however, gives the highest viscosity in the zinc series in this formulation. Zinc Stearate A which has the lowest pH of the zinc stearates gives a low viscosity at the 3% level.

In the commercial system, the calcium stearates are giving initial viscosities as expected and very similar to viscosities obtained with zinc stearates.

The magnesium stearates, which have the highest pH's (10.4 and 10.2) produce the highest initial viscosities.

The pH of the various stearates is:

Metallic Stearate	pH
Magnesium Stearate I	10.4
Zinc Stearate B	9.1
Magnesium Stearate K	10.2
Calcium Stearate F	9.3
Calcium Stearate H	8.9
Zinc Stearate D	7.9
Calcium Stearate G	9.3
Zinc Stearate E	7.7
Metallic Stearate	pH
Zinc Stearate C	7.1
Zinc Stearate A	5.8

In general, the stearates with high pH values give the highest viscosities when added to the polyester. There does appear to be a strong correlation between the pH of a 1% dispersion of the stearate and the viscosity it produces in the polyester.

We have not discussed the possible mechanisms for the viscosity increases caused by metallic stearates. On the next slide, we see the effect of adding magnesium hydroxide to poly(diethylene adipate) on the infra red spectra of the mixture at the 1, 3, and 5% level; and on the initial viscosity of the polyester. Adding 1% magnesium hydroxide has almost no effect on the viscosity of the poly(diethylene adipate). Adding 3% magnesium hydroxide increases the viscosity by about 50 cps. Adding 5% magnesium hydroxide increases the viscosity by about 100 cps. The infra red spectra of the four materials are essentially the same in the 1400-1800 cm^{-1} region.

The increase in initial viscosity caused by the magnesium hydroxide in this case is probably because of the particle size distribution of the magnesium hydroxide, and normal pigment/volume relationships.

In contrast, the next slide shows that when the viscosities and infra red spectra are observed four days later, significant differences are obtained. The viscosity increases from 929 cps for the 1% dispersion to 160,000 cps for the 5% mixture. In conjunction with the large viscosity increase a peak in the 6.22 - 6.25 micron area has formed. This peak is generally attributed to magnesium carboxylate absorption. Here one can be fairly confident that the increase in viscosity is due to a chemical change in the mixture. The large increase in viscosity after 4 days is caused by a chemical linking of the polyester. The polyester chains react with $Mg(OH)_2$ to form larger polyester chains. The magnesium functions as the link between the chains. This increase in viscosity occurs because of this chemical reaction, while the initial small increase in viscosity can be attributed to normal pigment volume-viscosity relationships.

The chemical reaction is illustrated on the next slide. Here we see two polyester chains reacting with magnesium hydroxide to form a chain roughly twice as large with the formation of two moles of water. It has been observed (1) that the viscosity of this reaction mixture continues to increase even after the magnesium hydroxide is completely reacted with the terminal carboxylic acid groups. The continued rise in viscosity can be accounted for by complex formation. The complex shown here is a coordinate bond between the magnesium ion and the carbonyl group of the polyester. This coordination complex reversibly crosslinks different linked polyester chains. The formation of these crosslinks results in an increase in effective molecular weight and therefore the viscosity of the system continues to rise.

The mechanism of action of metallic stearates must proceed by a similar mechanism. In the case of metallic stearates, the metallic ion (Mg, Zn, or Ca) obviously links the two polyester chains to cause an increase in molecular weight as indicated by the polyester metal soaps, time vs viscosity curves. The monofunctional stearic acid (carboxylic acid) is displaced by the bifunctional poly(diethylene adipate) carboxylic acid terminated polymer. The exchanged metallic ion from the metallic stearate, then performs the same function as the metallic ion from magnesium hydroxide, calcium hydroxide, or zinc oxide in the linking stages. Once the ionic bond is formed with the metal ion from the metallic stearate, the carbonyl group from the polyester can then further cause an increase in viscosity by forming coordination complexes.

On the next slide, we have listed all the metallic stearates in order of decreasing average particle size. What one would expect in terms of viscosity, if particle size were the most important factor, is that those stearates with the smallest average particle size would produce the highest viscosities (at least initial viscosities) when mixed with the polyester or in an SMC formulation. The stearates with the three lowest particle sizes are:

Calcium Stearate H	2.02
Calcium Stearate G	2.14
Calcium Stearate F	2.26

Calcium Stearate H has the smallest average particle size but does not produce the mixtures with the highest viscosity. The same is true for Calcium Stearate G with a particle size only slightly larger than Calcium Stearate H.

Calcium Stearate F, on the other hand, gives high viscosities but not as high as would be expected if the particle size were the dominant factor affecting the thickening process.

In fact, two stearates which give consistently very high viscosities are Magnesium Stearate I and Magnesium Stearate K. Magnesium Stearate K has the largest average particle size (9.05μ) and based on this consideration it should produce the lowest viscosity. In fact, Magnesium Stearate K produces the 2nd or 3rd highest viscosity. Magnesium Stearate I gives the highest viscosity of the stearates evaluated. Yet, it is intermediate on the list of metallic stearates arranged according to particle size.

It is clear that while average particle size of a given metallic stearate is a factor in determining the initial and final viscosity of the polyester resin mixes, it is not an important one.

The next slide compares the viscosity results after 3 hrs and after 7 days with the pH, average particle size, and % FFA of the zinc stearate series. The viscosity results were obtained in the following formulation containing 5% zinc stearate.

Poly(diethylene adipate) AN 71	100.0
Calcium Carbonate	150.0
Magnesium Hydroxide	2.5

Here we see that the viscosity after 3 hrs and after 7 days increases as the pH of the zinc stearate increases. The pH is again defined here as the pH of 1 gram of stearate dispersed in 100 ml of distilled water. We see that pH yields the best correlation with respect to the viscosity of the polyester system.

We have already discussed average particle size, but we can again note some correlation. If, Zinc Stearate D were interchanged with Zinc Stearate A a much better correlation would result. Stearates can contain unreacted free fatty acid (stearic acid). There has always been some question about how excess free fatty acid affects the ciscosity of the polyester resin system. The results obtained in this slide could indicate that a large excess of free fatty acid in the metallic stearate, around 5%, may cause a drop in viscosity.

In an attempt to resolve this question, we extracted Zinc Stearate A until there was no detectable free fatty acid. We then added 0, 1, 3, 5, 7 and 9% excess free fatty acid back to A. Note, that: This excess is based on the Zinc Stearate A. I might also point out that, zinc stearates rarely contain more than 3.0% excess free fatty acid, and more commonly, less than 1% excess free fatty acid.

The excess acid appears to cause a small increase in the viscosity of the polyester formulation at the 1%, 3% and 5% level, but then it decreases to its original 1% level at the 7% and 9% levels. Essentially what we are seeing here is that excess free fatty acid has practically no effect on viscosity. The maximum at the 1%, 3% and 5% excess tallow levels is present throughout the 7 day evaluation.

This slide essentially completes the presentation. I would like to summarize and emphasize several points.

CONCLUSIONS

1. The Acid Number of the polyester affects viscosity because of reaction with the metallic stearate. The lower the acid number the higher the viscosity produced by the metallic stearate.
2. Metal Stearates in polyester systems, in general, increase viscosities in a predictable pigment volume relationship.
3. Increasing the concentration of the metallic stearate increases the viscosity, but sometimes not in a linear manner.
4. The free fatty acid concentration has an effect on viscosity but it is minimal in the 0 to 9.0% excess range.
5. Stearates cause increases in viscosity in polyester systems because of chemical reaction and chemical interaction with the carboxylic acid and carbonyl groups in the polyester.
6. Average particle size plays a role in determining the viscosity but it is not as significant as pH.
7. The pH of the metallic stearates has the most significant impact on the viscosity.

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(1) The Interaction Between Unsaturated Polyester Resins and Metal Oxides by Dr. I. Vansco - Szmercsanyi. Paper presented during the Anniversary Meeting of the "Arbhdsgemeinschoft Verstarkte Kunststoffe" (Society for Reinforced Plastics) Oct. 6-9, 1970 Freudenstadt.

(2) U.S. Patent 2,628,209, C. F. Fish, U.S. Rubber Co., Feb. 10, 1953.

(3) U.S. Patent 3,110,690, L. W. Friedsam, Sherwin-Williams, Nov. 12, 1963.

PHYSICAL PROPERTIES OF METALLIC STEARATES

	% Free Fatty Acid	% Metallic Oxide	Coulter Counter Average Particle Size	pH
ZINC STEARATE				
A	4.40	12.8	4.80	5.8
C	0.47	13.6	6.21	7.1
E	1.70	13.3	5.89	7.7
D	1.40	14.3	7.39	7.9
B	0.61	13.3	2.62	9.1
CALCIUM STEARATE				
G	0.10	9.31	2.14	9.2
H	1.09	8.87	2.03	6.4
F	0.10	9.25	2.26	7.7
MAGNESIUM STEARATE				
I	1.40	7.60	5.54	10.4
K	0.24	7.80	9.05	10.2

METALLIC STEARATES
VISCOSITY EFFECTS
$Mg(OH)_2$ THICKENED ROHM & HAAS RESIN
$CaCO_3$ FILLED

3% METALLIC STEARATE	INITIAL	3 HRS.	1 DAY	4 DAYS	7 DAYS
Zinc Stearate A	6.32×10^3	7.76×10^3	4.26×10^4	2.94×10^6	5.14×10^6
Zinc Stearate B	7.47×10^3	8.74×10^3	4.80×10^4	2.52×10^6	4.40×10^6
Zinc Stearate C	5.63×10^3	7.39×10^3	4.06×10^4	3.65×10^6	6.38×10^6
Zinc Stearate D	5.97×10^3	6.93×10^3	3.80×10^4	3.07×10^6	5.36×10^6
Zinc Stearate E	8.99×10^3	9.17×10^3	5.04×10^4	2.97×10^6	5.89×10^6
Calcium Stearate F	6.88×10^3	1.02×10^4	1.52×10^5	1.43×10^6	2.50×10^6
Calcium Stearate G	8.24×10^3	9.20×10^3	1.37×10^5	7.87×10^5	2.56×10^6
Calcium Stearate H	8.80×10^3	1.03×10^4	1.36×10^5	1.59×10^6	4.24×10^6
Magnesium Stearate I	8.80×10^3	1.09×10^4	5.52×10^4	8.45×10^5	9.60×10^5
Magnesium Stearate K	9.36×10^3	1.25×10^4	6.48×10^4	1.02×10^6	3.16×10^6

FORMULATION:

60.0	Paraplex 340
40.0	Paraplex 701
150.0	Camel Wite
2.5	Marinco H-1241
3.0	Metallic Stearate

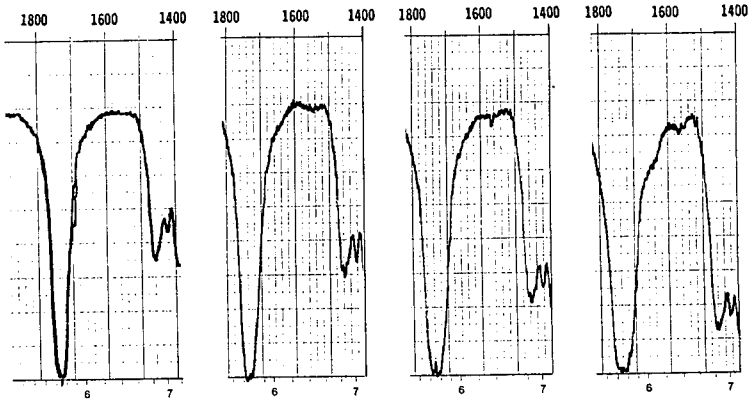
METALLIC STEARATES
VISCOSITY EFFECTS
$Mg(OH)_2$ THICKENED ROHM & HAAS RESIN
$CaCO_3$ FILLED

5% METALLIC STEARATE	INITIAL	3 HRS.	1 DAY	4 DAYS	7 DAYS
Zinc Stearate A	6.37×10^3	8.48×10^3	4.54×10^4	2.59×10^6	4.52×10^6
Zinc Stearate B	9.04×10^3	9.76×10^3	5.23×10^4	2.63×10^6	4.60×10^6
Zinc Stearate C	7.39×10^3	8.69×10^3	4.66×10^4	3.74×10^6	6.54×10^6
Zinc Stearate D	8.40×10^3	1.03×10^4	5.52×10^4	3.02×10^6	5.28×10^6
Zinc Stearate E	1.04×10^4	1.09×10^4	5.84×10^4	3.66×10^6	7.27×10^6
Calcium Stearate F	7.04×10^3	1.19×10^4	2.24×10^5	1.64×10^6	2.85×10^6
Calcium Stearate G	8.32×10^3	9.87×10^3	1.29×10^5	1.05×10^6	2.80×10^6
Calcium Stearate H	1.04×10^4	1.08×10^4	2.60×10^5	2.19×10^6	4.76×10^6
Magnesium Stearate I	9.92×10^3	1.21×10^4	6.48×10^4	1.13×10^6	2.96×10^6
Magnesium Stearate K	9.84×10^3	1.08×10^4	5.60×10^4	8.99×10^5	2.84×10^6

FORMULATION:

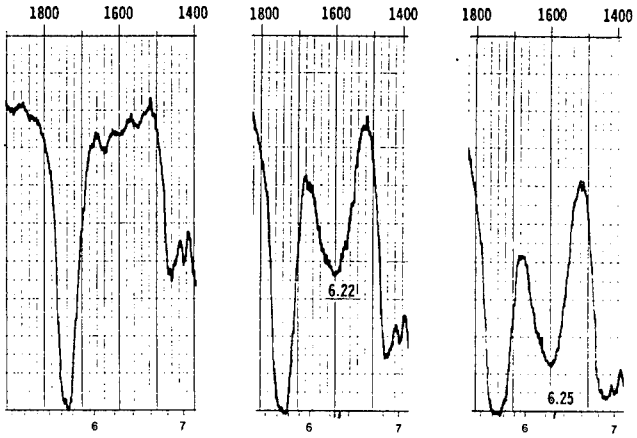
60.0	Paraplex 340
40.0	Paraplex 701
150.0	Camel Wite
2.5	Marinco H-1241
5.0	Metallic Stearate

EFFECT OF MARINCO H-1241 ON VISCOSITY OF POLYESTER
AND INFRA RED SPECTRUM OF POLYESTER 281-169
IMMEDIATELY AFTER MIXING



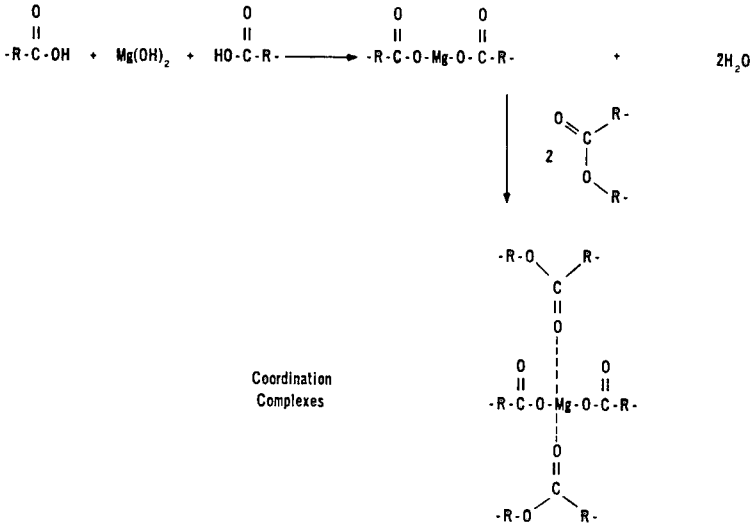
Concentration %	0	1	3	5
Initial Viscosity	614	501	659	715

EFFECT OF MARINCO H-1241 ON VISCOSITY OF POLYESTER AND INFRA RED SPECTRA OF POLYESTER 281-169 AFTER 4 DAYS



Concentration %	1	3	5
Brookfield Viscosity (cps)	929	35,000	160,000

REACTION OF MAGNESIUM HYDROXIDE WITH POLYESTER TERMINAL CARBOXYLIC ACID GROUPS



METALLIC STEARATE AVERAGE PARTICLE SIZE COULTER COUNTER

Metallic Stearate	Average Particle Size Particle Weight Basis Microns
1. MAGNESIUM STEARATE K	9.05
2. ZINC STEARATE D	7.39
3. ZINC STEARATE C	6.21
4. ZINC STEARATE E	5.89
5. ZINC STEARATE X	5.77
6. MAGNESIUM STEARATE I	5.54
7. ZINC STEARATE A	4.80
8. ZINC STEARATE B	2.62
9. CALCIUM STEARATE F	2.26
10. CALCIUM STEARATE G	2.14
11. CALCIUM STEARATE H	2.02

ZINC STEARATES VISCOSITY EFFECTS EFFECT OF pH, PARTICLE SIZE, FREE FATTY ACID

Zinc Stearate	Viscosity 3 Hrs.	Viscosity 7 Days	pH	Particle Size	% FFA
A	15,600	68,000	5.8	4.80	4.40
C	17,200	93,000	7.1	6.21	0.47
E	16,800	94,000	7.7	5.89	1.70
D	17,000	122,000	7.9	7.39	1.40
B	24,000	146,000	9.1	2.62	0.61

EFFECT OF TALLOW ACID ON THE VISCOSITY OF POLYESTER FORMULATION

TALLOW ACID	INITIAL	3 HOURS	1 DAY	4 DAYS	7 DAYS
0%	10,400	18,000	58,400	81,200	104,000
1%	11,400	18,600	63,200	83,600	104,000
3%	11,300	17,800	62,400	89,700	117,000
5%	11,000	17,400	67,800	93,900	120,000
7%	10,400	15,000	60,600	88,800	117,000
9%	10,800	17,200	54,600	82,300	110,000

FORMULATION:

100	Poly(diethylene adipate) A.N. = 71
150	Camel Wite
2.5	Marinco H-1241
3.0	Zinc Stearate A
0% to 9%	Free Fatty Acid (based on Zinc Stearate A)

THERMOFORMED SHEET PLASTICS FOR INTERIOR COMPONENTS

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Introduction

In this paper I will attempt to outline some of the experiences of the firm I work for, GOR of Turin, with thermoformed sheet plastics for interior body trim.

These experiences have matured at first in an essentially Italian motor industry context, but from 1976 have been considerably enriched by the work which directly, or indirectly through our licencees, has been progressively undertaken in Brazil, France, Spain, Germany, Japan, England and the U.S.A.

Trends of some importance to us in the Car Industry

Though the trend may appear more or less strong, depending on the specific manufacture or country, still the motor trade greatest overall concerns today are weight reduction for improved mileage and reinforced by the fact that increasingly stringent safety, emission and noise control standards, have tended to add weight to the average car (estimated at 300-350 lbs for the average USA car). Again market resistance has not led to the drastic reduction in car size that was initially predicted at the beginning of the petrol crisis.

Today, therefore, the market for plastics in cars is expanding rapidly; in Detroit for example, the 1973 models had this plastic content weight:-

Compacts and sub-compacts	105 lbs
Speciality cars	160 lbs
Intermediate and standard cars	150 lbs

By 1978 the plastic total for Detroit's average car was 190 lbs, with an estimated 10 lbs yearly rise up to and including 1980.

Again one has to note that at times the need to maintain costs while reducing weight have been contradictory aims, and the industry's often singleminded concentration on cost control, has provided a barrier to large scale substitution of plastics for other low cost materials.

If the above-mentioned needs have been the prime movers of the car industry requirement, we should not forget two additional important trends:-

(1) Styling evolution (often the result of increasingly stiff competition)
(2) Labour costs and resistence to some materials (such as fiber glass) by line workers.

(1) It is perhaps useful to mention almost randomly some of the developments in car design that have had or will have significant potential relevance to thermoformed sheet plastics for interior components.

In the last few years an increasing number of models (even in the luxury class Rover, Lancia, etc.), have moved to a three or five door design, therefore creating a market for a pivoted rear shelf of often sizeable proportions, and giving greater imortance to the overall look and trim material of its underside and boot.

The attempt to make the most of interior space, pioneered by the Mini's hollow door concept, has led to a wide acceptance and design of the new type of door and side panels, which can achieve some of the same effect in a more luxurious context.

The increasing importance of safety in interior car design has led to the virtual covering of all metal parts with moulded components, and tend to priviledge collapsible shaped forms as opposed to flat rigid panels.

The industry is continually engaged in an upgrading of its interiors, both in terms of shape and the type of finishes and fabric used.

We note a move away from all cold looking parts to the use of increasingly rich fabrics. Softness to the touch is also much valued by today's car purchasers.

The industry tends to offer a variety of models and finishes on the same framework, and last but not least, the industry is switching to frequent restylings; both trends which put flexibility of finishes at a premium.

(2) The escalation in labour costs seems to push car manufacturers to transform themselves in assemblers of bought-in components.

Rejection of some materials by line workers, as well as labour saving orientation, has created a market for ready for mounting one-piece headliners.

In house door panel finishing is on a decrease.

These, in an obviously brief outline, seem to be some of the problems and opportunities which have been and are being met. This paper is not an encyclopedic outline of all possible solutions, and not even an outline of all possible solutions using thermoformed plastic sheet, but a review of our specific attemps, in the hope that our specific experience may have enough points of general use and application to be of general interest.

Again, our choice and development of a specific thermoplastic sheet and a technology for its use are by no means the only possible ones, but are partly the result of historic circumstances and the application of a philosophy orientated to simplicity and flexibility.

THE THERMOPLASTIC SHEET WE DEVELOPED AND USE

We soon realised that the market could not offer us a thermoformed sheet which could respond to all of the specific requirements of the Italian car industry and our own production philosophy. We wanted a sheet with multiple applications with, if possible, only one transformation technology, easy to use, flexible in its finishes, and which could lead to the manufacture of finished components with one-step production whenever possible.

We adopted PP both for its physical characteristics, availability and cost.

It was well known that certain types of fillers had been developed for incorporation into PP to achieve benefits

in such physical properties as for instance stiffness and heat distortion characteristics. However, the price of such composites is often high because of the costs of compounding which offsets the cost advantage of the fillers, and moreover increased properties are achieved with an often unfavourable weight ratio, both in terms of the original thermoplastics but even more if compared with some of the possible non-thermoformable competitors (paper board, wood fibres and phenolics, etc.)

We thus chose wood flour as a filler, both for its universal availability, cost, and its low-bulk density of 0,6 g./cc, giving an obvious weight advantage from the point of view of the final weight of the car.

In addition, it appeared from our first tests that the thermoformable sheet produced with a 50/50 compound had better sound insulating properties than composites with more conventional fillers, whilst the balance of physical properties were those desired by FIAT:-

A stiffness comparable to rigid PVC.
Good abrasion resistance.
Good heat distortion properties.
Adequate flexural strength and impact resistance to withstand the assembly operations in the plant and guarantee satisfactory performance during the expected normal life of a car.

Further tests showed that the physical properties remain unchanged in a humid environment.

A table is set out at the end of this paper outlining some of the PP/Wood flour-sheet (our brand name - Wood-Stock) properties . In particular shold be noted a notable increase in rigidity and very good dimensional stability at temperature. The rigidity of Wood-Stock is about 7-8 times that of unfilled PP at 100%.
Again important is the good behaviour of the material even without the addition of a flame retardant to burning velocity tests.

An important point in our decisions was the concern to maintain low initial production investment and so, though Wood-Stock can be calandred, the majority of Wood-Stock produced in the world is extruded (both processes have been patented).

Finally, though Wood-Stock is normally a 50/50 compound with the above characteristics, a number of Wood-Stock sheets with different wood flour/PP percentages or additives are produced to meet all problems we have so far encountered.

THE PRODUCTION OF FINISHED PARTS WITH WOOD-STOCK SHEETS.

The most suitable technology for all the above aims we felt was compression forming, which also had the advantage with high universal familiarity. It was adopted as our only transformation technology, whatever the part that had to be made.

The process and Working Conditions

(1) The temperature of Wood-Stock must be raised to about 190°C so that it may be worked at 165°C.

Pre-heating can take place by

Infra-red lamps in an oven with either a mobile belt or moveable plane.

Heating planes (electric)

Hot air

(2) Press forming takes place by the pressure of cooled moulds; Wood-Stock is formed when is has reached a temperature of 165°C, and the formed part is extracted within cycle times of about 1 minute. Used pressures vary between 4 to 20 Kilos/cm2 depending on shape of object and the type of surface required.

First orders were obtained in 1975 and were for naked door panels, on which PVC could then be welded, or which could subsequently be finished by foaming. The orders were awarded by Lancia and Alfa Romeo; direct competitors were hardboard and paper board. An acrylic resinated fibre mat applied at the extrusion stage of the thermoformable sheet solved both welding and poliurethane foam adhesion problems.

Steel water-cooled tools with integral perimetral blades and punches provided the technology for finished parts in simple one-stage operations.

The next market we turned to was that for supported rear shelves with an embossed finish. The main competitor was vacuum pulled ABS. Steel tools with embossed surfaces were used, with integral blades and punches. Coloured grades of the sheet were developed, and for small-batch production paints compatable with the material were researched and obtained. Orders were won from FIAT. In 1976 FIAT adopted non-woven materials as the interior finish for its 126 and 127 model range.

We developed a technology for simultaneous forming, coupling, trimming and punching of thermoformed sheets and non-woven textiles. Bonding problems were solved by the coupling of an adhesive film to the Wood-Stock sheet at the extrusion stage: an expanded foam sheet can and has been added to the rear of the panels within the one operation press cycle. Bonding is partly by fusion, partly mechanical.

This technology has then been applied to the manufacture of a wide variety of components, amongst which supportes textile finished rear shelves take pride of place. Competitors were ABS, fire board, paper board, press-stock, etc.

In 1977 at our Brazilian plant for GM and at our Italian plant for the FIAT Strada, work began for the simultaneous lamination and forming of a PVC and Wood-Stock sheet. Bonding problems were solved either by the use of sprayed adhesives, or by the use of a film on the thermoplastic sheet if the PVC is supported. Alternative methods are under study at the moment.

A specific technical problem encountered both on the Strada and on VW's panels has been the need to trim the thermoplastic panels but not the PVC to allow it to be folded over and pinned or glued around the edges. A special steel tool which allows simultaneous coupling, forming, punching and trimming of supporting panels, leaving covering fabric uncut or trimmed around a wider perimeter, was developed and patented. Press cycle about one minute.

Again in 1977 development took place for VW's Golf, FIAT 127 and Ritmo for a hinged fabric covered rear shelf. The insertion of a pivotal hollow bar between two sheets of Wood-Stock have provided increased rigidity, and pivotal points. Today, hinged rear shelves with fabric top and bottom are produced in one press operation by two workers on a 1,5 minute cycle.

In 1978 we developed a perforated Wood-Stock sheet with one-piece headliners can be produced with very good acoustic properties. Orders have been won with Peugeot and FIAT's heavy goods vehicles.

In 1978 we also entered into production in Brazil for FIAT and VW with dashboards with a core of Wood-Stock in replacement of metal ones. Both are two-part boxed (for air ducts and strenght) constructions,ultrasonic welded together, giving a finished piece which achieves high standards of lightness and safety.

CONCLUSIONS

This has been a brief outline of the development of one technology for the production of interior panels from thermoformable plastic sheets. We have been single mindedly committed to it because of the advantages it seems to offer both to us and to the car manufacturer, and we believe also to the end user of the finished car. The benefits are:-

Only one material used - this is an aid also to the car producer

Only one easy one-step technology

With the same moulds a variety of finishes can be applied

Door panels and dashboards made with thermoformable plastic are safer in a collision than traditional components.

There is no danger of pollution or harm to workers in the productive process

The technology gives greater scope to the stylists, especially in the design of door panels

The lightness of the material helps to keep price and weight down.

To conclude, it is perhaps useful to mention two additional qualities of the technology:-

(1) Press forming can be achieved with epoxy, aluminium, steel or hybrid tools, thus allowing prototypes to be quickly made and tooling costs to be tailored to the quantities to be produced.

(2) Increasingly the problem of re-cycling finished parts is going to become crucial. Already we can re-cycle all our parts made with non-wovens, and we have under study the possibility of re-cycling up to 70% of our end product.

The use of thermoformable sheets for interior panels is just beginning; from our experience, its scope is truly enormous.

W O O D - S T O C K

Properties of Wood-Stock Sheet

Test	Method	Units	Result 2.4 mm Wood-Stock Sheet
Density	ASTM D792-66	gms/cm3	0.95-1.10
Melt Flow Index	ASTM D1238-73 190°C/10 Kg	gms/10 mins	1.0
Drop Weight Impact Strenght	BS2782:306B	ft lb	Dependent on Surface Material
Flexural Moduls	ASTM D790-71	N/mm2	3398
Tensile Strenght	ASTM D638/77	N/mm2	15.5
Elongation at Break	ASTM D638/77	%	3.5
Heat Distortion Temperature	ASTM D648/72	°C at 0.45 MN/M2	120
Rockwell Hardness	ASTM D785-76	R Scale	77
Shrinkage Test	180°C on fine sand 5 mins	%	No Change
Water Absorption	24 hours at 23°C 100 hours at 23°C	%	+ 1.5 + 3.5

DEVELOPING AND PROCESSING OIL PANS WITH STAMPABLE PLASTICS

ROBERT R. BRAIN

CADILLAC MOTOR CAR DIVISION

GENERAL MOTORS CORPORATION

INTRODUCTION

The purpose of this paper is to present Cadillac Motor Car Division's development of a stampable glass reinforced nylon oil pan. This report will highlight the reason for selecting a nylon stampable plastic, development of the manufacturing process, and experience to date.

REASON FOR PLASTIC OIL PAN PROJECT

As the automobile industry moves into the 1980's, it faces increasingly stringent regulations concerning safety, emissions, and mileage. The Federal Corporate Average Fuel Economy (C.A.F.E.) Standards took effect with the 1978 model year with a fleet fuel economy requirement of 18 m.p.g. (7.65 km/l), with yearly increases thereafter, eventually culminating in a fleet average of 27.5 m.p.g. (11.69 km/l) for the 1985 model year (illustration #1). In order to meet this standard, General Motors Corporation, and therefore Cadillac Motor Car Division, has embarked on a program of engineering improvement coupled with vehicle weight reduction.

In order to apply the favorable weight characteristics of plastics, Cadillac has been examining a variety of applications...including the manufacturing of a plastic oil pan. One material that looked promising was a newly developed nylon-based material from Allied Chemical called STX 363 (STX is an Allied Chemical Company trade name). This material possesses excellent temperature stability and impact resistance as well as forming characteristics that are well suited to engine/transmission oil pan applications.

Initial investigation of a nylon oil pan originated with the 1976 model DeVille. While vehicle tests were promising, the project was not pursued due to cost ineffectiveness when compared to the existing one-piece steel pan. However, with the weight reduction demands to increase vehicle mileage, more compact underhood packaging resulted. Oil pans with deep drawn sumps (illustration #2) were required to meet oil capacity requirements.

Due to forming limitations of steel, certain oil pan designs required multiple-piece weldments. In light of added manufacturing costs and potential weight advantage of plastic, with its lower specific gravity (illustration #3), development work on the nylon oil pan was accelerated.

CURRENT STATUS OF PLASTIC OIL PAN PROJECT

Preliminary testing of the deep draw plastic pan concept is completed. Dimensionally acceptable parts have been molded off of pilot tooling (illustration #4). The pans are currently on high mileage durability cars at the General Motors Proving Grounds, Milford, Michigan, and Cadillac Motor Car Division foresees production approval in the near future.

BASIC PROCESS AND FLOW DESCRIPTION

The conventional material for the construction of an oil pan is steel. When the design of the oil pan necessitates processing the pan in multiple pieces from steel (such as in the case of a deep draw oil pan), it results in a very complex and costly manufacturing process (illustration #5). In order to process a typical two-piece steel pan, 12 dies, two welders, and 18 operations are necessary.

A similar plastic pan, on the other hand, involves relatively few operations in the process (illustration #6). Only one die and four operations are necessary in the manufacturing process. The resultant reduction in assembly costs and capital expenditure allows for a potential 33% per car cost savings over the two-piece steel design.

DESCRIPTION OF STX 363

Since usage of STX 363 in the plastics industry is not widespread, the material properties of this glass reinforced polymer will be discussed.

The material used for the development has the Allied Chemical designation of STX 363 (hereafter simply referred to as STX). It is a structural grade material (as opposed to an appearance grade) supplied in sheet form. The sheet is a multi-ply lamination consisting of filled Nylon 6 and a continuous fiberglass non-woven mat (illustration #7).

There are three constituents in the STX sheet: resin (50%), mineral filler (17%), and fiberglass reinforcement (33%). At least half of the fiberglass reinforcement is continuous strand, with the remainder being short chopped fiber about 3 mm (1/8 inch) in length. The polymer consituent, Nylon 6, serves as the matrix of the composite sheet. A mineral filler is added to increase the flexural modulus and reduce material cost.

It is the continuous fibrous reinforcement that distinguishes this thermo-formed material from typical nylon glass filled polymers used in injection molding. In addition to random 3 mm (1/8 inch) short strand fiberglass, a continuous strand fiberglass mat is sandwiched between the nylon layers. This combination gives the material inherent isotropic physical properties (equal on all axis) together with excellent heat and creep resistance and minimum water absorption.

OTHER MATERIAL CONSIDERATION

Other materials investigated for the oil pan application included: SMC, glass reinforced stamped polypropylene, and aluminum.

Sheet Molding Compound

In 1971, Cadillac considered Sheet Molding Compound (SMC) as an alternative to steel in oil pan application for the 8.2 liter (500 cubic inch) Eldorado engine. The use of SMC was not pursued because of sealing difficulties and cost ineffectiveness. Compared to a nylon-stamped thermoplastic material, thermoset SMC has a process cycle time two to three times greater. If compounded in-house, SMC also requires a large cure room, special handling of the uncured SMC rolls, and added concerns with styrene emissions.

Glass Reinforced Stampable Polypropylene

A glass reinforced stampable polypropylene was also considered. However, high engine oil temperatures adversely affected its physical properties.

Aluminum

Aluminum possesses many of the same disadvantages of steel (component assembly, high capital expenditure, etc.) as well as poor formability. Aluminum's drawability is significantly less than steel; it is more difficult to weld (higher power levels, porosity, etc.); and it has poor dent resistance. Also, the aluminum weldment would require corrosion protection, and pose a problem in assembling a drain plug nut that would withstand sufficient torsional load without stripping.

CADILLAC'S ACTUAL EXPERIENCE

As was stated earlier, Cadillac's experience with stampable nylon began in the 1976 model year on the DeVille series. This section will describe these experiences in more detail including areas such as part design, mold design, blank development, blank heating, blank handling, stamping and Product Engineering testing.

Part Design

Stampable plastics offered Cadillac product engineers both the opportunity to obtain a more integrated product (illustration #8) as well as a potential 50% (2.5 kg) weight reduction over steel designs.

The oil pan wall thickness design was varied to strengthen high impact areas. Since STX derives its isotripic mechanical properties from the fiberglass mat, wall thickness changes were gradual and care was taken to avoid very thin sections that would not allow the long fibers to readily flow.

An advance which was crucial to the development program in 1976 was the molded-in drain plug nut. With any assembled component, proper sealing and torque retention were continual problems. These concerns were overcome through use of a hardened square steel molded-in nut (illustration #9).

In the first generation of plastic pans, the standard steel wall thickness of 1.52 mm (0.060 inch) was increased to 2.54 mm (0.100 inch). In high impact areas, wall thickness was increased to 3.8 mm (0.150 inch). The design at this point was identical to the steel pan except for the thicker walls and application of RTV (room temperature vulcanized)sealent to the pan face. Ribs were also added to strengthen the pan rail. Under performance test conditions, however, this design permitted oil leakage at the crank seal area, where conventional rubber seals were used. Because of the high tensile loads necessary to secure the rubber seals, cracks occurred along both ends of the pan (illustration #10).

The second generation design replaced conventional rubber seals at both ends of the pan with RTV sealent applied continuously from the pan rail.

While RTV sealent solved the problem of pan deflection, oil sealing was still inadequate. Further investigation found the difference in thermal expansion characteristics between the nylon pan and the cast iron engine block to be the cause of the sealing problem. To remedy this situation, a "groove" was designed into all the RTV sealing areas, which successfully sealed the pan (illustration #11). Presently, production plans are to apply RTV automatically to the pan rail face during engine assembly.

Mold Design

Stampable plastic mold design is the combination of sheet metal stamping and injection molding technology. In order to produce a plastic part with little or no finishing operations, a number of specific features were included in the mold design.

The first of these is the concept of a mold with a variable volume, as opposed to a fixed volume injection molding tool. The mold was designed so that all available pressure from the press is on the blank, not on stops or pressure relief devices. This was because all the pressure necessary to flow the material must come from the difference in cavity volume. In order to accomplish this, the mold was equipped with telescoping shear edges together with stops, which prevent metal-to-metal contact if a short charge condition exists. The actual shut-off or telescoping shear edge has a clearance of 0.04 mm (0.0015 inch) to 0.05 mm (0.002 inch) (illustration #12). If this tolerance is not maintained, flashing will occur allowing the mold halves to come closer than intended.

Stamping presses frequently allow platen wander. This necessitates that the mold provide its own guidance during closing and contain the lateral forces from stamping the asymmetrical pan. These features were incorporated into the mold design with heavy guide pins and heel blocks (illustration #13).

Other than guidance provisions, the mold design specifications parallel those of most conventional injection molds. The mold ejector system consists of integral cylinders constructed into the core half to minimize the mold open space requirement. The shear edge was flame hardened to approximately 45 - 60 R_C, with the balance of the tool constructed of P20 steel or equivalent.

The mold operates at the elevated temperature of approximately 121 C (250 F). Temperature is maintained by means of temperature control lines and an oil heater/chiller (one set per mold half). (Note: The unit is considered a heater/chiller because to start production, the mold must be brought from ambient to operating temperature, and after a few cycles, there is enough heat rejection from the approximately 228 C (550 F) blanks to make chilling necessary).

Temperature control lines about 13 mm (1/2 inch) in diameter were gun-drilled in steel tooling approximately 13 mm (1/2 inch) below the surface and 153 mm (6 inches) apart. Hot oil or synthetic fluid is then pumped through the tool at a high volumetric flow rate to optimize heat transfer conditions (illustration #13).

Mold venting was necessary to allow the displacement of air as the press closes. This was accomplished by grinding 0.01 mm (0.005 inch) depth flats on the ejector pins, and by allowing air passage through the telescoping shear edge.

Pan face mounting holes were pierced rather than molded. This was to avoid interruptions to the flow of fiberglass into the pan area. This area is very critical for sealing purposes, so maximum strength with minimum distortion was desired.

Finally, as was mentioned in "Part Design," was the incorporation of the "molded-in" drain plug nut. A long pin attached to a cylinder was incorporated into the tool. During stamping, the pin protrudes to locate the nut and also block the flow of plastic into the nut's threads. At the end of the cycle, just prior to ejection, the pin retracts, allowing ejection of the pan (illustration #14).

Blank Development

Blank development is a very important phase of STX stamping. Blank layout should be developed to:

- provide fast cycle times
- minimize material flow over long distances
- avoid knit lines
- facilitate material handling
- minimize press tonnage

STX blanks are presently limited to a width of about 590 mm (23 inches). Actual oil pan blank dimensions were determined at the prototype mold tryout (approximately 300 mm (12 inches) wide by 600 mm (24 inches) long).

Blank thickness is related to heating time (more detail in the following section concerning blank heating). Rather than increase the thickness of the blank and consequent heating duration, two heated blanks, 4.58 mm (0.180 inches) thick, were stacked on top of one another to achieve the desired charge geometry and weight. This simplifies the automation and material handling requirements especially since two identical blanks are used.

Blank Heating

Blank heating is performed with an infrared oven using elements emitting radiation between one and six microns in wavelength. The blank temperature is raised about 37 C (100 F) above its melting point (213 - 218 C or 415 - 420 F).

To minimize the temperature differential between the interior and surface of the blank, a pulsed high-low heating cycle was used. This yields a more uniform, although longer, cycle (illustration #15).

The conveyor system of the oven is still under development. At present, a stainless steel conveyor using 1.59 mm (1/16 inch) rods spaced 6.35 mm (1/4 inch) apart on an axis perpendicular to conveyor travel are used in order to allow the top and bottom of the blank to heat simultaneously. However, blank adhesion poses a problem which is still not resolved, and will be covered in more detail in the next section.

Material Handling

There are three aspects of stampable plastics handling which Cadillac is attempting to automate (currently done manually):

1. Loading blanks into the oven
2. Unloading the blank from the oven and placing it into the tool
3. Unloading the part from the press

The first and last phases pose no problems, for technology currently exists to perform the operation. The second step, unloading the hot blank from the oven poses the most difficulty. As mentioned previously, the stumbling block involves blank adhesion to the oven conveyor. Upon reaching the stamping temperature, the blank assumes a viscous, sticky mass held together by the fiberglass mat (an image which comes to mind is a material of "pizza dough" consistency). Many alternatives are being examined, although the current approach centers on utilizing a thin "veil" of non-wetted fiberglass which would fully wet during stamping. Development continues.

Stamping

In general, plastic stamping seems to have few specific demands, and some advantages as compared to other plastic processes. The most significant benefit is that standard mechanical and hydraulic presses can be utilized to perform this operation.

The necessary press sequence is: rapid close, rapid full press pressure build-up, dwell, slow open, and rapid open. In the mechanical press, this dwell is accomplished by disengaging the clutch as the press nears bottom, and engaging again at the termination of the dwell phase. Hydraulic presses have the distinct advantage of always being on "bottom dead center." Cadillac opted for hydraulic presses because mechanical ones demand accurate set-up and close blank weight tolerance.

Cadillac has found that press specifications should include:

1. Rapid closing speed to minimize blank heat loss before forming.
2. Continuous pressure application to avoid a frozen flow front.
3. Sufficient tonnage to insure proper packing of the part.

Product Engineering Testing

Testing on cars has been on-going since 1976. Concern was expressed for the pan's ability to withstand the high temperatures observed in the field, and possible increase in engine oil temperature because of the insulation effect of the plastic. In both instances, no detrimental results were noted at the Desert Proving Grounds in Phoenix, Arizona, where temperatures on the oil pan reached as high as 176 C (350 F).

In addition to other impact and performance tests, parts were sectioned, glass burn-outs performed, and X-ray photographs taken to check for knit lines, porosity, voids, glass content and orientation. All testing to date has yielded no foreseeable problems.

CONCLUSIONS

With the increasing demands for weight reduction of tomorrow's automobiles, we expect reinforced nylon thermo-formed plastic to be a viable candidate for future oil pans.

The future also looks promising for other automotive applications such as: torque chain covers, decklid inners, fender extensions, load floors, brake dust covers, rear deifferential covers, and engine accessory bracketry.

ACKNOWLEDGMENTS

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Mr. Robert R. Brain is currently Assistant Master Mechanic of Process Engineering - Plastic and Sheet Metal Fabrication, Cadillac Motor Car Division. Mr. Brain began his career at Cadillac in 1959 when he enrolled at General Motors Institute. He received his BSME degree from G.M.I. in 1964.

In addition to working in Cost Estimating and serving as a Commissioned Officer in the U.S. Navy, Bob worked as a Tool Engineer over final assembly, painting and plating, and axle machining. He became an Engineering Supervisor - Engine/Axle Machining in 1972. In 1975, he assumed supervisory responsibility over Final Assembly Tooling and held that position until his present appointment in 1977.

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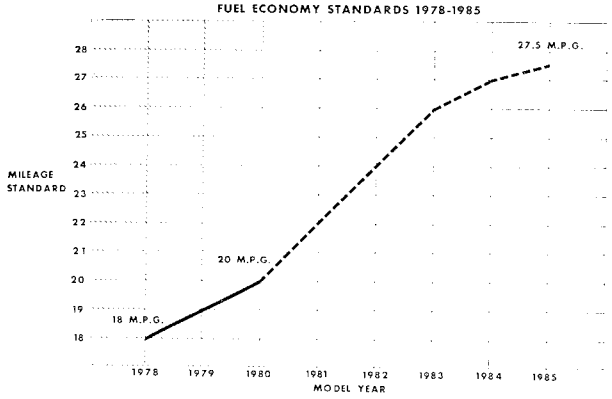
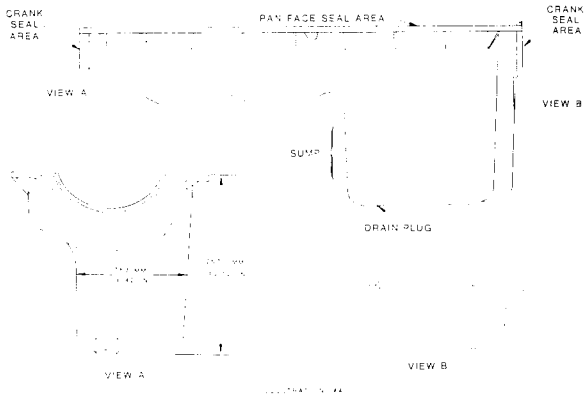
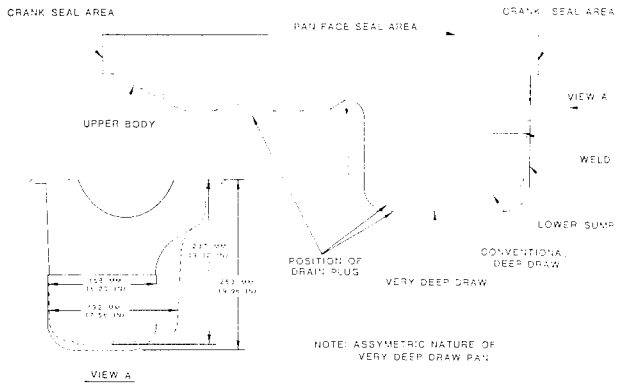
FEDERAL CORPORATE AVERAGE
FUEL ECONOMY STANDARDS 1978-1985



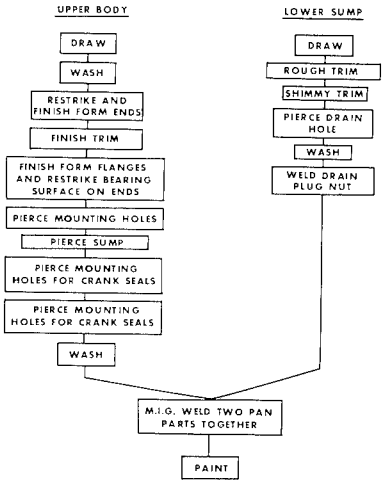
FUTURE MODEL PLASTIC OIL PAN



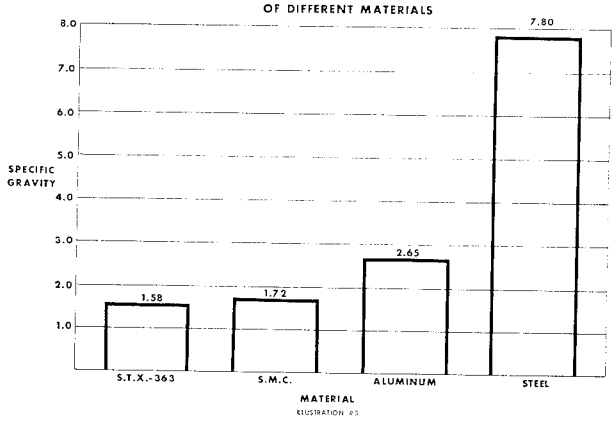
COMPARISON OF DEEP AND
VERY DEEP DRAW SUMP DEPTHS



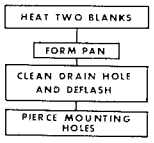
TWO PIECE STEEL OIL PAN PROCESS



SPECIFIC GRAVITY COMPARISON
OF DIFFERENT MATERIALS



NYLON OIL PAN PROCESS



DELAMINATED STX SHEET DETAILS

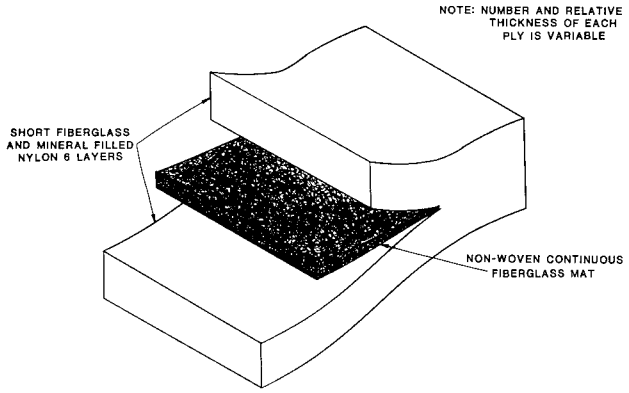


ILLUSTRATION #7

COMPARISON OF PARTS NECESSARY TO CONSTRUCT STEEL AND PLASTIC OIL PAN

EXPERIMENTAL PLASTIC OIL PAN PROBLEM SEALING AREAS

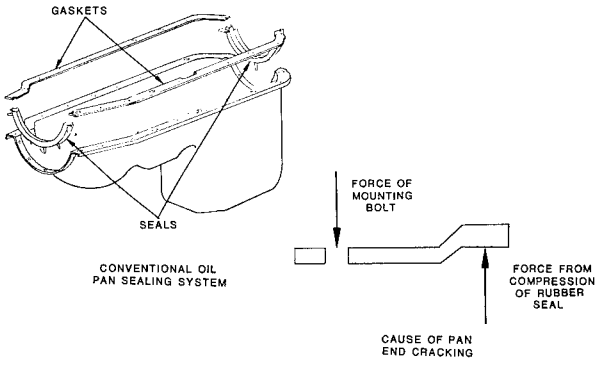


ILLUSTRATION #10

PLASTIC OIL PAN SEALING DETAILS

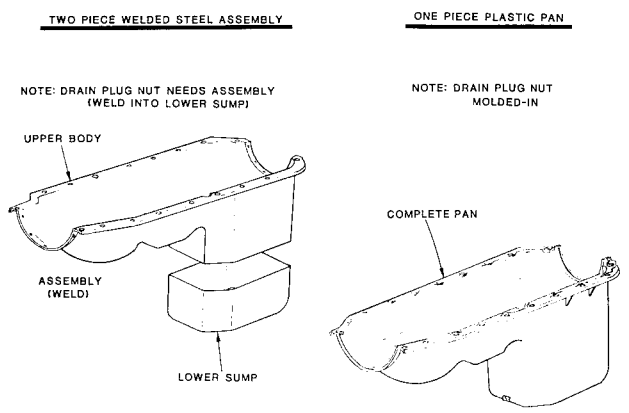


ILLUSTRATION #8

PLASTIC OIL PAN DESIGN FEATURES

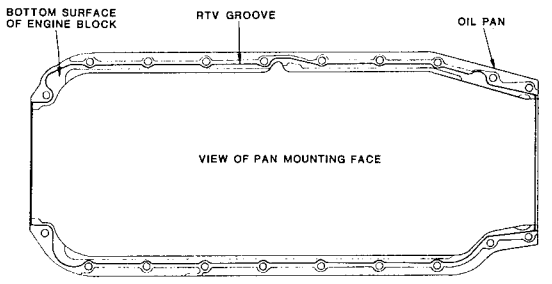


ILLUSTRATION #11

TELESCOPING SHEAR EDGE DETAILS

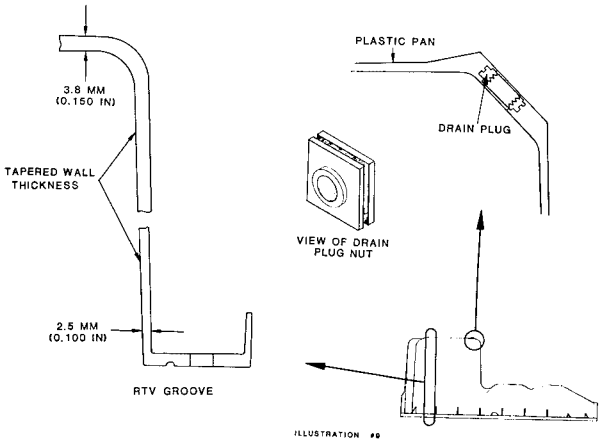


ILLUSTRATION #9

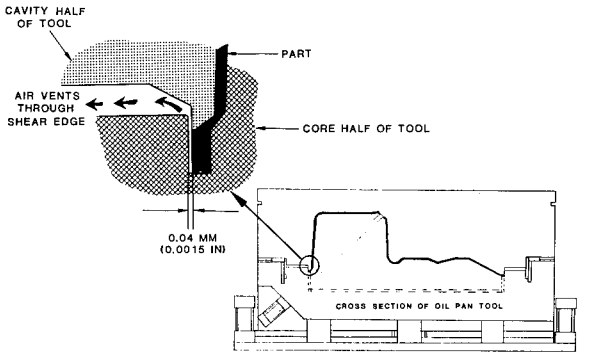


ILLUSTRATION #12

HEEL BLOCK AND MOLD HEATING DETAILS

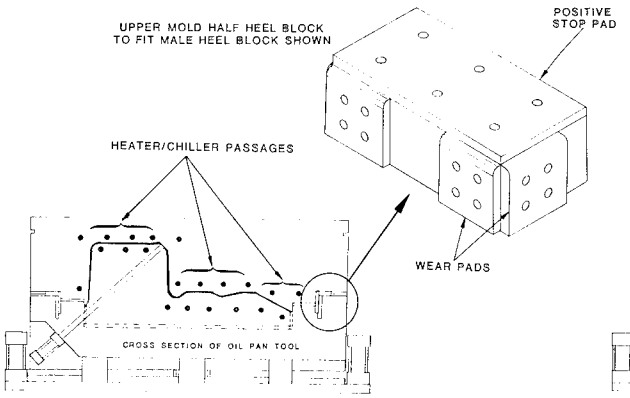


ILLUSTRATION #13

OIL DRAIN PLUG NUT RETAINING PIN DETAILS

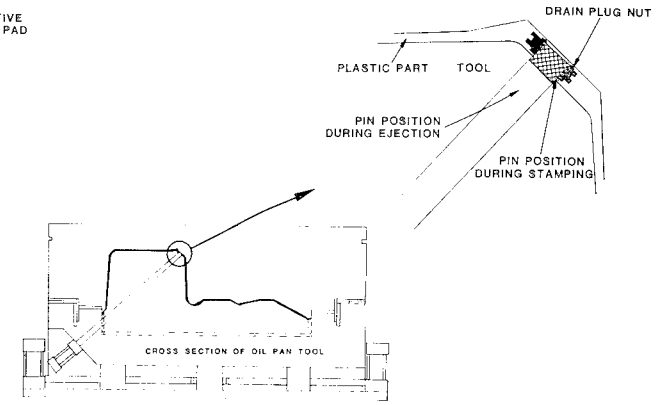


ILLUSTRATION #14

TEMPERATURE vs. PULSED HEATING TIME

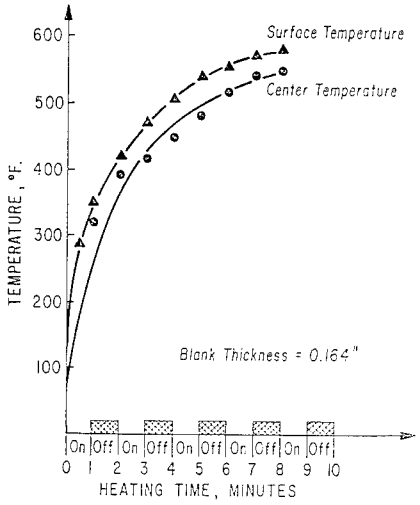


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ILLUSTRATION #15

THE DEVELOPMENT OF A BLOW MOLDED VACUUM RESERVOIR

Dennis N. Tino

Plastics, Paint and Vinyl Division

FORD MOTOR COMPANY

THE DEVELOPMENT OF A BLOW MOLDED VACUUM RESERVOIR

Introduction

The incorporation of new plastics applications for transportation in the '80's will be based on varying trade-offs of weight reduction, cost and functional improvements. Those applications offering advantages in all three of these categories will be sought after and adopted quickly. Next likely to be chosen are the "big" lightweight plastic opportunities at parity or nominal cost penalties. And finally, the smaller, less cost/weight efficient opportunities will be adopted as required to meet increasingly difficult weight reduction requirements.

This paper describes the development of a relatively large vacuum reservoir fabricated in blow molded polypropylene. The function of this reservoir is to provide a vacuum reserve for the actuation of headlamp doors on luxury vehicles. (Figure 1) In contrast to previous smaller plastic reservoir applications, this reservoir has a volumetric capacity of 500 cubic inches (8195 cm^3).

The objective of utilizing plastic was to achieve weight savings compared to welded steel. Two piece injection molded plastic construction would result in increased complexity and questionable reliability due to potential leak paths at the sealed joint line. Also, as with all high volume applications, piece cost was an important consideration. Prior experience had indicated that so called "engineering resins" with high temperature resistance were required to withstand implosion at vacuum levels of 27 inches of mercury (13.3 psi; 92 Pa) and elevated temperatures. Since these higher priced resins would not be cost efficient, the challenge was clear: develop a large volume container in a commodity priced resin to withstand the specified functional requirements.

Functional Requirements

Product Engineering established the following key performance requirements:

1. Loss of not more than 2 in. Hg. over a 24 hour period when set initially at 20 in. Hg. under the following conditions:
   - Room temperature
   - Soaking at 220°F for a minimum of 16 hours
   - Soaking at -20°F for a minimum of 6 hours
   - After aging for 1,000 hours at 250°F

Functional Requirements - continued

2. Inlet/outlet stem must maintain a vacuum of 27 inches of mercury at room temperature when loaded radially with a 50 lb. (22.68 kg.) load.

In addition, durability bench cycling and rough road vehicle durability cycling were required.

Packaging the reservoir was critical and involved the following considerations:

1. Volumetric requirements: 500 in^3 (8195 cm^3)
2. Location: outside of engine compartment between the fender and wheel apron.
3. Inlet/outlet nozzle: located for accessibility of installation and service.
4. Mounting provisions: limited access from beneath vehicle.

Concept Development

With the functional requirements and packaging criteria established, concept work was begun to develop a shape which met all the parameters. A smaller blow molded reservoir of a foreign vehicle utilized adjacent spheres with partial intersections providing a "waffle" shaped container. Unfortunately, this construction was too inefficient in terms of space/volume restrictions. Increasing the size of the spheres significantly increased the unit loading stress for a thin walled container. Calculations, based on a pressure vessel equations, indicated that a 7.25 in. (18.4 cm) dia. sphere would require a wall thickness of .150 inches (3.81 mm) in polypropylene. Polypropylene was selected because of the high temperature functional requirement and its excellent blow molding properties. Further calculations indicated that three spheres of this size in tandem would provide the required 500 $in.^3$ volumetric capacity. While the calculations were encouraging, the proof lay in actually testing parts, especially at elevated temperatures. The weight savings potential of one to two lbs. was enticing enough to warrant a low cost concept development tool. No provisions for attachment were incorporated in the tool in order that costs be minimized and a pure evaluation of the intersecting sphere concept could be made. (Figure 2)

Upon completion of the aluminum tool, initial parts were found to pass the leak test at room temperature. However, parts collapsed locally in the high temperature leak test. Sectioning of the failed parts indicated uneven wall thickness with a minimum thickness at the point of failure of only .12 inch (3.05 mm). Even-walled samples were obtained by modifying the blow molding machine extruder program. Also, parts of varying wall thicknesses were obtained to determine the minimum acceptable wall thickness. The second series of evaluations proved the reservoir to meet the leak

Concept Development - continued

test requirements. Testing indicated that a minimum wall thickness of .150 inch (3.81 mm) was required. A nominal wall thickness of .190 inch (4.83 mm) was established to assure that the minimum thickness would always be maintained.

Final Design

With the concept feasibility established the next step involved designing the attachments and inlet/outlet nozzle. The steel design which the plastic would replace had been designed with two screw attachments in different planes of the body sheet metal (Figure 3). A small tab served as a locator for installing the reservoir in the proper position. The fact that the two mounting planes were 90° apart and on the same side of the reservoir created an apparent molding problem. Another design concern was the weakening effect of mounting tabs interrupting the spherical surface.

Both potential problems were resolved through designing the tabs as truncated prisms. (Figure 4) This design approach minimized the mold halve kiss-off problem while providing a stiffening effect at the reservoir/tab intersections. Ribbing between the spheres provided additional stiffening while simplifying the post mold trimming operation. The upper locating tab was designed on the parting line resulting in a solid section approximately .150 inch (3.81 mm) thick.

Final packaging checks indicated a substandard clearance requiring a minor reorientation of the spheres. Consequently, the center line of the three spheres was changed from a straight line to a sweep.

Nozzle Design

The inlet nozzle was designed as a two piece injection molded nylon stem and rubber grommet assembly to achieve a virtually leak proof junction. (Figure 5) Nylon was chosen as the stem material to withstand the required 50 lb. (22.68 kg) side load and for impact strength. The neoprene rubber grommet provided retention of the stem to the reservoir with semi-rigid compliance to assure adequate sealing under side loading conditions.

Prototype Part Evaluation

A new aluminum mold was required to incorporate the final design configuration. Prototype parts were evaluated by conducting the basic leak tests prior to being subjected to more extensive performance testing. Additional tests conducted were as follows:

. Bench durability cycling - 40,000 cycles of evacuation to 20 in. Hg.
. Thermal cycle - Evacuate reservoir to 20" Hg. cycle three times: Room temperature for 24 hours; 220°F for 16 hours; -20°F for 16 hours.

Prototype Part Evaluation - continued

. Rough road durability.
. Induced vehicle vibration.
. 1000 hour heat aging at 250°F.

All tests were completed satisfactorily, indicating a high degree of confidence in meeting all field performance conditions.

Cost and Weight

Initial cost and weight estimates indicated savings of $1.40 and 1.0 lb. compared to the released .032 gauge terne plated steel part. However, by start of production the savings had been reduced to $.38 and .2 lb. due to gauge and plating changes incorporated in the steel design.

Summary and Conclusion

While the project investigation was successful in meeting cost, weight and performance objectives, other factors related to supply prevented production incorporation of the plastic part. Obvious economic benefits were achieved through precipitation of the more efficient steel design as a result of the plastic investigation. Also, valuable data was developed which will be available for future similar applications.

Acknowledgement

The author wishes to gratefully acknowledge the efforts of Mr. D. S. Silver of Ford Motor Company and the Winn-General Division of McCord Corporation for their extensive contributions to the blow molded reservoir project.

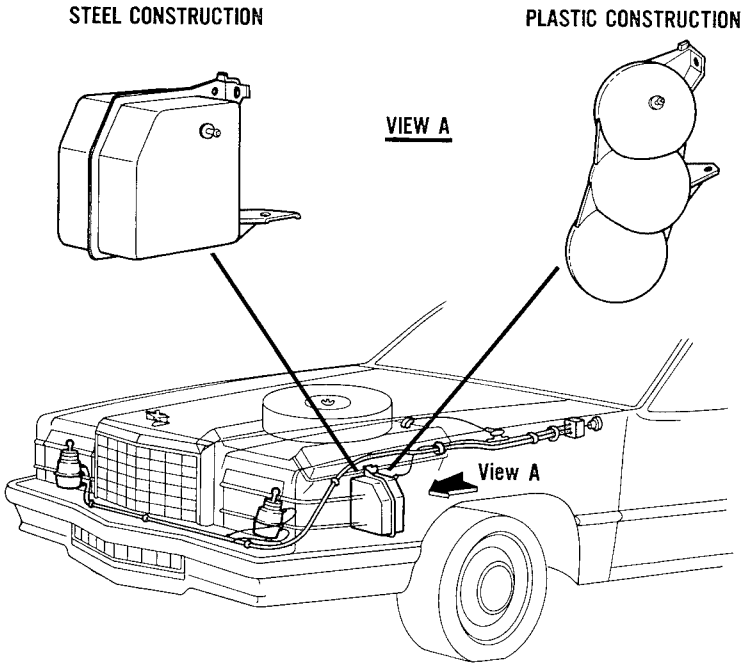

Figure 1

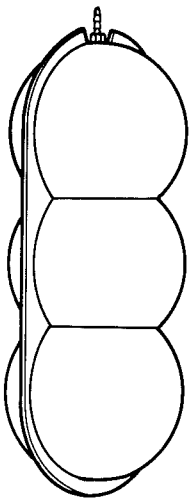

Figure 2
INTERSECTING SPHERE CONCEPT CONFIGURATION

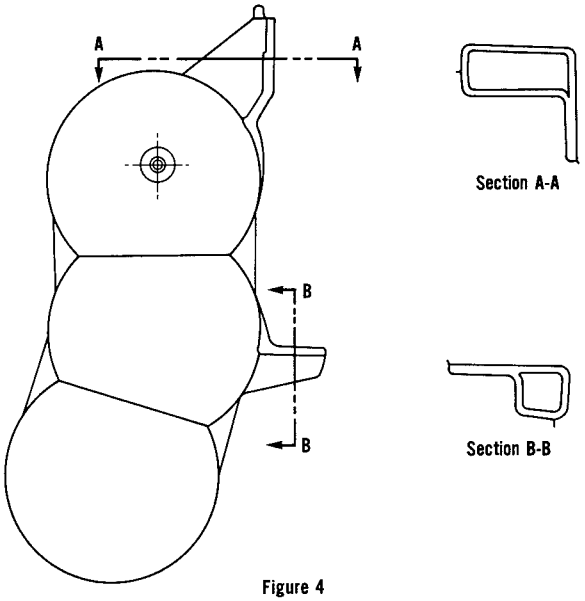

Figure 4
MOUNTING TAB DESIGN

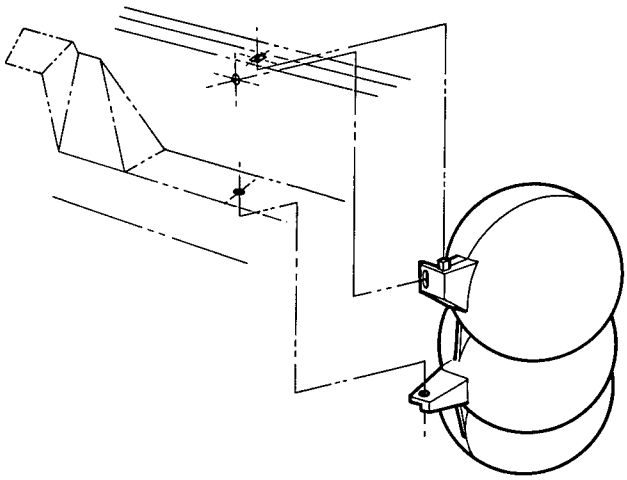

Figure 3
BODY MOUNTING CONDITION

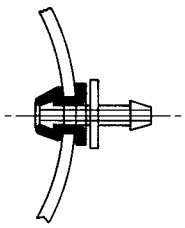

Figure 5
NOZZLE AND GROMMET ASSEMBLY

ABRASION RESISTANT/ ANTI-FRICTION TUBING IN AUTOMOTIVE PUSH-PULL ASSEMBLIES

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The design of modern automobiles frequently requires the transmission of control commands from one location to another. The controlling device --- either the driver, a mechanical device, or a computer --- must convey a motion to the relevant component in order to interface the driver with the vehicle. Examples of applications requiring such remote control include the throttle, clutch, shift mechanism, emergency brake, cruise control, hood release, heater controls, and remote mirrors. One of the easiest and most versatile ways of accomplishing these controls is with push-pull cable assemblies.

A typical high performance push-pull cable assembly consists of a wire cable riding inside abrasion-resistant, anti-friction (AR/AF) tubing, which is in turn protected by some combination of wire wraps, an outer extruded jacket and various end fittings. Although all components of the assembly can effect the performance, the AR/AF liner is the primary bearing surface, and in a good assembly will be the limiting factor. Since the most demanding and critical application is the throttle cable assembly, this paper will concentrate on this use,although the findings can be applied to others.

TUBING FRICTION AND WEAR

The crucial performance factors for push-pull liners are friction and wear. Friction in a throttle cable liner has a dual effect on driver fatigue, since higher friction materials require stronger return springs and the driver must overcome both forces. If friction becomes excessive, seizing can result, possibly causing accidents. Lower friction, however, can enable more versatility, increasing the functions and routing possible. The wear properties are also important, since a liner which wears through will cause metal to metal contact between the cable and the supportive wires and possible seizure. Another consideration is abrasion of the inner cable by the liner, which can cause strand failure and increasing friction.

In the tubing field, friction is usually measured in terms of frictional efficiency, defined as the ratio between a weight and the force necessary to raise the weight via the push-pull cable, expressed as a percent. Variations of this definition exist, but the concept is essentially the same. Efficiency can be correlated to another common measurement, coefficient of friction, although this is not a practical value for tubing applications. Basically, as friction increases, efficiency decreases and the coefficient of friction increases.

Wear of push-pull liners is frequently measured by the ability of a liner to survive a life cycle test without wearing through. With modern high-performance materials, this is insufficient to discriminate improvements or detect potential problems. A better technique for use with tubing is to measure weight loss in milligrams after life cycle testing. This can predict the potential life of a material beyond the limits of the test.

FRICTION AND WEAR TESTING

Testing of AR/AF tubing is crucial to its use. The complex nature of friction and wear requires that testing simulate as nearly as possible the end use for maximum validity. Tests designed for rotary bearings and thrust washers are irrelevant for tubing. Many specifications require a minimum initial efficiency and the ability to survive a life cycle test. These specifications are not sufficiently discriminating to insure predictable performance throughout the life of the liner. Additionally, most testers were found to be inadequate to distinguish consistently the effects of minor formulation changes. For these reasons, we developed an improved tester for push-pull cable liners.

The Markel Dynamic Efficiency and Wear Tester comprises an "S" shaped routing over two 8" cylinders for a total contact angle of 240° (See Figure 1). The tubing is secured while a 1/16", 7 x 7 stainless steel cable is reciprocated at 60 cycles/minute. Adjustable tensioning springs provide the return force through the 1-1/2" cycle. The wear test is carried out to 500,000 cycles, a value determined by actual measurements to be roughly equivalent to 80,000 miles of throttle use with a manual transmission in suburban driving. Efficiency checks are made at four cycles/minute with a five-pound weight in place of the springs. A load cell transducer and strip chart recorder are used for the force readings. The entire samples are enclosed in an oven chamber allowing testing at any temperature from -40 to +400°F. This allows simulation of any environment while obtaining efficiency data periodically throughout the wear test. All data presented in this paper was obtained on this machine, frequently with confirmation with other testers.

PTFE FRICTION AND WEAR PROPERTIES

Most modern high-performance push-pull cable assemblies use liners of polytetrafluoroethylene (PTFE or TFE). This material, often known by the DuPont trademark, "Teflon", has the best frictional properties of any polymer. In addition to extreme chemical inertness, PTFE can withstand temperatures of -400 to +500°F for non-mechanical applications. The useful temperature range of mechanical applications is probably narrower.

The frictional properties of a polymer are sometimes assumed to be material constants, but this is not the case. None of the classical "laws" of friction are obeyed by PTFE or other polymers. Actually, the friction is dependent on load, contact area, velocity, temperature, nature of movement, surface roughness and other factors. Generally, friction is considered to be the result of the forces required to shear surface irregularities, called microasperities. The unusually low friction of PTFE is related to its ability to shear off a transfer layer onto the mating surface to overcome this drag.

The highly crystalline structure produces blocks of material which can shear along crystal planes. While other polymers may tear long chain molecules which are intertwined in the bulk of the material, PTFE crystal sections slip over one another like cards in a deck slide when spread out on a table. This process causes both low friction and high wear. This wear can be controlled by the use of special additives.

When pure PTFE is tested as a push-pull liner with a clean, dry cable on the efficiency and wear tester, the results look like the graph in Figure 2. It can be readily seen that pure PTFE is unsuitable as AR/AF tubing because wear-through occurs within the first 30,000 cycles. The efficiency curve shows an immediate drop which levels off as wear-through occurs. This effect is seen with most formulations and is caused by the increasing surface contact which occurs as the cable wears a groove in the tubing. The greater contact area produces higher frictional force and lower efficiency.

HIGH-PERFORMANCE AR/AF TUBING

To produce an AR/AF tubing for use in automotive push-pull assemblies, it is neccessary to add certain reinforcing materials to PTFE. The effects of these fillers in improving abrasion resistance depends on the type, volume concentration, particle size distribution, shape and hardness. The desired result of this compounding is that as the resin surface wears away to expose filler particles, the load will be supported by the filler and, therefore, limit the wear.

One of the early AR/AF tubings to get widespread automotive use was formulated with zirconium silicate and patented in 1968. The initial efficiency and abrasion resistance were good, so the material passed most specifications easily. When the dynamic efficiency and wear tester was developed, we discovered the unexpected data shown in Figure 2, Curve "A". After break-in, the efficiency dropped to the extent that halfway through the test, the force needed to lift five pounds had increased from 7 to 15 pounds. Microscopic examination also showed that the formulation was abrasive to the inner cable and that the wear debris from this action may have been responsible for the drop in efficiency. Additional testing has shown that similar behavior occurs with several other formulations available on the market.

Two newer types of materials currently in use are represented by Curves "B" and "C" of Figure 2. These formulations perform more consistently and overcome the primary shortcoming of the earlier tubings. After break-in curves similar to unfilled PTFE, the efficiency levels and holds steady to the end of the test. The weight loss results show that abrasion-resistance was not substantially altered by the changes in formulations.

To meet the demand for more severe future applications, we recently developed new (patent pending) AR/AF liner materials. As shown in Figure 2, AR-501 demonstrates substantial improvements in both efficiency and abrasion resistance. Figure 3 shows that the good performance of this material is maintained at elevated temperatures, in this case 250°F. The low weight loss indicates an almost unlimited lifetime under the test conditions.

In response to the automotive specifications requiring higher initial efficiencies that was available with normal use of currently available AR/AF tubings, some push-pull assemblies have been tried with silicone oil added to the cable as a lubricant. Although initial efficiencies can be increased in this manner, our results (Figure 4) show that in the long run, this increase is not permanent and can lead to even poorer results than the unlubricated cable. A new formulation, AR-500, eliminates this problem in our testing. When oiled, this tubing maintains a constant efficiency with no measurable wear. At 250°F, the performance remains constant for the oiled AR-500.

CONCLUSIONS

The results of this study of tubing friction and wear can be summarized as follows:

1. Friction and wear measurements made for rotary bearings are irrelevant for tubing applications.

2. Friction and wear measurements made with different test conditions or conformations yield different data but can give relevant trends and comparisons.

3. Initial efficiency measurements are inadequate and misleading.

4. Weight proportions of fillers in polymers are irrelevant; specifications should be based on performance.

5. The use of lubricants must be carefully tested; for best results, liners formulated for oil compatibility should be used.

6. Consistently high performance is possible through careful formulating and testing.

When the mechanics of friction and wear are properly applied, test methods and specifications can be designed to ensure safe and reliable performance in automotive push-pull cable assemblies.

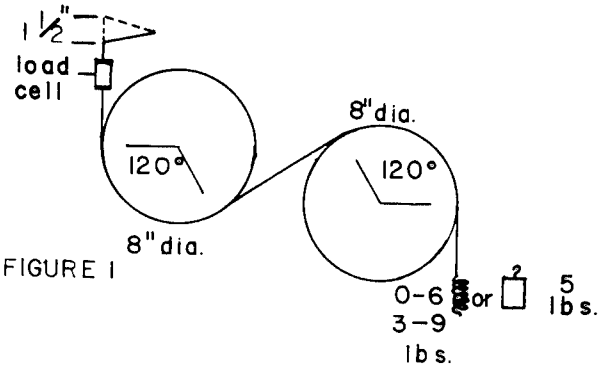

FIGURE 1

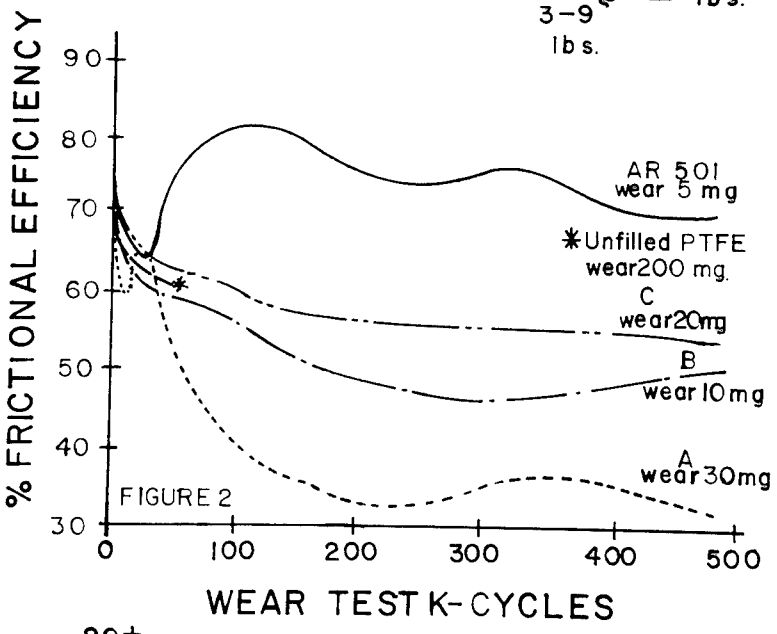

FIGURE 2

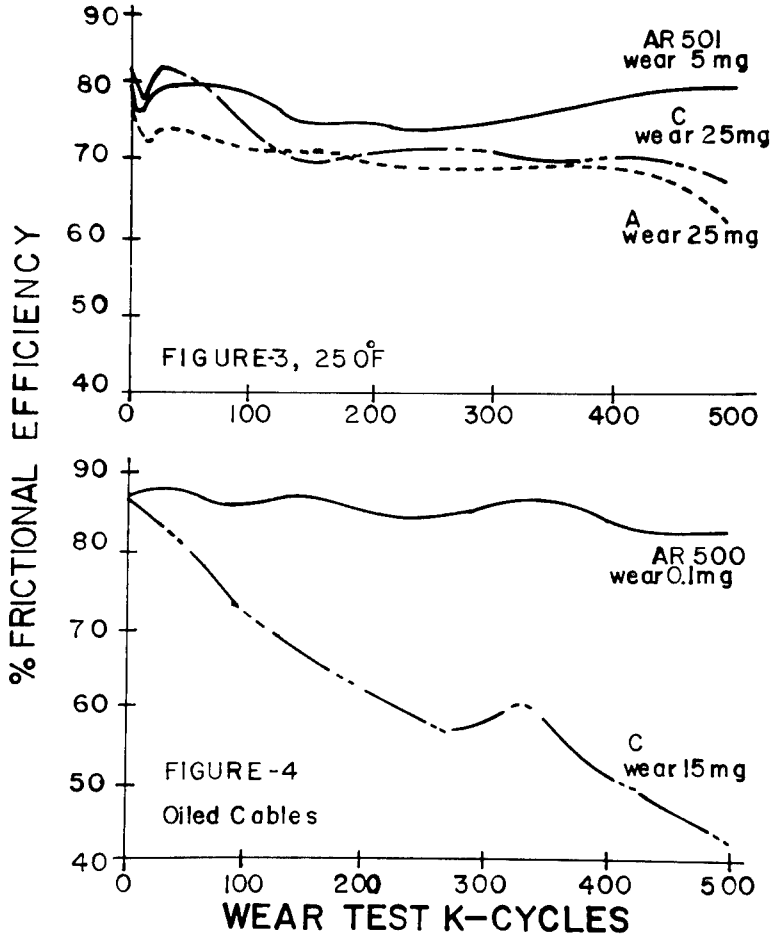

FIGURE-3, 250°F

FIGURE-4
Oiled Cables

PROCESSING AND PROPERTIES OF REINFORCED BAYFLEX

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Lothar Klier

Bayer A. G., Leverkusen
West Germany

Polyurethane (PU) integral skin foams have been used by the automotive industry for over a decade. These semi-flexible products, which are used for headrests, armrests, instrument panels, and steering wheels increase the interior safety of the automobile. Furthermore, high density, microcellular PU elastomers applied to exterior parts such as energy absorbers, front and rear parts have proven to be very reliable. For example, the Ford Capri, the MGB, the Triumph TR-7, and, lately, the Polish Fiat Polanaise are equipped with elastomeric bumpers. The soft face principle is used in designs of many automobile types: in Europe for example, for the Porsche 928, and the Ford Escort RS 2000; and in the USA for the Chevrolet Monza 2+2, the Pontiac Firebird and others.

Now a situation is developing which will increase the penetration of plastics into the automobile industry. The requirement to save energy has produced legislation which mandates improved fuel economy. By 1985, the Corporate Average Fuel Economy (CAFE) for all cars must be 27.5 miles per gallon. This means that only small cars will be produced, or the weight of current-sized cars must be drastically reduced. Most efforts at the moment are directed toward the latter goal. Weight reduction through the replacement of metal with plastics is a realistic possibility.

Plastics which could be used for the production of fenders, trunk lids, hoods, or doors must possess three essential qualities:

1. The stiffness must be sufficient to cover large areas of the car without additional supports,
2. The coefficient of Linear Thermal Expansion (CLTE) must be as low as possible in order to obtain good dimensional stability in the case of temperature extremes and to minimize tension at the metal/plastic interfaces,
3. The high temperature dimensional stability (as measured by the SAG test) must be sufficient to avoid damage during the painting process.

Polyurethanes can meet these requirements when they are reinforced with inorganic fillers. In this presentation we will describe the effects of granular, flakey, and fibrous fillers on the qualities of Bayflex. These include natural minerals along with chopped strand and milled glass fibers.

RRIM TECHNOLOGY

Due to the high viscosities and abrasiveness, one-way piston pumps and special mixheads are used for filled RIM systems. The conversion of conventional high-pressure metering machines by the addition of a lance or dosing cylinder permits operation with filled systems. In this manner the function of the metering pump is changed to that of a hydraulic pump. Future industrial applications will feature dosing units served by hydraulic accumulators; wherein the metering velocity, ratio, and volumes are controlled by electro-hydraulic servo systems or impulse frequency guidance. The possibilities for electronic control of the process parameters will be significant for large volume production operations. The subject experiments were carried on with an RRIM machine equipped with linear intensifiers.

THE CHEMICAL SYSTEM

These experiments were conducted with Bayflex 110-50, a product with the following specifications:

	SI	U.S.
Specific Gravity	1.1	1.1
Flexural Modulus	350 mPa	50,000 psi
Heat Sag,* 1 h./160°C	15MM	0.6 in.
CLTE $x10^{-6}$	180/°C	100/°F
Elongation	320%	320%
Charpy Impact @ -20°C	pass	pass

* The temperature of the SAG test was changed from 120° to 160°C to meet the anticipated, "on-line" paint-curing temperatures.

THE FILLERS

The search for appropriate reinforcing agents included the different structures - granular (particulate) flakey, and fibrous substances.

MINERAL FILLERS

The family of granular substances was represented by:

$Al(OH)_3$, aluminum hydroxide

$CaCO_3$, calcium carbonate

Mg-Al-Silicate

Several types of these with different sizes and size distributions were tried. The average particle size was between 5-65 microns (/um). Mica was selected as the flakey substance. This layered silicate, which is found naturally shaped in thin platlets, was used in three sizes: 60, 200, and 350 mesh.

GLASS FIBERS

Both chopped strands and milled glass fibers were used. The chopped strand is supplied in bundles which consists of as many as 800 fibers per bundle. The strand was chopped to a length of 3.2mm (1/8"). This is the shortest chopped strand commercially available.

Milled fibers are hammer milled and then sieved. In other contries, as in the USA, the types are classified according to the sieve size, eg. 1/32", 1/16" or 1/8", which is not representative of the actual fiber length. Such milled fibers show a normal or slightly skewed distribution of fiber lengths. Those five types selected for these studies showed length distribution maxima between 100 and 500 microns.

THE APPLICATION OF THE FILLERS

In all of these experiments, the filler was added to the polyol as a precaution since the possibility of interactions of the filler with the isocyanate was unknown. In the meantime, experiments have shown that most of these fillers can be added to the isocyanate. The exception is moist materials, since the water will react with the the isocyanate and produce urea and carbon dioxide. Also, substances which can produce surface reactions, that is a disproportionate viscosity increase, should be incorporated via the polyol.

Particulate fillers do not increase the viscosity as much as fibers. Therefore polyols containing up to 150% by wt. of filler have been processed on the newer dosing units.

With mica, the application concentration lies between 30 and 80 wt., percent. Finer types, eg. the 325 mesh product, can be used in higher concentrations than the coarser 200 or 60 mesh types

Chopped strand can only be processed with great difficulty. Small concentrations of chopped fibers produce very high viscosities. Therefore the 1/8" chopped strand was used to an upper concentration of 5-6 wt. %. The shorter milled fibers do not increase the viscosity as dramatically and therefore can be used in the range of 40-75 wt. % in the polyol. The limit is determined by the maximum point of the length distribution curve.

THE PHYSICAL PROPERTIES

Using our selected experimental plan, that is Bayflex 110-50 as the polymer matrix and processing of the filler on the polyol side, polymers with 25-30 wt. % filler-even 40 wt. % in the case of particulates - were prepared. Within this concentration range, the experiments show a linear relationship between filler concentration and physical properties. In retrospect, the use of the different filler types led, in the case of the significant properties - namely modulus, SAG and CLTE - to very different results.

PARTICULATE FILLERS - TABLE I

The chemical composition of the particulate minerals does not exert a significant influence on the physical properties of the final product:

1. These fillers cause very little increase in the modulus,
2. They deteriorate the high temperature, dimensional stability and,
3. reduce the CLTE no more than 25% of the original value.

CHOPPED STRANDS - TABLE I

The fiberous materials show pronounced tendencies toward orientation in the flow direction of the polyurethane matrix. This results in anisotropy of the material. Only small amounts of chopped strand can be added to the polyurethane. Therefore the effect is small. The small advantage is that there is almost no property variation perpendicular to the flow direction. Parallel to the flow direction neither the modulus nor the CLTE values are changed significantly. The elongation drops disproportionately and the impact resistance deteriorates. The resistance to deformation at high temperature increases. 3 wt. % of chopped strands decreases the deformation of the test specimens at 160°C down to 1/10 of the original value.

MICA - TABLE II

Through the addition of MICA, the modulus, SAG and CLTE are improved. 25 wt. % of this flakey material in Bayflex 110-50 produces:

1. A threefold increase in the flexural modulus, to approximatley 1400 mPa (200,000 psi),
2. a 2/3 reduction in the sag value,
3. and a decrease in the CLTE from 100 to less than $50 \times 10^{-6}/^{\circ}F$ (to $90 \times 10^{-6}/^{\circ}C$).

Disadvantages are the sharp decreases in elongation and impact resistance.

MILLED FIBERS - TABLE II

The property variations resulting from the incorporation of milled fibers are similar to those resulting from MICA, except that the fibers definitely orient themselves in the direction of flow of the polyurethane matrix.

The stiffness of the glass-reinforced product increases with the glass content. The values for flexural modulus and elastic modulus reach as much as fourfold over the initial (ie. without glass) value, when measured in the direction of flow. Perpendicular to the flow direction, the values only double. The high temperature dimensional stability is improved. The deformation, after exposure to 160°C for one hour, of the cantilevered specimen under its own load, is less than 2.5mm (0.1 inch), when measured in the flow direction. The value measured perpendicular to the flow direction is less than 7.5 mm (0.3 inch). The anisotropy, as indicated by the greatest property difference, appears in the measurement of the CLTE. Perpendicular to the flow direction there is almost no perceptable change in the value. Parallel to the flow direction, it is reduced to $27 \times 10^{-6}/^{\circ}C$ ($15 \times 10^{-6}/^{\circ}F$). This brings the value down to the vicinity of that for metals-steel=$11 \times 10^{-6}/^{\circ}C$; Aluminum=$23 \times 10^{-6}/^{\circ}C$.

Elongation and impact resistance also decrease with increasing glass content; yet these changes are not as dramatic as those experienced with mica addition.

SUMMARY

Particulate minerals are not the favored reinforcing materials for application in automobile body panels. The property variations are too trivial. These materials are difficult to disperse, alter the modulus, sag and CLTE in a favorable manner, but simultaneously reduce the values for elongation and impact resistance.

With fiber reinforcements, the advantages postulated for applications in automobile body panels can be fulfilled. They change modulus, sag, CLTE in greater quantities than mica, yet do not reduce the elongation and impact resistance to as great a degree.

Milled fibers are preferred over chopped strands. The advantages lie with their simpler processing, capacity for greater quantities of reinforcement in the polymer, and in the improved surface quality of the molded parts.

The anisotropy of the fiber-reinforced materials is not a disadvantage. It must certainly be considered during the constructions of the mold and used to advantage.

Fiber reinforced Bayflex offers itself as a material with which the necessity for energy - conserving, lighter,building elements for cars can be successfully attained. To date, the practical applications are being explored by use on lower volume model runs. The results so far are full of promise.

Authors - Biographical Information

Dr. Klaus Seel, born in 1943, studied chemistry at the University of Cologne and graduated in 1973. He began work in 1974 in the Application Development Department, Polyurethane Division of Bayer A.G., Leverkusen. He supervises the group responsible for Reinforced RIM Polyurethane.

Ing. (grad.) Lothar Klier, born in 1942, studied (plastics) processes/processing technique at the Niederrhein Technical School in Krefeld. He began work in 1972 in the Application-Development Department, Polyurethane Division of Bayer A.G., Leverkusen. He is engaged in development of the processing techniques for reinforced polyurethanes.

TABLE I

Properties of Reinforced Bayflex 110-50

$Al(OH)_3$, $CaCO_3$, Mg-Al-Silicate, Chopped Glass Strands

Reinforcement Level	0	$Al(OH)_3$, $CaCO_3$ Mg-Al-Silicate 20%	40%	1/8" Chopped 3%
Specific Gravity	1.1	1.2	1.35	1.1
Flexural Modulus, mPa	352	394-450	507-563	598
psi (10^3)	50	56-64	72-80	85
Heat Sag - 1 hr @ 160°C, mm	15	17-19	20-22	1
inches	0.6	0.68-0.76	0.80-0.86	0.04
CLTE (10^6)/°C	180	153-162	135-144	110
(10^6)/°F	100	85-90	75-80	61
Ultimate Elongation, %	320	250-270	180-200	130
Charpy Impact @ -20°C	pass	pass	pass	fail

TABLE II

Properties of Reinforced Bayflex 110-50

Milled Fibers, Mica

Reinforcement		Milled Glass Fibers				Mica	
Level/Flow Dir.	0	12.5% //	12.5% ⊥	25% //	25% ⊥	12.5%	25%
Specific Gravity	1.1	1.2		1.3		1.2	1.3
Flex. Mod., mPa	352	734-793	965-648	1352-1069	648-503	810-951	1232-1338
(10^3)psi	50	106-128	71-92	192-224	93-114	115-135	178-190
Heat Sag 1hr./160°C mm	15	4-6	7-9	1-2	5-7	6-8	3.5-5.0
inches	0.6	.16-.24	.28-.36	.04-.08	.20-.28	.24-.32	0.1-0.2
CLTE (10^6)/°C	180	65-95	145-165	25-34	110-130	108-126	72-90
(10^6)/°F	100	36-47	81-92	14-19	61-72	60-70	40-50
Ult. Elong., %	320	230-250	200-240	80-100	150-170	120-150	10-30
Charpy Impact @ 20°C	pass	pass	pass	fail	fail	fail	fail

SYNCRO-RAM METERING AND MIXING RESIN FORMULATIONS FOR SMC, BMC, TMC, ETC., AND OTHER LIQUID COMPONENT APPLICATIONS

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MODERN TOOLS DIVISION
LIBBEY-OWENS-FORD COMPANY

INTRODUCTION

Many improvements have been made in processing equipment and procedures for the manufacture of reinforced plastics---especially sheet molding compound (SMC), and bulk molding compound (BMC). With the advent of TMC, HMC, XMC, injection-moldable BMC or TMC, and other materials, a new generation of composites and processes is emerging. All of the aforementioned processes depend upon newly-designed machinery or modifications to existing equipment in order to accomplish the new technology.

A basic requirement for most of these processes involves the accurate metering of formulated resins into the processing equipment. There is a system demand to maintain consistent, high-quality standards, when utilizing high filler loadings, unusual filler materials, and sophisticated mixes, especially where three or more components are required of high ratio, and precisely metered outputs. While great strides have been made in processing machinery design, very little has changed within the critical resin metering, mixing, and dispensing areas.

A newly developed and production proven system, employing lance-type ram cylinders, together with a dynamic mixing head, is now being offered to industry. This system can be used in all kinds of fluid dispensing applications where precision is demanded over a broad range of volumes, pressures, temperatures and viscosities.

STATE OF THE ART

The most common and established method for metering polyester and other resinous formulations for SMC, BMC, TMC and other reaction processes is by the application of standard rotary fluid pumps. The use of rotary pumps to convey resinous liquid components under pressure, and requiring these same pumps to function as a positive metering device, has been the proven standard method for years. Without doubt, this method will satisfy many requirements at the lowest capital equipment costs and will provide good metering capabilities at the outset; however, its effectiveness will steadily erode until rendered useless, unless it is critically maintained and expensively supervised.

Rotary pumps are of necessity mechanically linked, in order that the ratioed output can be achieved by varying the rotational speed of one or both of the pumps. The mechanical interlocks must be capable of providing individual pump control and, at the same time, must also be able to slave all of the pumps, to raise or lower the total output, at the preset ratio setting.

Pumps can also be driven individually with DC motors, electronically coupled to gain proper ratios with overall output control. The pumps are ratioed through tachometer readouts and accuracy is dependent upon the rpm control of the pump motor drives. With solid-state reliability, the rpm locking has been proven, but the pumps do not perform in a straight-line relationship with the drive-motor rpm over extended production periods. The same principle has been applied, using hydrostatic drives for the pumps, to meter the compounds.

Most rotary type pumps are not true metering devices. Machined clearances must be designed into the pumps or heat will affect the components as they are moved through the pump. Back pressure in the downstream line will also cause slippage and loss of the preset meter output. In some applications, this pressure is intermittent and undeterminable, and becomes difficult to compensate for in the initial ratioing setup. Rotary pumps are subject to normal use wear which increases slippage clearances-varying in severity as determined by the quantity and type of filler used in the formulation. Pump life can be very limited and can require frequent maintenance to provide the maximum degree of metering accuracies. Some abrasive fillers cannot be used in rotary pumps under any conditions.

Most rotary pumps will not meter highly-filled viscous formulations because overload protection devices necessary to prevent pump failure due to high torque loads will cause excessive metering interruptions. For this reason many materials and formulations must be modified to compensate for this equipment limitation.

Another effort to achieve metering accuracy with rotary pumps is the incorporation of flow meters in the outlet of each pump, and with electronic circuitry, monitor and control each pump drive maintaining a preset ratio balance. This system is functional with most resin systems, but must be evaluated with very high filler loaded formulations.

From the above discussions, it is apparent that metering accuracy is a prime requisite to insure quality in production. The industry now has equipment available that will accurately meter the vast majority of resins and filled systems that are required in the plastics industry. The capability has been demonstrated to mix and combine the metered components and to introduce additional fillers, fibers, and particulates into the discharge stream.

SYNCRO-RAM METER (SRM)

The meter unit employs the proven and tested lance-style ram displacement cylinders that are mechanically affixed to a variable, hydraulic-driven oscillating frame. The design is unique because the valving is automatically powered and activated by the adjustable system pressure. This insures exact metering from the ram displacement cylinders for a measured shot dispense or a continuous metered output.

Ram displacement metering equipment has many specific advantages over all other designs. This type of metering is absolutely accurate as long as the liquids remain air-free and incompressible. The unit accepts a wide range of viscosities. Variations in viscosity that are affected by temperature changes will not influence the metering.

Figure 1 graphically shows the advantage of ram displacement metering versus common rotary type pumps.

The Syncro-Ram Meter design provides several advantages that give the meter the capability to accurately ratio highly viscous and filled compounds. The valving that couples the two syncronized ram cylinders operate in sequence from the differential pressures established by the ram discharge pressure. This pressure is adjustable over a wide range and is limited only by the setting of the machine and system design. (Pressures are usually set at several hundred to several thousand pounds per square inch, (Kg./Sq. Cm.) depending upon the volumes, types of material being metered, and other set conditions.) This design provides a simple,positive and automatic valve sequencing without the application of external power to the valves, together with timing circuitry, etc. It is also possible to interface fluid-powered assisted valving, if the requirements are so demanding that additional closure force is required (such as when fibers, fiberglas and fillers that tend to agglomerate and not evenly disperse, or homogeneously mix, are metered).

The metering rams of the SRM unit are uniquely designed to provide a consistent flow and flushing action within the cylinder cavity. The resin mix enters the bottom of the cylinders and is discharged at the top section of the cavity. (See figure 2.) This prevents stagnated areas and cavities in which filler/resin mix can accumulate. This principle of providing full flow and

constant flush is carried throughout the entire piping system of the machine.

Another positive benefit from this design is the ability to pressure feed the meter to always positively fill the ram cylinders, without affecting the metering accuracy. The meter will intensify the pressure from the supply source, but will always accurately meter and dispense only the ratioed volumes. The need to pressure feed the meter to prevent possible cylinder cavitation is mandatory when the resin system is highly viscous and heavily filled. Without pressure feed, these formulations will not fill a cylinder cavity without some cavitation. Cavitation will result in the loss of metering capability and possible off-gassing of the low volatile constituents of the compounds. Pressure tanks can also be used, but are restricted to low-viscosity compounds. For the transfer of high viscosity filled components any number of rotary style pumps can be used that will not impart heat and will always supply sufficient volume of material to the meter under a set pressure head. Since the pressure-feed pump is not required to meter, all the previously mentioned disadvantages do not apply. A relief pressure circuit in the discharge side of the transfer pump, directed back into the holding tank will always keep the meter supplied and also provide some movement and agitation to the materials in the holding tank and piping circuitry (See figures 3 & 4).

With the Syncro-Ram Meter incorporating the oscillating beam, it becomes easy to couple any number of paired cylinder/rams to the oscillating frame and achieve exact slaved, meter-ratioed outputs for any number of components. The oscillating frame is hydraulically powered, and controllable for speed of oscillation and pressures. Because of the linkage design, inherent mechanical advantage provides all the necessary force on the ram cylinders. Fail-safe limits can be established for any machine setup by the adjustable hydraulic pressure relief valves built into the system. With the application of sensors, rate counters, microprocessers, and servo valving, the meter unit can become as sophisticated as the demand warrants.

The metering of minor components requiring a high ratio setup, resulting in use of small cylinders and rams, has the capability of generating high metering pressures with the standard hydraulic-driven frame. The high pressures obtainable are of direct benefit for injecting the minor components into the downstream piping of the high-viscosity base resin.

All valves must have minimum pressure drop, and must contain no dead cavity areas that are not continually flushed by the flow and circulation of the medium. Because of these inherent problems it has become necessary to design and build valve components that are compatible with all resin systems.

Also under development is a metering-block module which encompasses the Syncro-Ram principle, and provides greater flexibility for customers to build a metering system consisting of a single component to any multiples required. All modules are coupled, and precise ratios will be maintained after initial setup. The design also provides an easily adjusted stroke-variator for the individual ram modules that will provide for variable meter ratio output. The design will provide a simple, straight-forward metering approach to chemical formulating, dispensing and reaction processes.

From the foregoing discussion, it becomes obvious that the majority of the inherent problems associated with the metering and ratioing of difficult and problem compounds can be overcome with the aforedescribed unit. After many months of in-plant use, it is now concluded that the units can and do provide answers to processes that involve chemical processing, etc.--with or without fillers, particulates, etc.

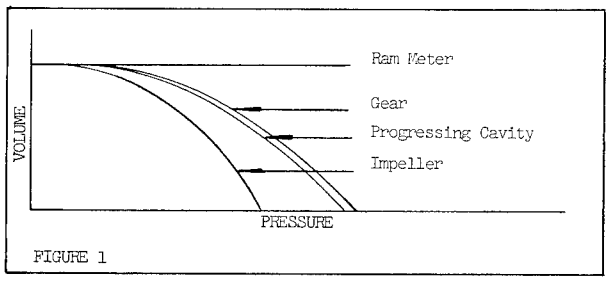


FIGURE 1

CONTINUOUS IN-LINE MIXER

An in-line mixer has also been developed to effectively combine and homogeneously mix the metered components from the SRM unit. The coupling of the dynamic mixer to the meter will provide a complete package resulting in lower system pressures and maximum mixing efficiencies required for reactive resins and related processes.

DYNAMIC MIXING HEAD WITH DRY FILLER ADDITIVE CAPABILITY

It is important to recognize that the SRM Meter (together with standard feed pumps) can operate up to a maximum ratio level of dry additives vs. liquid. This limit is dependent upon many rheology factors determined by the base materials. When formulating high viscosity filled systems, a level can be reached with dry components that prohibits the pumping, transfer and metering of the components. For this reason, many processes remain batch type operations.

A solution is now provided for many of these problems in the development of the Dynamic Mixer, designed for the introduction of dry free-flowing, fillers, particulates, fibers, aggregates, (including sand) into the mixing head. The residence time within all stages is very rapid (seconds) and allows fast reaction mixes to be processed. The efficiency of the unit has been demonstrated in many applications, including the bonding of sand with reactive resins (at 2%-3% by wt. Resin/Sand) at 1,000 lbs./min. (453.6 kg./min.).

CONCLUSION

Advancements have been achieved that will improve quality and efficiency, and allow for more diverse chemical formulating advancements. The equipment as described will provide the potential for new processes, methods of manufacture, and ultimately, new and evolutionary products that future industry will demand. SRM metering and mixing equipment (production proven) is now available to provide the necessary link between the chemical industries, with its prolific capability to create new and needed revolutionary products, and the mechanical realities required to take full advantage of these chemical advancements.

BIOGRAPHY

Wallace F. Krueger

Received a Bachelor of Science Degree in Mechanical Engineering at the University of Toledo after serving two years in the Naval Air Corps. He has been engaged in the reinforced fiberglas industry since 1947, and was instrumental in the early development and application of resin metering equipment, for polyesters, urethane foams, elastomers, adhesives, etc.

At present, he is actively involved in solar design and applications for Libbey-Owens-Ford Company, Solar Energy Systems and research and development for Modern Tools Division. He has fourteen patents granted and/or pending, including five within the solar energy field.

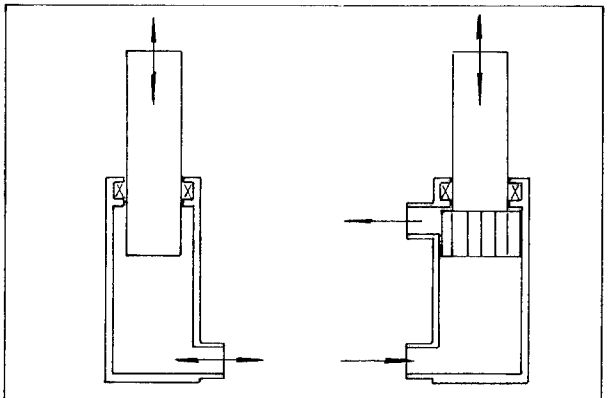


FIGURE 2

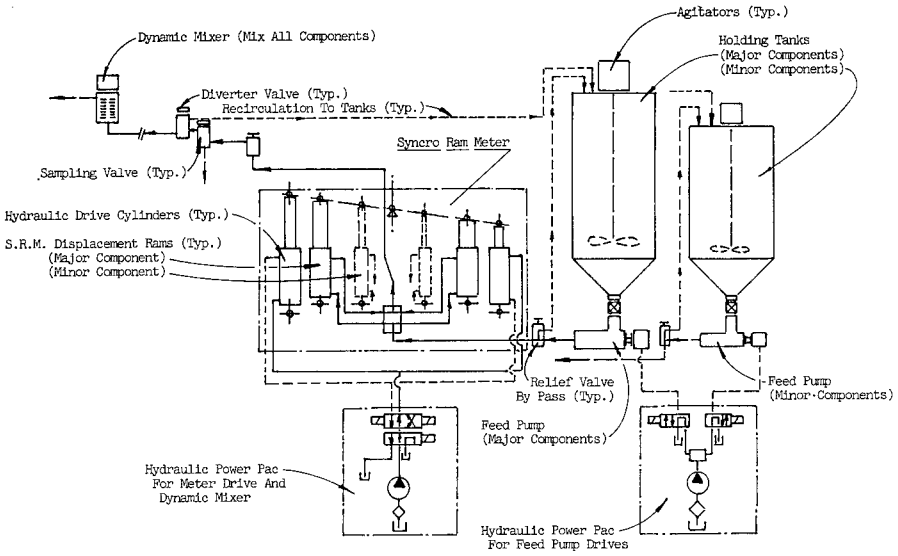
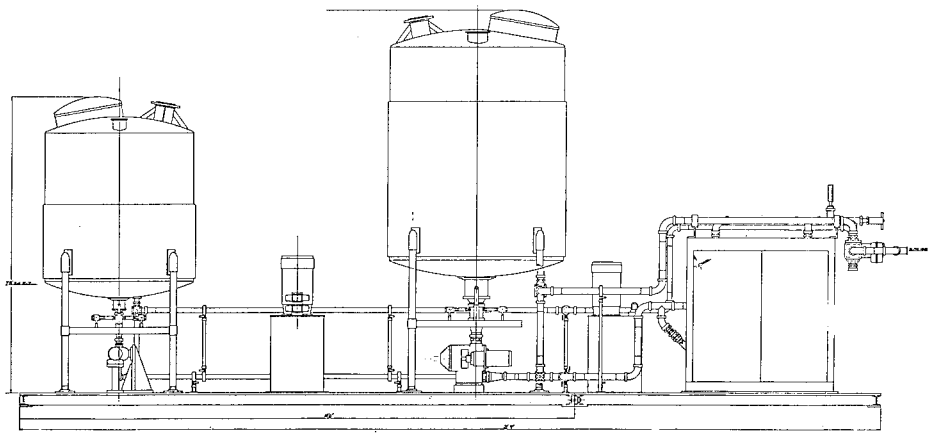
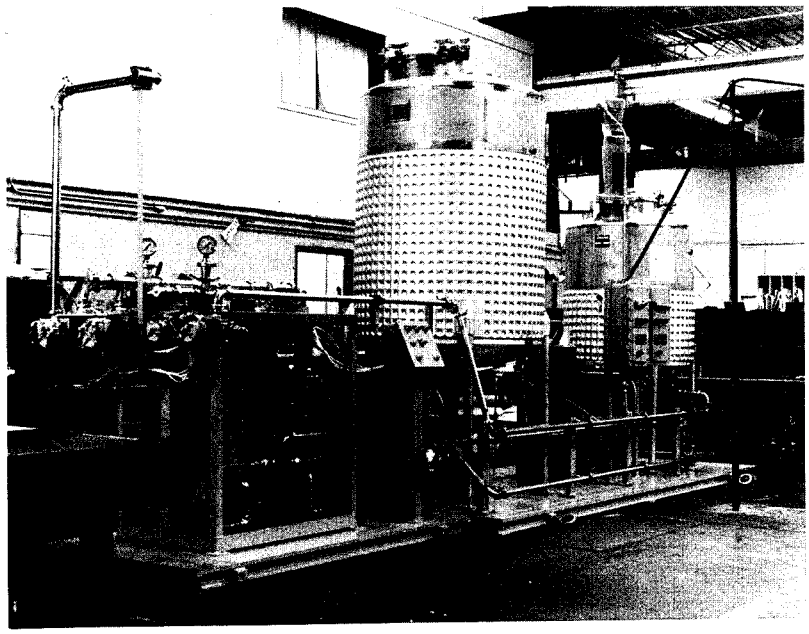


FIGURE 3

FIGURE 4





ANALYSIS OF MOLD FILLING FOR THE REACTION INJECTION MOLDING PROCESS

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Introduction

Reaction Injection Molding (RIM) is a relatively new polymer processing method.[1,2] Building on automotive success, it is moving into broader markets via improved systems which can give custom molding capability. Large parts are now being Reaction Injection molded in less than a minute from liquid components.

The basic unit operations[3] of the RIM process are illustrated in Figure 1. There are two streams, one containing isocyanate groups (usually a liquid form of 1, 4 diphenyl methane diisocyanate). The other containing hydroxyl groups (usually a mixture of 1, 4 butane diol and a polyether polymer polyol) and the catalyst (usually dibutyl tindilaurate). These are brought into intimate molecular contact by impingement mixing, in a time scale short compared to the process cycle time. As the material flows in the mold, the hydroxyl groups react with the isocyanate groups to form polyurethane. The basic chemical reaction is shown in Figure 1. This reaction is highly exothermic. Thus, heat is usually removed during the filling stage. Due to the chemical reaction the viscosity of the mixture increases. After the mold is filled, the material is left in place, reacting (curing) until the part is stiff enough to remove. A post curing step is used to improve modulus and dimensional stability. In this work we concentrate in the filling step.

As RIM molds become larger and more complex, and as more reactive systems are used, understanding the filling step takes on greater importance. Incomplete filling has been reported to give problems in complex parts. Weld lines are also a potential problem. If the extent of reaction of the fluid streams meeting each other, is higher than a critical value, the materials will not interpenetrate and the weld line will be visible and weak. Criteria are needed to predict incomplete filling and weld lines. The pressure to fill the mold must also be predicted, since it is needed for the mold design. It is also important to know when the flow front becomes unstable. If the flow front is highly unstable, it could entrap air bubbles, which can bring about poor surface appearance.

Little work has been published on mold filling for the RIM process. Domine and Gogos[4,5] have done a numerical simulation of the RIM process, however they did not compare their theoretical results with experiments. Broyer, Macosko, Critchfield and Lawler[6] have done experimental work on a commercial RIM machine. Although this study was mainly of the curing step, they determined the flow front position as a function of time in a long rectangular cavity. They found, as expected, that the flow front was nearly perpendicular to the flow direction and moved with the pump flow rate. Prepelka and Metzger[7] have reported high speed photographs in a study of gate design. Castro, Macosko, Critchfield, Steinle and Tackett[8] have done experimental work in a rectangular thin mold. They used a commercial RIM machine and chemical system. They report filling pressures for several mold thicknesses using materials with different catalyst levels. They recorded filling patterns with slow motion cinematography. They found that as the flow rate is increased the flow front goes from stable at low flow rates to highly unstable at high flow rates. The results presented here are an extension of that work.

We begin by describing the mathematical model used to represent the flow field, from which useful conclusions can be withdrawn. Then we give the experimental results, which are mainly of two kinds, pressure rise during filling and flow visualization.

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Mathematical Model

During mold filling a well mixed low viscosity material is fed into the mold. As the material progresses in the mold, the viscosity increases due to chemical reaction. Neglecting entrance effects the material particles during the filling of a narrow gap mold can be considered to have straight path lines, except on the vicinity of the flow front where, as shown on Figure 2, the flow is of a spreading or smearing nature (fountain flow). This region constitutes a small portion of the flow field, except at the beginning of the filling process. The pressure drop across the fluid front is usually very small[9]

For the mathematical modelling the flow field is then divided into two subdomains. Main flow, where the material particles have straight path lines and the flow front. Both solutions are then matched up through a mathematical boundary. The equations shown below are valid for the main flow. Useful conclusions can be withdrawn without even solving them. They are written for a rectangular mold with an end gate like the one shown in Figure 3.
The assumptions are:

1) Constant density (ρ) and thermal properties ($\tilde{k}$, C_p)
2) Negligible molecular diffusion ($D_{AB} \cong 0$)
3) Neglect side walls ($w/h \gg 1$)
4) Second order kinetics ($r_A = kC_A^2$)
5) Neglect entrance length
6) Laminar flow
7) Newtonian fluid ($\eta = \eta(C^*, T)$ only, not shear rate)
8) The flow is considered to be one dimensional thus, the only non zero velocity is in the x direction ($v_y \cong 0$ $v_z \cong 0$)
9) Constant flow rate (Q = constant)
10) Negligible heat conduction in x and y direction

Thus, the main field equations in terms of dimensionless variables (defined in the nomenclature section) are

Continuity

$$\frac{\partial v_x^*}{\partial x^*} = 0 \qquad (1)$$

Balance of linear momentum in the x direction

$$\left(\frac{h\,Re_w}{L}\right)\frac{\partial v_x^*}{\partial t^*} = -\left(\frac{\partial p^*}{\partial x}\right) + \frac{\partial}{\partial z^*}\left(\eta^* \frac{\partial v_x^*}{\partial z^*}\right) \qquad (2)$$

Accumulation of Linear Momentum — Generation — Dissipation

where

$$Re_w = \frac{\rho \langle v_x \rangle h}{\eta_o} \qquad (3)$$

The dimensionless quantity ($\frac{hRe_w}{L}$) can be interpreted as the ratio of accumulation to generation or dissipation of linear momentum. In general for typical RIM situations

$$\frac{hRe_w}{L} << 1 \qquad (4)$$

Therefore a steady state balance of linear momentum can be assumed

$$\left(\frac{\partial p}{\partial x}\right)^* = \frac{\partial}{\partial z^*}\left(\eta^* \frac{\partial v_x^*}{\partial z^*}\right) \qquad (5)$$

With assumptions 2 and 4 the mole balance becomes

$$\frac{Dc^*}{Dt^*} = \bar{K} k^* (1 - c^*)^2 \qquad (6)$$

Rate of change of c* following the motion — disappearance due to Chemical Reaction

where $\frac{D}{Dt}$ is the material derivative

$$\frac{Dc^*}{Dt^*} = \frac{\partial c^*}{\partial t^*} + v_x^* \frac{\partial c^*}{\partial x^*} \qquad (7)$$

The dimensionless parameter $\bar{K}$, is the most important parameter for the filling step. It can be interpreted as

$$\bar{K} = \frac{\text{filling time}}{\text{characteristic reaction time}} = \frac{t_f}{t_r} \qquad (8)$$

where

$$t_f = \frac{h\, w\, L}{Q}$$

and $t_r = \frac{1}{k_{\theta M} C_o}$, a reaction half life.

Thus, if $\bar{K}$ is large considerable chemical reaction will take place during filling. On the contrary if $\bar{K}$ is small almost no reaction will occur during the filling step.

With assumptions 1, 4, 8 and 10 the balance of energy becomes

$$\frac{D\theta^*}{Dt^*} = \beta_1 \left(\frac{\partial^2 \theta^*}{\partial z^{*2}} \right) + \beta_2 \eta^* \left(\frac{\partial v_x^*}{\partial z^*} \right)^2 + \beta_3 k^* (1-c^*)^2 \qquad (9)$$

Temperature change following the motion — Temperature change due to conduction in the transverse direction — Temperature change due to viscous dissipation — Temperature change due to chemical reaction

where

$$\frac{D\theta^*}{Dt^*} = \frac{\partial \theta^*}{\partial t^*} + v_x^* \frac{\partial \theta^*}{\partial x^*} \qquad (10)$$

$$\beta_1 = \frac{\tilde{k}\, w\, L}{h\, \rho\, C_p\, Q} \qquad (11)$$

$$\beta_2 = \frac{\eta_o\, L\, Q}{h^3 w\, \eta\, C_p\, \theta_M} \qquad (12)$$

$$\beta_3 = \frac{k_{\theta M} C_o^2 H_R\, w\, h\, L}{\rho\, C_p\, Q\, \theta_M} \qquad (13)$$

Each of the dimensionless parameters β_1, β_2, and β_3 appearing in equation (9) can be interpreted as giving the order of magnitude of the temperature change due to conduction, viscous dissipation and chemical reaction respectively. For typical RIM situations β_2 is very small (10^{-5}). β_1 is also in general small (10^{-2}) but not as small as β_2. Thus, the major contribution to the temperature change is from the chemical reaction (β_3).

Based on the dimensional analysis of the field equations, we can classify the mold filling unit operation of the RIM process into three cases. First if β_3 and $\bar{K}$ are low we can assume that the viscosity remains constant during filling. For this case, the simple isothermal plane Poiseuille flow equation, can be used to predict the pressure needed to fill the mold. This can be obtained by direct intergration of equation (5), using the no wall slip boundary condition. The final result is then

$$\Delta P_f = \frac{12\, \eta_o\, Q\, L}{w\, h^3} \qquad (14)$$

Second if β_3 is low but $\bar{K}$ is large, the filling stage can be assumed isothermal but we must account for the increase in viscosity due to chemical reaction. The third case is when both β_3 and $\bar{K}$ are large. In this case, the filling stage is non isothermal, the temperature and extent of reaction effects on the viscosity need now to be considered. For cases two and three a numerical solution is necessary because the balance equations are strongly coupled through the viscosity. It should be noted that polyurethane reaction injection molding as it is presently carried out corresponds closest to case 1. Typical values for the properties for these systems are given in the nomenclature section.

Experiments

The experiments were performed using a specially designed mold (457 mm x 305mm x variable thickness) consisting of an aluminum base plate and transparent plastic top for visualization of the mold filling process. The movies were taken using a Nizo professional camera with Schneider F1.8 lens. The film used was Kodachrome 40,8mm; 3200°K quartz lights were used.

The mold was instrumented with one pressure transducer (Entran Devices, Inc., Model No. EPS-1032-100) and two thermocouples (20 gauge cooper constantan sheathed thermocouples 1/16" O.D. type s.s. sheath length 2 1/2", 35477-102 Marlin Manufacturing Co.) as shown in Figure 3. The pressure transducer was screwed into the base plate. The thermocouples were introduced through 1/16" holes in the side walls. The pressure transducer was calibrated in situ. A commercial RIM machine was used (Admiral 900-2HP-dual speed, 15-90 lb/min throughput).

The pressure and temperature data were recorded using real time data aquisition with a Modcomp II minicomputer. The chemical system used was Union Carbide's RIM 2200, without the blowing agent. Its components are given in table 1. The resin and isocyanate temperatures were 60°C (140°F) and 24°C (75°F), respectively. The mold was preheated in an oven to an operating temperature of 65°C ± 5°C, as determined in the aluminum base plate.

Two mold thicknesses, three flow rates and two catalyst levels were studied. The experimental conditions are summarized in table 2. The gel times for the two catalyst levels were 2 secs. for the high level (0.1 pphr) and 3 secs. for the normal level (0.075 pphr). They were determined by allowing the material to flow from the mixing head into a disposable bucket (25 cm diameter, 30 cm deep) and recording the time at which the mixture could no longer be stirred by hand.

To model mold filling for the RIM process, kinetic and rheological data are needed. The kinetics were obtained by the adiabatic temperature rise method (3,11)Viscosity vs. time was recorded using a cone and plate viscometer under isothermal conditions (12). These methods are described in detail elsewhere.

Results and Discussions

Figure 4 shows a typical pressure and temperature rise versus time. The pressure increases fairly linearly during filling. After the mold is filled, there is a pressure decrease if the mold is not overpacked or reaction is not too fast ($\bar{K} \ll 1$). The pressure increase afterwards is due to foaming, probably due to the small amount of dissolved water. The temperature remains nearly constant during filling, increasing afterwards. Figure 5 shows the pressure rise for experimental sets 2 and 3. The data from several different runs is fairly repeatable, particularly considering the low pressures involved. As can be seen they are fairly linear, as would be the case for a constant viscosity material. For both sets, the ratio of filling time to characteristic reaction time ($\bar{K}$) is small.

Figure 6 shows the pressure rises for sets 4, 6, 7 and 8. For sets 4 and 8 the pressure rise is linear; $\bar{K}$ is less than 0.2. For sets 6 and 7 $\bar{K}$ is greater than 0.2 and the increase in viscosity due to chemical reaction is noticeable, especially for set 6. For set 6 the material gelled before the mold was completely filled as shown in Figure 7. The results are summarized in table 2. The last column contains the predicted pressures using equation (14). The viscosity used was obtained by the weight average of the viscosities of the starting materials. For the thick mold they were taken at the starting material temperature. For the thin mold better agreement with the pressure data was found when viscosities were evaluated at the mold wall temperature. This is due probably, to the higher effect of heat conduction from the wall for the thin mold.

The flow front was found to be unstable at high flow rates and stable at low flow rates as shown in Figure 8. The transition from stable to unstable was estimated to occur at an average speed of ~0.55 m/s (1.8 ft/s). Experiments are currently in progress to obtain a better estimate of the transition speed. Evidence of fountain type flow was obtained. For example, when a drop of ink was placed in the mold, if its height was less than h/2, the ink drop appeared only in the bottom of the molded plaque. If the height of the ink drop was more than h/2, the ink appeared in the top and bottom of the molded part.

Conclusions

As can be observed from the experimental data, the pressure rise during filling for the RIM process is low. If the ratio of filling time to the characteristic reaction time, $\bar{K}$, is less than 0.2, the viscosity can be assumed constant during filling. If $\bar{K}$ is greater than 0.2 incomplete filling and weld lines may be a problem. The flow front is unstable at high flow rates.

Experiments are currently in progress with large molds. A systematic study of weld line development and flow front instability is being undertaken. The mathematical model for cases when the viscosity can not be assumed constant is being tested.

Acknowledgements

This research was supported by grants from the National Science Foundation, Division of Materials research and the Union Carbide Corporation.

Nomenclature

Where given the numerical values of the constants were those used in this study

C_A = concentration of species A (mole/m^3)

C_o = initial hydroxyl concentration = 2.4 x 10^3 mole/m^3

C^* = dimensionless extent of reaction = $(C_o - C)/C_o$

C_c = catalyst concentration = 0.07 and 0.1 pphr (Kg/100Kg resin)

C_p = heat capacity at constant pressure = 1.7 x 10^3 $\frac{J}{Kg\ °K}$

D_{AB} = diffusion coefficient = 10^{-12} $\frac{m^2}{sec}$

h = mold thickness = 3.2mm and 6.4mm

$\tilde{k}$ = thermal conductivity = (33 - 67)10^{-2} J/m °Ks

k = reaction rate constant = $\frac{m^3}{mol\ s}$

$k_{\theta M}$ = reaction rate constant (evaluated at temperature θ_M) = 37 x 10^{-6} $\frac{m^3}{mol\ s}$ (at C_c = 0.07 pphr) and 49 x 10^{-6} $\frac{m^3}{mol\ s}$ (C_c = 0.1 pphr)

k^* = dimensionless kinetic rate constant = $\frac{k}{k_{\theta M}}$

L = length of mold = 457 mm

Q = flow rate (m^3/s)

t = time (s)

t_f = filling time (s) = $\frac{w\ h\ L}{Q}$

t^* = dimensionless time = $\frac{t}{t_f}$

t_r = reaction half life (s) = $(k_{\theta M}\ C_o)^{-1}$

v_x = velocity in the x direction (m/s)

v_y = velocity in the y direction (m/s)

v_z = velocity in the z direction (m/s)

v_x^* = dimensionless velocity = v_x / $\langle v_x \rangle$

$\langle v_x \rangle$ = average velocity (m/s)

w = mold width = 305 mm

x^* = dimensionless axial variable = x/L

y* = dimensionless neutral direction = y/w

z* = dimensionless transverse direction = z/h

$\left(\frac{\partial p}{\partial x}\right)^*$ = dimensionless pressure gradient = $\frac{\left(\frac{\partial p}{\partial x}\right)}{\frac{Q\,\eta_o}{h^3 w}}$

ρ = density (Kg/m^3)

θ = temperature (°K)

θ_M = mean temperature = $\frac{\theta_o + \theta_w}{2}$

θ_o = incoming material temperature = 328°K

θ^* = dimensionless temperature = θ/θ_M

θ_w = wall temperature = 338°K

η = viscosity = (Pa. s)

$\eta_{\theta o}$ = viscosity of the initial materials (at θ_o) = 5.8

$\eta_{\theta w}$ = viscosity of the initial materials (at θ_w) = 2.4

η^* = dimensionless viscosity = $\eta / \eta_{\theta M}$

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Table 1 Composition of Union Carbide RIM 2200

Polyol Stream (weight percent)	%	Isocyanate Stream (weight percent)	%
Niax Polyol 31-23 (polyether polymer polyol M = 5000)	85.0	Isonate 143L (1, 4 diphenyl methane diisocyanate)	100.0
1, 4 butane diol	15.0		
dibutyltindilaurate (catalyst)	(0.075, 0.1)		
gr. of polyol / gr. isocyanate	= 1.8		

Table 2 Results of Mold Filling Experiments

Set No	Experiment	h(mm)	C_c(pphr)	Q(cm^3/s)	t_f(s)	$\bar{K}$	β_1	β_3	Pressure (Pa x 10^{-3}) Exp	Predicted
1	21,22	3.2	0.075	369	1.20	0.11	0.026	0.044	31.7	49.6
2	14,15,16	3.2	0.075	521	0.85	0.08	0.018	0.032	60.7	70.3
3	11,12,13	3.2	0.075	737	0.60	0.05	0.013	0.020	75.8	99.3
4	23,24,27,28	6.4	0.075	553	1.60	0.14	0.009	0.056	16.5	22.8
5	46,47,48	3.2	0.1	328	1.35	0.16	0.030	0.064	47.6	44.1
6	38,39,40	6.4	0.1	364	Short Shot	0.29	0.013	0.116	>100	15.2
7	30,31,32	6.4	0.1	492	1.80	0.22	0.010	0.088	25.5	20.0
8	41,42	6.4	0.1	644	1.38	0.16	0.008	0.064	20.7	26.9

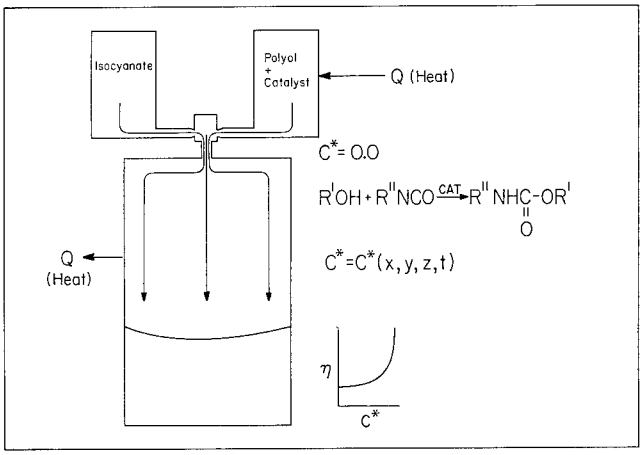

Figure 1 Schematic representation of the RIM process

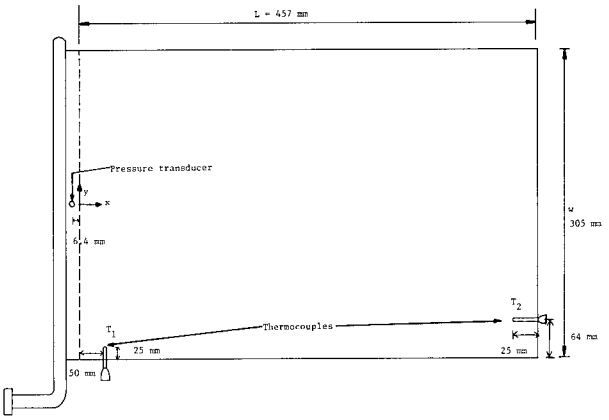

Figure 3 Schematic of transparent mold

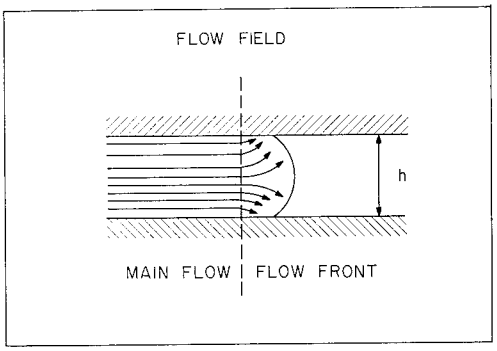

Figure 2 Side view of flow field for a narrow gap mold

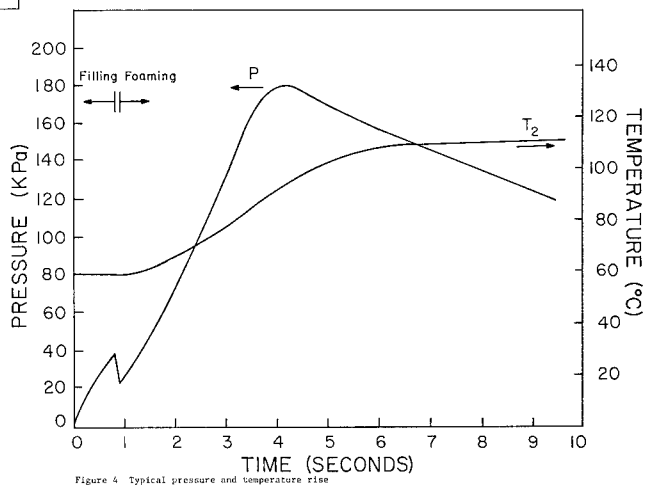

Figure 4 Typical pressure and temperature rise

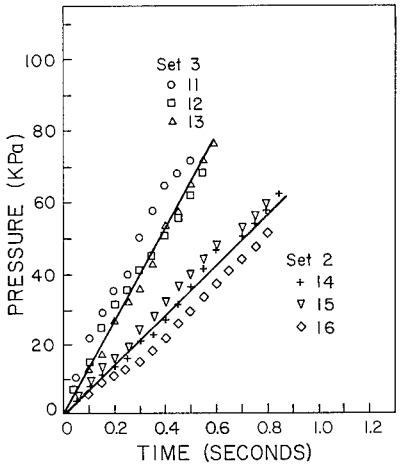

Figure 5 Pressure rise for sets 2 and 3 (the experimental conditions are indicated on table 2).

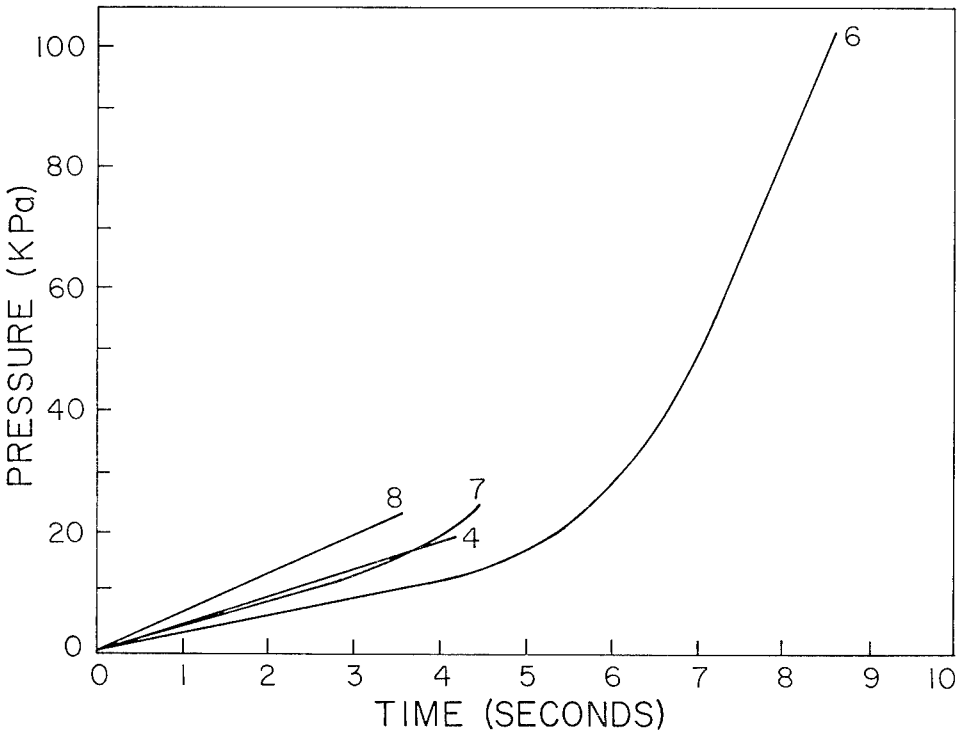

Figure 6.Pressure rise for sets 4, 6, 7 and 8 (the experimental conditions are indicated on table 2).

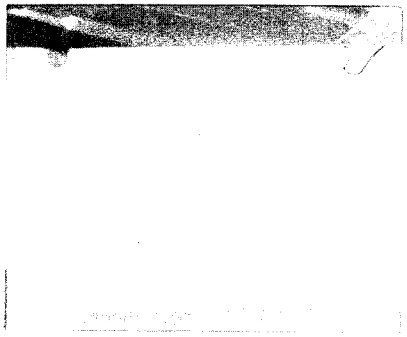

Figure 7 Material gelled before filling was completed.

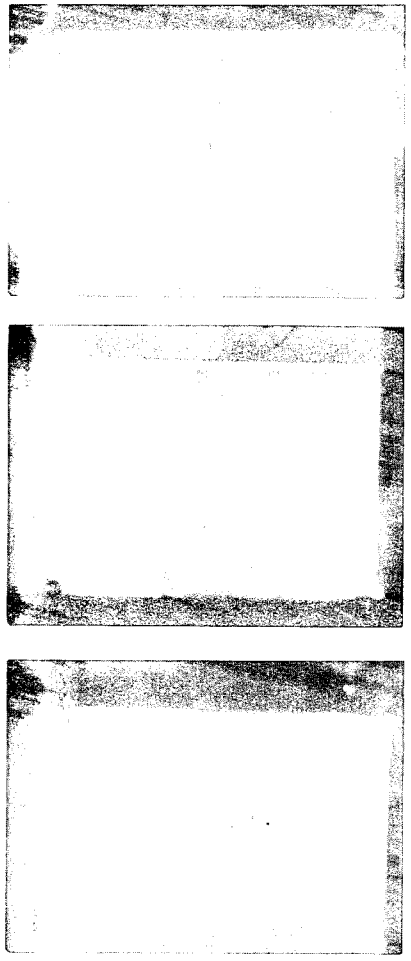

Figure 8 Development of flow front instability
a) Stable ($\langle V_x \rangle$ = 0.4 m/s)
b) Semistable ($\langle V_x \rangle$ = 0.5 m/s)
c) Unstable ($\langle V_x \rangle$ = 0.8 m/s)

SHRINKAGE IN RIM URETHANES

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and

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The use of plastics in automotive applications by all estimates will increase dramatically in coming years as the industry strives to meet demands for vehicle weight reduction. Polyurethane elastomers produced by the reaction injection molding (RIM) technique will play an important role in this increase. Since its introduction on large scale production basis in 1975, RIM urethane has seen steady growth. Most of this growth has been in the low modulus, 20 to 30,000 psi, range for fascia or bumper cover applications. From a market share of approximately 6 percent in 1977, RIM fascia/bumper applications hold an approximately 33 percent share in the 1980 U.S. automotive market.

A number of technical papers have presented data on various processing parameters which influence the physical properties of RIM elastomers. Largely ignored has been the problem of tool sizing as related to various factors influencing shrinkage. Often when a part is in the early design stages, the exact requirements for the design and elastomer properties are not known. The RIM process permits the use of relatively low cost tooling for prototyping which speeds development efforts. Unfortunately, this can lead to erroneous conclusions regarding not only the properties, but to the shrinkage rates when production tooling is used.

While any changes in physical properties are important, changes in part shrinkage can become particularly critical. Production tooling may be sized for a specific amount of shrinkage as specified by the supplier of polyurethane systems or as determined in prototype tooling. The shrinkage in the production part may be different if material requirement change, if the tooling materials are different, or if an alternate source of material is required. Shrinkage characteristics must be controlled to achieve satisfactory results.

Evaluations were carried out on a fascia grade system to determine the effects of type and amount of blowing agent, mold material, mold temperature, part thickness, and post cure conditions. The most significant effect seen was the level of blowing agent; as the blowing agent level increased, so did shrinkage. Essentially no difference was seen between the use of fluorocarbon 11 and methylene chloride on a molar basis. Temperature was the second most important factor. This effect includes not only the initial mold temperature, but also the effects of exothermic heat. The test mold had both aluminum and epoxy sections and sections of varying cross section thickness. For a given controlled temperature for mold heating/cooling, the epoxy section always had a lower surface temperature than the aluminum section. The temperature of the polyurethane during molding was, however, higher in the epoxy section because the exothermic heat is dissipated slower. Similar effects are seen in thick cross sections. As the temperature increases, shrinkage increases. Post cure appears to have only a minor effect. Most shrinkage occurs after demold as the part cools.

Reinforced RIM (RRIM) is expected to see significant usage in large automotive body panels requiring greater structural integrity than do fascia. Most of the development work to date has been centered around the use of milled glass fibers as the reinforcing agent. Shrinkage is significantly reduced depending on the use level of glass fiber. The effect is, however, highly directional. Part design and gating must be carefully considered to take advantage of this effect.

Careful attention to the factors which affect shrinkage can aid in the proper sizing of production tooling. On the other hand, use of these factors can be used to change the shrinkage of a specific chemical system to accommodate existing tooling.

A UNIQUE RUBBER-MODIFIER FOR SMC

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INTRODUCTION

The use of polymers as low shrink additives in sheet molding compounds (SMC) has been important for controlling dimensional stability. The high performance, polymeric additives have been successfully used to give Class A surfaces for automotive application. SMC with Class A surface is expected to grow rapidly for exterior body panels with recent emphasis on weight savings in automotive design.

Most additives are thermoplastics and generally do little to improve energy-absorbtion. Recently, rubber-modifiers for SMC have been developed to give energy-absorbing characteristics. One type of these rubbers is a class of carboxy-terminated, butadiene-styrene block copolymers. These block rubbers impart not only energy-absorbing characteristics, but also a good balance of mechanical properties, low shrinkage, little or no sink marks, greatly reduced long term waviness, and excellent pigmentability. This is a unique combination of qualities found in one additive. This paper describes the use of Solprene® 312 rubber and related carboxy-terminated, butadiene-styrene block copolymers as additives for SMC.

Energy-absorbing Characteristics - Brittleness is an inherent property of the crosslinked polymeric matrix of SMC. Increased energy-absorption is important in the automotive industry to reduce scrap and rework of molded SMC from breakage in handling and shipping. A number of methods have been established to show energy-absorbing characteristics of SMC. These methods generally test the resistance to failure of moldings from either a moving projectile or an applied stress. Several have been used to evaluate SMC modified with the block rubbers.

Reverse impact strength of rubber-modified SMC improves with increased molecular weight and amount of rubber (Table I). Failure was determined as the minimum height of drop of a 277g (0.6 lb) dart necessary to crack the side reverse to the point of impact of a 63.5-cm (6-in) diameter, unsupported area. Most failures of rubber-modified SMC were a single crack whereas star cracks were generally observed with thermoplastic additives.

More severe drop impact tests have shown rubber-modified SMC to have only a few cracks on the side of impact with a drop of a 1.46 Kg (3.2 lb) dart from a height of 91.5 cm (3 ft). Thermoplastic modified SMC exhibited severe cracking on the side of impact under these conditions.

Tensile stress-strain curves have also been used to determine toughening characteristics of SMC. Figure 1 shows some comparisons of typical curves which were obtained on an Instron with an extensiometer. The rubber-modified SMC had higher tensile strength, more area under the curve, and higher elongation than the thermoplastic modified SMC. The shapes of the curves are also different. The thermoplastic modified SMC showed an abrupt change in the slope of the curve after very little elongation. The rubber-modified compounds gave curves with a more uniform continuous change in slope.

The flexural fatigue of SMC was improved with increasing level carboxy-terminated block rubbers (Figure 2). The thermoplastic modified SMC had the least resistance. It should be pointed out that there was scatter in the data possibly from the machining of the sample and its shape. The relative positions of the curves should remain the same although the slope and shape of the curves could change as more data are gathered.

Other tests such as bending and twisting have been used and have also shown rubber-modified SMC to be energy-absorbing. Such moldings did not emit the "cracking sounds" typical of thermoplastic modified SMC when flexed. One such test, a torsion test, was run at Eagle-Picher on an automotive front end, Table II. The rubber-modified front end could be twisted to a greater degree and required greater force before first creak and crack than the thermoplastic modified front end.

A radial bend test was run at General Tire. Test bars were bent to conform to arcs of various radii until the surface cracked. Elongations at this failure were determined and showed the elongation of rubber-modified SMC to be greater than thermoplastic modified SMC (Table III).

Characteristics and Mechanical Properties of Rubber-Modified SMC - Energy-absorbing characteristics alone are not the only considerations for a modifier. Mechanical properties, appearance and other properties are also important. Variations in a typical SMC formulation (Table IV) have given some interesting results with rubber-modified SMC. Solprene 312 rubber with a number average molecular weight of about 100,000 is the rubber used in this paper unless otherwise indicated.

The mixing procedure was important for obtaining the best stability of SMC paste with these block rubbers since the rubber is inherently incompatible with polyester resins. Mixing zinc stearate first with the polyester resin and a styrene solution of rubber was better than later addition of the stearate. Typically, the polyester and the rubber solutions are mixed 1-2 minutes followed by the addition of zinc stearate with 1-2 minutes of mixing with a Cowles mixer. The remaining components are added in typical order. Stable pastes are made by this method.

Although these carboxy-terminated rubbers impart low shrinkage, addition of PEP-100 cure promoter not only reduces shrinkage further, but also decreases surface roughness and increases gloss (Table V). This same effect has been found in rubber-modified BMC. The biggest improvements in shrinkage and appearance were realized at a t-butyl perbenzoate/cure promoter weight ratio of 4/1. At this ratio very little or no sink marks were noted.

Rubber-modified SMC with the cure promoter was comparable to thermoplastic modified SMC with respect to surface roughness and gloss (Table VI). In general, flexural modulus was decreased slightly with the rubber modifier, but other mechanical properties are comparable to or better than those with thermoplastic additives. Additional data in another system are in Tables VII and VIII.

Although the effect of the molecular weight of the rubber has not been screened as rigorously in SMC as in BMC, similar trends have been found. The surface roughness decreased and gloss increased as the molecular weight increased (Table IX). There were some variations in mechanical properties with molecular weight but not enough data has been accumulated to make generalized statements. Significant trends of mechanical properties with molecular weight have not been seen in BMC.

The amount of calcium carbonate was shown to be critical in rubber-modified SMC. At least 150 parts per 100 parts of total monomer-polymer was necessary for good molded appearance (Table X). If less calcium carbonate was used, hardness was low. Greater than 150 parts carbonate gave better moldings than 150 parts. The average roughness height and shrinkage decreased with increasing filler.

Although most moldings have been small laboratory test moldings, large ones have also been made. These large moldings also had excellent low shrinkage but most importantly they had very

little long-term waviness and Class A surface. Large and relatively flat, automotive, body panels can be obtained from SMC modified with these block rubbers. This is very important with consideration to replacing stamped metal with SMC for weight savings. Good sink control over ribs and bosses is another excellent feature of rubber-modified SMC which makes molded-in ribs probable in some applications. The design of the rib seems to be critical and is being investigated.

Viscosity-Associated Characteristics - Solutions of these carboxy-terminated butadiene-styrene block copolymers in styrene are more viscous than are thermoplastic modifiers. Figure 3 shows the temperature dependence of these solutions at 25 and 30% solids. Figure 4 shows the viscosity dependence upon concentration of rubber in styrene. The rubbers in Figures 3 and 4 are in the order of 100,000 molecular weight. The results of using 25% solids solution in SMC showed no disadvantages with the lower viscosity solution when used at a level of 12%, Table XI.

The use of ground rubber has some advantages over solutions in styrene in handling and storage. Although the use of ground rubber in SMC may just be an attractive curiosity at this time, some encouraging results were obtained (Table XI), which will be pursued further. The results with regard to molded appearance were not as consistent batch to batch as those obtained using the rubber solution. It is felt that with either proper mixing or a better mixer, reproducible good results can be obtained. Keeping the rubber from agglomerating when added to the polyester resin and styrene appeared to be important for best results. It is also noteworthy that the SMC paste viscosities with ground rubber, particularly at the 15% rubber level, were lower than with solutions (Table XII). This is an indication that the rubber has not completely dissolved, even though fairly good results were obtained as shown in Table XI.

Figure 5 shows the dependence of viscosity upon the molecular weight of the rubber. The effect of molecular weight upon appearance of moldings and energy-absorbing characteristics, as discussed earlier, have shown the higher molecular weights to be more desirable. A molecular weight of approximately 100,000 was felt to be the best compromise.

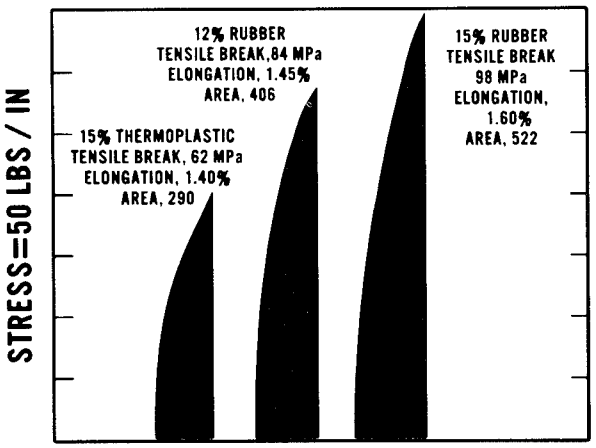
SMC pastes containing carboxy-terminated butadiene-styrene block copolymers respond to composition variables in the same fashion as pastes containing thermoplastic modifiers. Generally, pastes containing these rubbers are more viscous than analogous compositions with other modifiers. Even with the relatively higher viscosity, glass wet out is possible. SMC up to 40 oz in weight has been made even at 15% rubber level. Although the use of a chain mesh belt makes glass wet out easier on this heavy SMC, it is not necessary. The low thixotropic index of rubber-modified SMC helps to overcome the disadvantages of higher paste viscosity (Table XIII).

Figure 6 shows the viscosity of rubber-modified SMC pastes as a function of temperature. Although the viscosity decreases with increasing temperature, this may or may not be an advantage depending upon the reactivity of the system toward thickening. In a slow thickening system, either from the polyester resin and/or the level and type of thickener, the temperature dependence may be useful. However in a rapid thickening system, such as with magnesium oxide as a thickener, the rate of thickening increases with increasing temperature. Figure 7 shows the initial thickening as a function of temperature and the advantage of maintaining lower temperatures in a very reactive system. Long term thickening at 25C of the rubber-modified SMC is shown in Figure 8 with both magnesium oxide and magnesium hydroxide for one system. Rubber-modified SMC has a wide molding viscosity range for it has been successfully molded up to 100+ million cps paste viscosity.

Paintability and Pigmentability - Paintability of rubber-modified SMC has been found to be good, and paint pops were reduced over standard thermoplastic modified SMC. Table XIV shows the results of some paint tests.

Pigmentability completes the compliment of outstanding characteristics of carboxy-terminated butadiene-styrene block copolymers. A variety of pigments have been used, some of which are accepted as difficult pigments to use.

FIGURE 1
TYPICAL ENERGY ABSORPTION CURVES
RUBBER VS THERMOPLASTIC MODIFIED SMC-
25% GLASS



STRAIN-ELONGATION = 1% PER INCH
STRAIN RATE = 0.2 INCHES PER MINUTE

FIGURE 2
FLEXURAL FATIGUE OF MODIFIED SMC

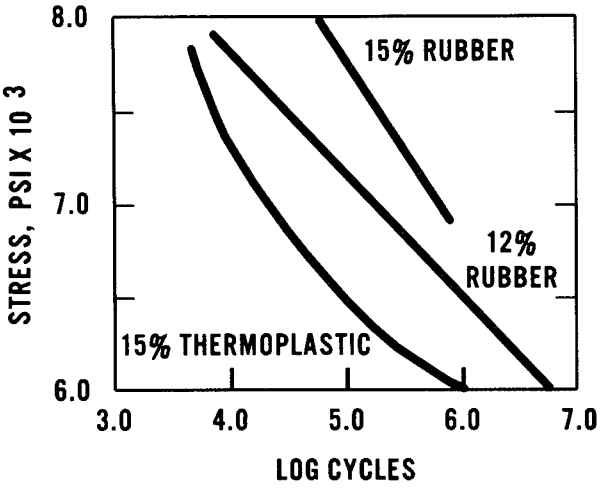


FIGURE 3
100,000 M_N RUBBER IN STYRENE
VISCOSITY VS. TEMPERATURE

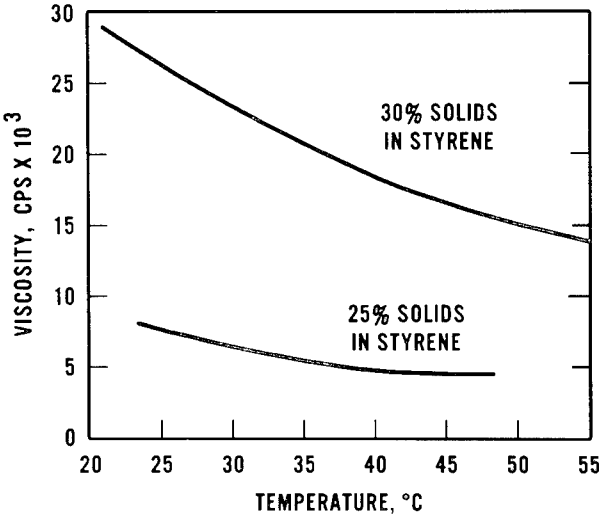


FIGURE 4
100,000 M_N RUBBER
CONCENTRATION IN STYRENE

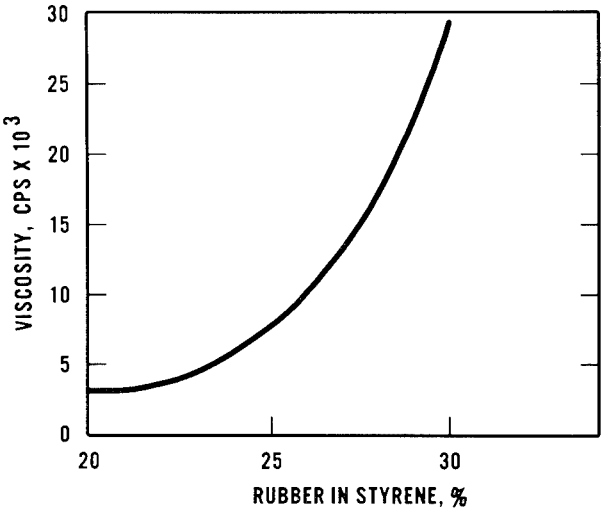


FIGURE 5
VISCOSITY AS A FUNCTION OF MOLECULAR WEIGHT

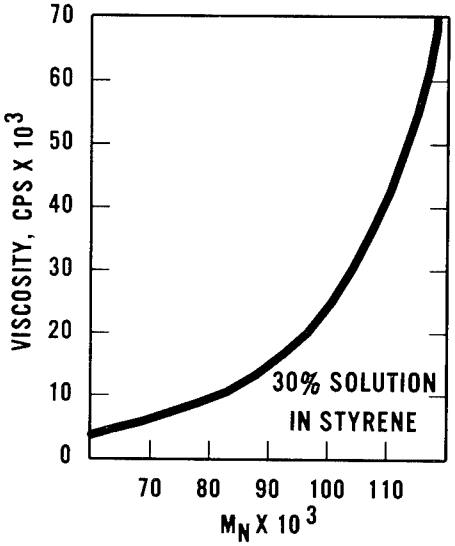


FIGURE 6
UNTHICKENED SMC PASTE
VISCOSITY VS TEMPERATURE

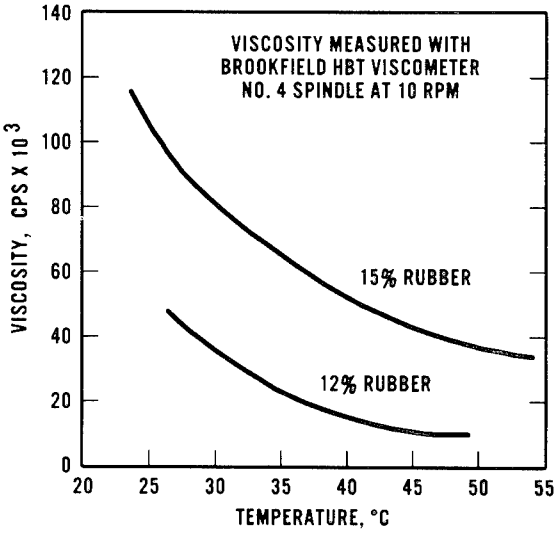


FIGURE 7
INITIAL THICKENING OF SMC PASTE
12% RUBBER, 1 PART MgO

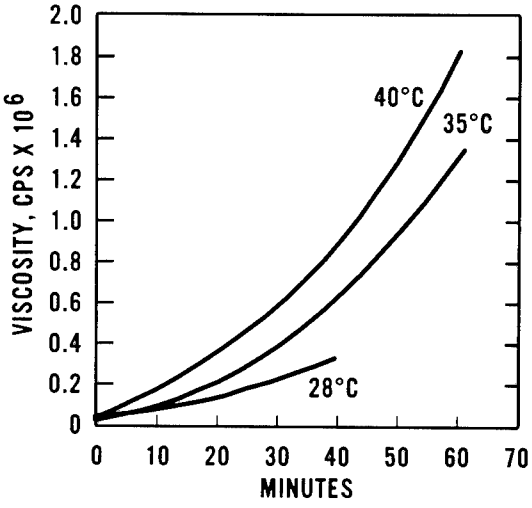


FIGURE 8
25°C THICKENING OF SMC PASTE
15% RUBBER

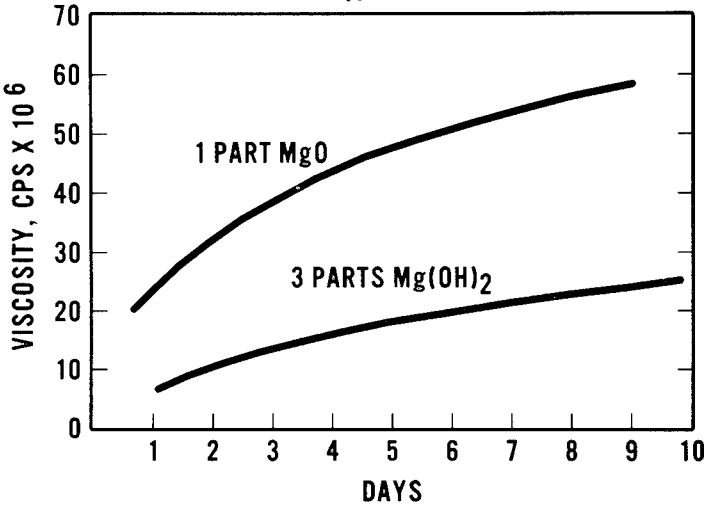


TABLE I

REVERSE IMPACT OF RUBBER-MODIFIED SMC

Modifier	Molecular Weight, Mn x 10^3	Percent Modifier[a]	Reverse Impact,[b] cm
Thermoplastic	--	15	9
Rubber	100	9	9
		12	10
		15	15
		20	30
Rubber	130	9	10
		12	13
		15	18

a - Modifier as a percent of total monomer-polymer.
b - 277g dart dropped on a 63.5 cm diameter unsupported area.

TABLE II

TORSION TEST[a]

Modifier	First Creak	First Crack
15% Rubber	35 lbs at 45°	40 lbs at 54°
Thermoplastic	20 lbs at 20°	30 lbs at 40°
Control standard	20 lbs at 28°	45 lbs at 45°

a - From Eagle-Picher Industries automotive front used.

TABLE III

RADIAL BEND TEST[a]

Modifier	Elongation at Failure, %
15% Rubber	1.86
Thermoplastic	1.26

a - From General Tire.

TABLE IV

TYPICAL SMC FORMULATION

60-50 Parts	Polyester resin[a]
40-60 Parts	Rubber solution (30% in styrene)[a]
150 Parts	Calcium carbonate
3 Parts	Zinc stearate
1 Part	t-Butyl perbenzoate
0.25 Part	PEP-100 Cure promoter[b]
0.5-3 Parts[c]	Thickener
25-28%	1-Inch glass

a - 100 Parts total polyester resin-rubber solution.

b - Air Products and Chemicals, Inc.

c - 0.5-1.25 parts MgO or 3 parts $Mg(OH)_2$.

TABLE V

EFFECT OF PEP-100 CURE PROMOTER IN RUBBER-MODIFIED SMC

Rubber, %[a]	PEP-100, Parts	Glass, %	Average Roughness Height, μ	Gloss, %	Shrinkage, mm/m[b]	Barcol Hardness	Flexural Modulus, MPa x 10^3[c]	Flexural Strength, MPa[c]	Tensile Break, MPa[c]	Notched Izod, J/m[d]
12	0	23	0.41	82	1.2	30-58	12	150	42	710
12	0.25	24	0.28	86	0.9	25-68	11	190	58	800
15	0	24	0.54	68	0.6	22-48	12	175	62	770
15	0.25	26	0.26	84	0.2	45-60	12	160	70	780
15	0.5	24	0.25	78	-0.1	30-58	11	145	67	730

a - Rubber as a per cent of the total monomer-polymer.
b - 1 mm/m = 1 mil/in.
c - 1 MPa = 145 psi.
d - 1 J/m = 0.0187 ft-lb/in.

TABLE VI

PROPERTIES OF THERMOPLASTIC AND RUBBER-MODIFIED SMC

Modifier %	Modifier Type	System[b]	PEP-100 Part	Glass, %	Average Roughness Height, μ	Gloss, %	Shrinkage, mm/m	Barcol Hardness	Flexural Modulus, MPa x 10^3	Flexural Strength, MPa	Tensile Break, MPa	Notched Izod, J/m
14	Thermoplastic I	A	0	25	0.29	82	0.75	58-70	12	150	80	740
15	Thermoplastic II	B	0	26	0.23	78	0.5	52-60	11	180	62	990
12	Rubber	A	0.25	24	0.28	86	0.9	25-68	11	190	58	800
15	Rubber	A	0.25	26	0.26	84	0.2	32-60	12	160	70	780
9	Rubber	B	0	24	0.33	37	1.4	42-67	11	160	75	970
12	Rubber	B	0	24	0.30	68	0.3	35-55	10	170	93	820
15	Rubber	B	0	26	0.41	57	0.3	38-59	10	180	97	970

a - Modifier as a per cent of total monomer-polymer.

b - Systems vary in types of polyester resin, calcium carbonate and glass used.

TABLE VII

EFFECT OF AMOUNT OF RUBBER ON SURFACE

Modifier %[a]	Modifier Type	Average Roughness Height, μ	Gloss, %	Shrinkage, mm/m	Barcol Hardness
12.5	Rubber	0.25-0.3	75	0.9	39-55
15	Rubber	0.4-0.5	69	0.5	22-39
20	Rubber	0.5-0.6	47	0.1	0-19
16	Thermoplastic	0.15-0.35	74	0.5	33-41

a - Per cent of total monomer-polymer.

TABLE VIII

EFFECT OF AMOUNT OF RUBBER ON MECHANICAL PROPERTIES

% [a]	Modifier Type	Flexural Modulus, MPa x 10^3	Flexural Strength, MPa	Tensile Break, MPa	Elongation, %	Tensile Modulus, MPa x 10^3	Notched Izod, J/m	Unnotched Izod, J/m	Broadside Impact, J/m
12.5	Rubber	12	190	70	0.8	18	840	970	650
15	Rubber	12	200	82	1.4	13	950	1100	760
20	Rubber	9.7	160	56	1.7	11	890	1200	640
16	Thermoplastic	12	180	76	0.9	14	830	1100	700

a - Per cent of total monomer-polymer.

TABLE IX

PROPERTIES OF RUBBER-MODIFIED SMC - VARIABLE MOLECULAR WEIGHT

15% Rubber M_N x10^{-3}	System[b]	PEP-100 Part	Gloss, %	Average Roughness Height, μ	Gloss, %	Shrinkage, mm/m	Barcol Hardness	Flexural Modulus, MPa x10^{-3}	Flexural Strength, MPa	Tensile Break, MPa	Notched Izod, J/m
60	A	0.25	22	0.62	40	0.1	6-45	10	130	60	820
80	A	0.25	20	0.49	36	0.1	28-60	11	150	61	760
120	A	0.25	26	0.26	84	0.2	32-60	12	160	70	780
100	B	0	26	0.41	57	0.3	38-59	10	160	77	960
130	B	0	27	0.38	30	0.3	30-52	9.6	170	68	960

a - Carboxy-terminated Bd-Sty rubber as a per cent of total monomer-polymer.

b - Systems vary in types of polyester resin, calcium carbonate and glass used.

TABLE X

EFFECT OF AMOUNT OF CALCIUM CARBONATE

$CaCO_3$, Parts[a]	Average Roughness Height, μ	Gloss, %	Shrinkage, mm/m	Barcol Hardness	Flexural Modulus, MPa x 10^3	Flexural Strength, MPa	Tensile Break, MPa	Tensile Modulus, MPa
125	0.4-0.5	73	0.6	0-20	9.4	170	63	12
150	0.4-0.5	69	0.5	22-39	12	200	62	13
160	0.35-0.4	69	0.2	29-39	12	220	76	13
175	0.3-0.35	75	0.2	29-36	12	200	76	20
200	0.25-0.3	79	0	24-43	14	170	--	--

a - Parts per 100 parts total monomer-polymers.

TABLE XI

PROPERTIES OF SOLPRENE 312 RUBBER-MODIFIED SMC - VARIABLE STYRENE AND FORM OF RUBBER

Rubber, %[a]	Form	Average Roughness Height, μ	Gloss, %	Shrinkage, mm/m	Barcol Hardness	Flexural Modulus, MPa x 10^{-3}	Flexural Strength, MPa	Tensile Break, MPa	Notched Izod, J/m
12	30% solution[b]	0.28	86	0.9	25-68	11	190	67	800
12	25% solution[b]	0.24	79	0.3	35-62	14	180	81	900
15	30% solution[b]	0.26	84	0.2	32-60	12	160	70	780
15	ground[c]	0.43	61	0.05	25-50	12	170	83	670
15	ground[c]	0.31	73	0	42-72	12	180	77	850

a - Rubber as a per cent of total monomer-polymer.

b - Per cent solids in styrene monomer.

c - Ground through 10 mesh screen, styrene monomer added to be equivalent to using 30% rubber in styrene.

TABLE XII

EFFECT OF MODIFIER FORM ON SMC PASTE VISCOSITY

Form	Level (phr)	Viscosity (cps)
Solution	15	50,000
Solid	15	29,000
Solution	12	18,000
Solid	12	17,000

Viscosities determined with HB4 spindle at 20 rpm; temperature approximately 50°C.

TABLE XIII

THIXOTROPIC INDICES UNTHICKENED SMC PASTE

Modifier	Thixotropic Index[a]
12.5% Rubber	1.5-1.8
15% Rubber	1.5-1.8
Thermoplastic	2.7
Thermoplastic	2.2

a - Measured with Brookfield HBT viscometer, number 6 spindle

$$\text{Thixotropic index} = \frac{\text{Viscosity at 5 RPM}}{\text{Viscosity at 50 RPM}}$$

TABLE XIV

PAINT TEST RESULTS

Test	Results with Lacquer
Adhesion[a]	
Initial	9+
Florida, 6 months	9+
Gravelometer	9+
Sand back	Pass
Blistering	None
Crack cycle[b]	Pass

a - Cross hatch tape adhesion.

b - Cycle from 100°F to -10°F at 100% RH.

SMC contained 15% rubber, 100,000 M_N.

IMPACT TOUGHNESS EVALUATIONS FOR RANKING SMC COMPOSITES FOR AUTOMOTIVE USE

MR. J. A. REITZ III
DR. L. J. FERRARINI
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As interest in high performance FRP composites as a feasible and cost effective alternative to either steel or aluminum in structural applications continues to develop, a need to more effectively characterize key composite performance parameters has also grown. Considering that the performance of a high strength composite is a function of its basic components -- type of reinforcement, filler, and resin -- the need for lab scale tests that accurately demonstrate the qualitative effect of any system variation is paramount to the optimization of the composite. As the difficulties involved in using any single laboratory test to efficiently rate materials in an order that correlates to the actual material ranking found in the end-use application are recognized, it is important to develop a testing strategy which fully characterizes a given material in regard to a specific performance parameter and a specific end use. One of the key parameters involved with applications requiring high strength, high performance composite systems is toughness. The field experience of ICI Americas with the ITP™ family of high performance resins is particularly relevant to this discussion, providing an actual case study of material screening program based on toughness.

The purpose of this paper is to explore a working definition of toughness as it relates to structural applications, discuss a testing strategy that leads to an effective material ranking through lab scale tests, and to relate a specific example of the application of this test strategy to material selection for actual end uses.

Difficulty is encountered in arriving at a generally accepted working definition of toughness due to its qualitative nature. Selection of a realistic toughness tests is complicated by the need to quantify this ambiguously-defined material characteristic. The definition which will be addressed in this discussion relates toughness to the comparative ability of a system to accommodate a shock load by dissipation or absorption of added energy. This definition thus focuses on a relative rate of energy loading, while allowing the mode of stress application to vary. By relating toughness to an energy value, the contribution and synergism of various individual factors, such as strength and elongation, to overall material toughness is recognized. This definition thus refers to practical impact situations encountered when a molding is dropped, struck with a missile, such as a flying stone, or shock loaded through a bolted fixture, such as a latch mechanism.

The toughness of composite materials is a function of the properties of both the matrix resin and the reinforcement as well as the interaction of the two. In an attempt to quantify toughness, single factors which partially contribute to overall material performance have often been measured. Thus, tensile elongation, energy required for tensile failure, elongation required for surface stress crazing initiation, interlaminar bond strength, and internal mechanical dampening have been presented as toughness indicators. Although each of these tests yields useful information concerning a particular aspect of material behavior, tests which evaluate a combination of these parameters of material toughness more accurately reflect the interaction of properties that contribute to toughness characteristics observed in actual use situations.

Overall, the most popular and efficient way to characterize toughness in fiber-reinforced composites is provided by impact testing. Impact testing encompasses a wide variety of test conditions and modes of stress application. Commonly used tests include notched Izod, tensile impact, falling weight, and puncture impact tests. The high rate of strain involved in impact testing is significant in characterizing material toughness, considering the viscoelastic sensitivity of plastic materials to strain rate. Thus, the effect of strain rate on material toughness may be minimized in the attempt to bridge the gap between lab test and actual part performance.

The deficiencies and limitations of the various impact tests have been well discussed in the literature. The thrust of the remainder of this discussion will be pointed toward an examination of how existing lab scale test tools may be used to more efficiently achieve an effective and relative performance ranking of materials.

This proposed testing strategy is a simple one: For a given application, the mode of part failure is identified and matched to the failure modes of the various bench scale tests for selection of the appropriate screening tools. For the purposes of this discussion, three commonly used tests will be examined -- notched Izod, instrumented tensile impact, and Rheometrics punch impact testing.

In the notched Izod test (ASTM D-256), the specimen is impacted in a two-point loading, cantilever beam configuration with a "V"-shaped notch on the tensile side of the specimen. The "V" notch concentrates and directs the impact stress while introducing a complex triaxial stress pattern and encouraging a brittle rather than a ductile failure. Due to the viscoelastic nature of plastics, the response of different materials to the notch (notch sensitivity) varies. Noting that the localized stress at the notch increases inversely with the notch radius, material comparisons with samples of two different notch radii results in a measure of a materials notch sensitivity. The notch sensitivity of a material thus describes the degree to which changes in localized stress concentrations affect impact resistance and is an important characteristic when considering specific end uses that involve sharp radii in the molded part, actual notches or effective notches such as drilled bolt holes.

A specific example which emphasizes the importance of evaluating notch sensitivity when appropriate to the end-use is polyether sulfone. An unnotched Izod test specimen cannot be broken at 200 ft. lbs./in. (ductile response) while notched specimens fail at less than two units (brittle response). The effective toughness of this material in a given application, then, is dependent on part design. The reliability of the test in ranking materials is dependent on the proper identification of the mode of failure as brittle or ductile. In the tensile impact test, ASTM D-1822, a type V dog bone tensile specimen is loaded in simple tension at a test speed of 7.6 mph. In addition to the total impact energy measured in the ASTM procedure, stress and energy levels at the point of initial fracture may be obtained with proper instrumentation. Considering the failure mode of a typical high performance polyester or vinyl ester composite, the total energy may be divided into two basic components -- initial fracture energy and fiber pull-out/fracture propagation energy. Since the failure point in actual end-use applications of structural plastics is seldom defined as catastrophic failure, this differentiation can prove quite useful in material ranking. Table I details the tensile impact properties of a series of SMC moldings based on ITP resin systems. Note that systems with similar total impact energy values, such as Samples D and F, may be effectively differentiated by both the values of initial fracture energy and initial fracture stress. Also, systems with similar total impact energy and initial fracture energy, such as Samples D and G, may be differentiated by initial fracture stress.

The Rheometrics punch impact tester does not represent a standardized test per se, but is most commonly used to perform a punch impact on a flat test panel with a 1/2" diameter ram at variable speeds. This impact situation results in a radial stress-strain distribution with a complex gradient of flexural and shear forces distributed through the test specimen. Upon impact, the specimen fails initially by tensile crazing on the test surface opposite the ram. As the impact sequence continues, fiber pull-out occurs on the specimen's tensile side until the ram penetrates the panel. Note that due to the rounded nose of the ram, the contact area of the ram and test specimen increases with ram penetration. Accurate normalization of test results over a range of thicknesses is not possible, requiring that test specimen thickness be held constant, preferably at a point comparable to those found in the prescribed end use.

The Rheometrics impact tester is fully instrumented and thus yields a breakdown of the total impact energy in the same manner as the instrumented tensile impact test. Because of the relatively complex mode of failure and lack of test standardization, care must be taken in interpreting test results. A typical load-vs.-time trace of a Rheometrics punch impact on a 65% chopped glass/fiber-reinforced SMC molding is shown in Diagram I. An initial inflection point is always observed prior to ultimate fracture and has often been attributed to the test specimen exhibiting yield properties or to a velocity change of the ram upon impact. Through a carefully designed series of experiments, this pseudo-yield point can be shown to be an initial point of specimen fracture in tension. The ultimate failure, then, represents the point of maximum specimen loading, accompanied by considerable fiber pull-out and penetration of the ram.

It should be again emphasized that selection of the above tests for discussion was intended only to introduce the diversity of recognized quantitative impact tests with their corresponding variety of general failure modes. The problem now becomes how to exploit existing test tools effectively in order to realistically differentiate composite systems and measure the effect of intra-system variations intended to optimize properties.

To explore the previously mentioned strategy of matching the failure mode of a particular application to those of various lab scale tests in order to optimize the material screening effort, an example of an actual material selection study will be discussed.

ICI Americas initiated a large scale material screening program to select an optimal high performance resin system for an automobile front bumper assembly. The primary objective was to select a system suitable for use in a chopped random glass SMC system capable of meeting performance requirements at relatively low part weights.

The first significant difference between the impact behavior of the bumper beam and the flat panel impact tests is that the stress distribution of the loaded bumper was a function of the geometry of the entire bumper assembly, and thus predictions of stress concentrations were complicated.

The bumper assembly consisted of a basic box-beam mounted to an automobile on either end by an energy-absorbing stroking device. The impact mode under consideration in this study consisted of striking the mounted bumper assembly on its centerline axis with a steel bumper attached to a weighted pendulum. Through finite element analysis of the bumper design, this type of impact was predicted to result in the mode of maximum deflection or strain, with a minimized torquing moment. Impact of the beam assembly represents a generalized three-point flexural loading situation with failure occurring in tension. This assumption was verified by actual performance testing of the bumper assembly. Part failure was defined as the energy loading required for initial cracking or crazing.

The actual screening program evaluated variations in type of resin, length of reinforcement, amount of filler loading, and the percent of reinforcement used in the SMC. This discussion will be limited to an examination of three 65% chopped random glass SMC systems, with the choice of resin being the principal variable (Table II). One system with a different level of filler and reinforcement loading 50% glass/25% filler has also been included to emphasize the degree of performance improvement possible with a given resin through variation of the other components of the composite system. Bench-scale impact tests conducted on these systems included the three previously discussed tests -- notched Izod, tensile impact, and Rheometrics ram punch impact. Note that fracture initiation in each test occurs in tension, yet the operative modes of stress distribution vary markedly.

Because the bumper assembly was bolted to the car at the ends of the beam away from the impact site and the provision for direct transfer of energy from the bolted section to the shock-absorbing mounts, the drilled bolt holes were not judged to be a critical factor in this particular mode of stress loading. The absence of other notches, sharp radii, or other similar stress concentrators in the bumper assembly diminished the importance of the Izod test in this screening program. The data presented in Table III indicates two general performance levels with no significant differentiation between materials within a group.

The Rheometrics punch impact tests provided a greater differentiation between materials, although performance ranking was dependent upon which test parameter was studied (Table III). Values for total impact energy mirrored the energies required for maximum fracture; however, ranking based upon the impact energy required for initial fracture differed significantly. Resin Systems A and B are almost equivalent, based on initial fracture energy, yet differ significantly when total impact energies are compared. One possible interpretation of this observation is that Resin System B has a relatively higher resistance to fracture propagation than System A under the given conditions.

The mode of stress loading of the punch impact test was determined to be unrepresentative of the bumper beam impact due to the following considerations:

1. The steel "bumper" of the pendulum provided a line impact instead of the point impact loading of the punch test.

2. The impact stress was not distributed in the radial pattern experienced in the panel testing. The part geometry distributed through the beam avoiding rupture of the contact surface.

The results of this puncture test, then, were not heavily weighted in the preliminary material ranking.

Overall, the tensile impact test, due to its simple mode of loading, was expected to most accurately reflect the failure mode of the bumper assembly under the selected test conditions.

Although the bumper was loaded in a flexural mode, fracture initiation occurred at the point of maximum tensile forces (Diagram II). Actual pendulum tests on the mounted assemblies demonstrated that fracture began dead center on the bumper's tensile side and propagated in a straight line perpendicular to the mounted assembly.

The actual performance ranking of the test systems, as measured by pendulum testing of mounted bumper assemblies, is also listed in Table III. A comparative review of the results of the laboratory scale flat panel tests demonstrates that the tensile impact test best reflects the actual performance ranking of the trial SMC systems in this particular application.

The results of this study indicate that tensile impact screening may effectively be used in this application to differentiate materials and obtain a composite system optimized for toughness. More importantly, this study indicates that the effectiveness of impact testing as a measurement of material toughness can be enhanced by proper interpretation of the failure mode that is operative in a particular application. Once a firm correlation between lab test and performance test is established, an efficient material screening program leading to the selection of a cost and performance effective composite is possible.

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TABLE I

IZOD AND TENSILE IMPACT PROPERTIES FOR A SERIES OF SMC MOLDINGS BASED ON ITP RESIN SYSTEMS

Sample Identification	A	B	C	D	E	F	G
Tensile Impact Initial Fracture Energy, ft. lbs./in.^{2}	12	9	9	5	3	11	4
Initial Fracture Stress, PSI	2600	2800	2700	2200	1100	3300	1300
Total Impact Energy, ft. lbs./in.^{2}	82	84	76	100	87	104	97
Notched Izod, ft. lbs./in. of notch	37	34	33	37	33	19	17

TABLE II

DESCRIPTION OF TRIAL SMC SYSTEMS

SYSTEM	SYSTEM DESCRIPTION	SMC COMPOSITION % RESIN/% FILLER/% GLASS
A	ITP-1056 Modified Vinyl Ester Resin	35/0/65
B	ITP-1054 Vinyl Ester Resin	35/0/65
C	ITP-1050 Isothalic Based Polyester Resin	35/0/65
D	ITP-1054 Vinyl Ester Resin	25/25/50

TABLE III

COMPARISON OF BENCH-SCALE IMPACT TESTS VS. BUMPER PERFORMANCE TESTING

		RHEOMETRICS IMPACT			TENSILE IMPACT		
SYSTEM	IZOD FT.LBS./IN.	INITIAL FRACTURE ENERGY, FT.LBS./IN.	MAXIMUM FRACTURE ENERGY, FT.LBS./IN.	TOTAL IMPACT ENERGY, FT.LBS./IN.	INITIAL FRACTURE ENERGY, FT.LBS./IN.^{2}	TOTAL IMPACT ENERGY FT.LBS./IN.^{2}	AUTO-DYNAMICS PENDULUM RANKING, FT.LBS.
A	30.5	117	1280	2520	13.0	188	6965 (1)
B	30.1	109	1560	3135	8.5	155	5260 (2)
C	24.8	163	1920	3460	3.3	75	4540 (3)
D	24.0	88	752	1960	1.7	73	>3040 (4) *

* Failure at base level of 3040 ft.-lbs. Equivalent to 5 mph at 3,000 lbs.

DIAGRAM I. TYPICAL LOAD VS. TIME TRACE OF PUNCH IMPACT ON HIGH STRENGTH SMC MOLDED PANEL

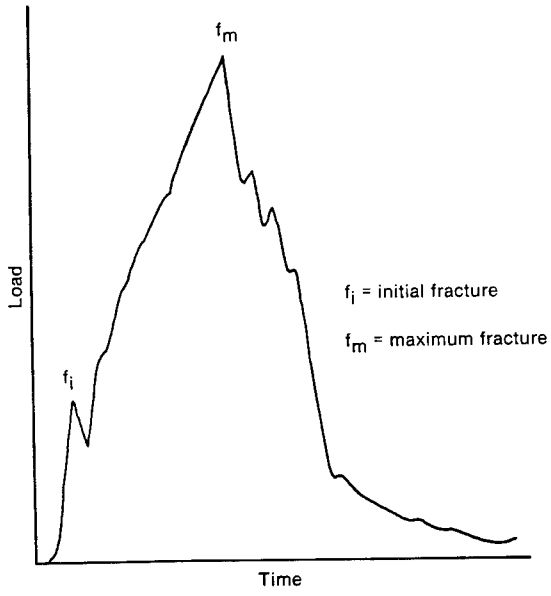
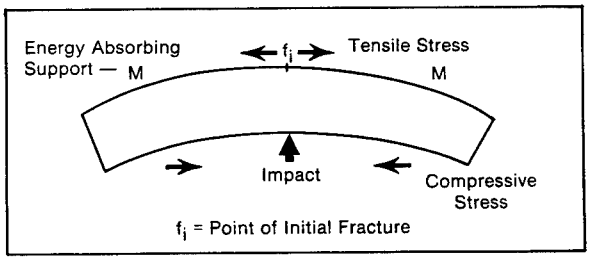


DIAGRAM II. SCHEMATIC DIAGRAM OF LOADED BUMPER



PROCESSING OF ONE-COMPONENT POLYURETHANE ELASTOMERS BY SMC TECHNOLOGY

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INTRODUCTION

Previous work published by General Motors Corporation has shown that one-component polyurethane elastomers can be successfully processed by the use of injection molding technology for potential use in automotive applications.[1,2,3] Less complex processing equipment -- in comparison with that used for conventional reaction injection molding (RIM) -- can be employed since the mixing and the molding steps are separate operations. Two key ingredients of this system are the solid catalyst, which initiates reaction only at elevated temperatures, and a solid, high-melting-diol chain extender, which is relatively unreactive at ambient temperatures. This combination makes possible an extended pot life for a one-component premixture prior to molding. When the mixed urethane ingredients are heated in the mold, melting of the diol and activation of the catalyst occur. Then, a rapid reaction with the diisocyanate accomplishes the cure.

The GM study clearly indicated that in order for the one-component urethane elastomer system to perform properly, it was necessary to form a stable dispersion of the solid chain extender in the liquid polyol. The purpose of a subsequent study at Eastman was to further the development of a feasible and practical technique for preparing such a dispersion. However, it is beyond the scope of this paper to cover specific details of dispersion preparation.

The most effective chain extender found in the GM studies was hydroquinone di-(beta-hydroxyethyl) ether, hereafter referred to as HQEE. This diol meets the criteria of being a high melting solid and being relatively unreactive with the diisocyanate component at room temperature. HQEE also imparts excellent mechanical properties to the molded urethane elastomer.

As cited in the GM studies, other potential advantages for this fundamentally new method for injection molding thermoset polyurethanes are:

1. The process increases the versatility of injection molding equipment by providing a means for molding thermoset urethane parts on existing and conventional equipment.
2. Much lower injection pressures are required than for molding thermoplastic polyurethanes.
3. Viscosity limits for one-component systems are less critical than for RIM.
4. The process is adaptable to the addition of glass fibers and fillers.
5. Virtually scrap-free molded parts can be produced by use of a cold runner system.
6. The thermo-mechanical properties of parts suggest their use in fascia applications.
7. A substantial increase in high-temperature modulus properties is obtained in comparison with current RIM materials.
8. Good mechanical properties are obtained without post curing.

The primary objective of this current study was to determine on a preliminary basis the feasibility of processing a one-component urethane system by means of sheet molding compound (SMC) technology involving compression molding. This was a pronounced departure from the use of injection molding technology utilized in the GM studies. A secondary objective of the study was to determine the effectiveness of incorporating one-inch chopped glass fiber as a reinforcing agent to enhance mechanical properties.

This evaluation covered preliminary processing parameters such as amounts of filler and glass and internal mold-release effectiveness. Mechanical properties of the compression molded specimens were determined and compared with conventional reinforced RIM as well as polyester-based SMC materials.

EXPERIMENTAL

The study by GM made use of the following formulation for the injection molded, one-component urethane system:

Ingredients[a]	Parts by Weight
Pluracol 581 Polyol/HQEE Dispersion (100/20)	120.0
Zinc Stearate	0.3
Isonate 181 Diisocyanate	50.1

In this current Eastman study, the GM resin formulation was altered by increasing the zinc stearate content from 0.3 to 5.0 parts by weight to function both as a catalyst and as an internal mold release agent, and the extender/diisocyanate content (referred to as the hard segment) was maintained at 40% by weight, based on the unmodified resin. To modify this basic resin, the one-inch chopped glass fiber content and calcium carbonate filler content were each varied from 0% to 40% by weight, based on the total weight of the modified system. In all of the filled, glass-fiber-reinforced compositions, however, the same 40% by weight ratio of hard segment to total unmodified resin was maintained.

The various compositions of sheet molded urethane elastomer compound (hereafter referred to as SMUC) that were evaluated are indicated in Figures 1-3, and are discussed in more detail in subsequent sections.

Preparation of the HQEE/Polyol Dispersion

The dispersion of 20 parts HQEE extender in 100 parts Pluracol 581 polyol (styrene/acrylonitrile graft polyol) may be prepared by any one of several methods outlined in a published report from Eastman (CSR-0095-IAD). All dispersions used in this evaluation were prepared by mixing molten HQEE with hot polyol (100°C) and cooling with agitation. These dispersions had particle size ranges of 5-50 microns and viscosities of 30-50,000 cP (Brookfield viscosity at 23°C). The HQEE/polyol dispersion is currently being produced in developmental quantities by a batch process, and work is continuing by several equipment and material suppliers to develop a fully commercial process for preparation of the dispersion.

[a] See section on "Suppliers of Raw Materials and Equipment" in the Appendix.

Preparation of SMUC Molding Compound

In the Eastman laboratory study, samples were prepared by weighing the components (HQEE/polyol dispersion, zinc stearate, calcium carbonate, and diisocyanate) into a suitable mixing container. A 4,000-gram dispersion batch was generally used and the ingredients were added in the order listed above. It is preferable to premix all ingredients first except the diisocyanate to minimize exposure of the diisocyanate to heat generated by mixing. It is extremely important that the dispersion premix, as well as the complete formulation, be mixed in such a manner that excessive heat is kept to a minimum, otherwise the diisocyanate will react prematurely, resulting in a reduced pot life. Either a Cowles dissolver (4-inch blade) or a Baker Perkins sigma-blade mixer was used to mix the components. Mixing times were generally 2-4 minutes for each stage with the Cowles dissolver.

The mixed compound was then stored at room temperature until initial reactions had begun to increase the viscosity to a suitable processing stage for proper handling on the SMC machine. Time for buildup in viscosity to occur was generally 30 minutes to 3 hours, depending on the mixture temperature and the filler content. Higher mixture temperatures and higher filler content reduced the time needed to reach the proper processing viscosity. Generally, the viscosity of an unfilled, unreinforced system was allowed to reach 80,000 cP (Brookfield method at 23°C), while a highly filled, high-glass-containing system was processed at 40,000 cP to ensure good flow and wet-out during the glass addition operation. An 18-inch Finn & Fram SMC machine was used to add the glass fiber and prepare the sandwiched rolls of SMUC material. One-inch chopped glass fiber (OCF Type 433) was employed throughout this study. The sandwiched layers were collected on an end roller, sealed, and stored at room temperature until the actual molding operation, generally after 24 hours. If desirable, the SMUC material could be molded within 1-2 hours or as long as 4 days after preparation, with some variations, depending on the filler and glass content. The higher filler- and glass-content systems showed the greatest allowable tolerance in aging time before being molded.

Molding Operation

A vertical Farrel compression press with a 16-inch ram was fitted with a chrome-plated mold to give a flat 8-inch x 8-inch x 1/8-inch specimen for this evaluation. Mold pressure was generally 75 tons, and the molds were steam heated to 155°C. Mold charge was 160-220 grams and mold times were 2-3 minutes, with the flat molded sheets being self-releasing because of the function of zinc stearate as an internal mold release agent. After demolding, the samples were stored at room temperature for 7 days prior to physical property evaluation.

Physical Property Determinations

The following physical properties were determined on molded samples in accordance with the standard ASTM methods listed.

Property	ASTM Method
Specific Gravity	D 792
Surface Hardness (Shore D)	D 2240
Tensile Strength at Fracture	D 638
Elongation at Fracture	D 638
Graves Tear Resistance (Die C)	D 624
Izod Impact Resistance	D 256
Flexural Modulus (-20°F, 72°F, 158°F, 258°F)	D 790
Flexural Strength (-20°F, 72°F, 158°F, 258°F)	D 790

The specimens for tear-strength determination were die cut, and specimens for the other tests were cut with a band saw or wetted diamond circular saw. Tensile samples were prepared with a standard SMC type template and router apparatus.

RESULTS AND DISCUSSION

Pot Life and Mold Life

The viscosity increase of the polyol/extender dispersion, diisocyanate, and filler mixture, prior to the glass addition on the SMC machine, developed more rapidly for the more highly filled systems (generally within 30 minutes to 1 hour). This was probably caused by frictional heat buildup, which was made more pronounced by the presence of the filler during the mixing step. Therefore, the pot life or flow-wet-out properties of the system are dependent upon both the time after mixing and the filler content. In a reversal of this trend, the mold life of the processed SMUC rolls appears to be extended by the increased filler and glass content. Apparently, a greater physical separation of reactive components occurs in these systems, and the reactions are retarded. Several of the systems could be satisfactorily molded after 4 days or more when stored at room temperature.

Specific Gravity

The specific gravity values of compositions shown in Figures 1-3 varied from 1.1 to 1.7, depending upon glass and filler content, with the more strongly reinforced samples having the higher values.

Effects of Filler and Glass Content on Hardness and Surface

There was a definite increase in surface hardness with increasing glass fiber content, with values ranging from 50 to 70 on the Shore D scale, but the effects on hardness of increasing the quantity of filler were insignificant at constant glass fiber content. Surface appearance was improved, however, with increasing amounts of filler, although a "Class A" finish -- desirable for automotive applications -- was not achieved in this preliminary study.

Mechanical Properties

The tensile strength values of SMUC are comparable or superior to those of conventional and milled-fiber modified RIM systems, depending on the amount of glass reinforcement added to the SMUC system. Tensile strength generally increased with the addition of glass fiber over a wide range of filler concentrations (see Figure 1). However, for a given glass fiber content, an increase in the filler level appeared to detract from the tensile values.

In the "Die C" tear test, samples did not tear smoothly but snapped cleanly at failure. Therefore, the data were considered to be more representative of tensile rather than tear properties. The values in Figure 2 show that an increase in glass fiber content improved the tear resistance, but again, as with tensile strength, the addition of filler appeared to detract from this property, although not as conclusively.

The Izod impact values at room temperature were much higher than expected. A large number of the samples tested at room temperature showed no break, as they were capable of either absorbing the impact or else deflecting to allow the hammer to pass. The samples were therefore tested at -20°F in an attempt to find conditions under which these samples would break. The results are shown in Figure 3. As expected, the increase in glass fiber content resulted in a marked improvement in Izod impact strength. The addition of filler decreased the values, especially at higher concentrations.

Flexural modulus properties were evaluated over an extended temperature range of -20° to 258°F. The values in Table I illustrate that the stiffness of the SMUC material was greater at the lower temperature range and decreased with an increase in temperature. Generally, an increase in glass fiber content at each filler level and over the entire temperature range increased the flexural modulus.

Flexural strength values of the SMUC material ranged from 400 psi (0% filler, 0% glass at 258°F) to 19,000 psi (30% filler, 40% glass at -20°F) (Table II). Generally, an increase in filler level noticeably lowered the flexural strength properties.

The coefficient of thermal expansion over a range of -58°F to 266°F was 93 x 10^{-6} in/in/°F for an unfilled, unreinforced SMUC system. The addition of 30% by weight of chopped glass fibers decreased this value to 9 x 10^{-6} in/in/°F.

A deliberate comparison of SMUC with other plastic materials was beyond the scope of this current study; however, some of the available flexural, impact, and tensile properties of SMUC compositions are compared with the corresponding properties of other molded systems in Figures 4, 5, and 6, respectively. The graphs in these figures are based on a compilation of data from various personal communications and published sources as well.

CONCLUSIONS

Following are the significant conclusions derived from this preliminary investigation:

1. A potentially promising new urethane elastomer system referred to as SMUC has been developed which incorporates certain features of both the RIM and SMC processes.

2. By use of a solid, dispersed chain extender and a solid, heat activated catalyst in a liquid polyol, SMUC offers the advantage of conventional RIM without the need for expensive metering and mixing equipment. Because this system offers an extended reaction time, the ingredients can be predispersed in conventional mixing equipment, and the proper ratios are then assured by the direct weighing of each component.

   The solid catalyst also functions effectively as an internal mold release agent, which eliminates the need for a spray-type mold release and offers the potential of

producing molded parts that are paintable without pre-treatment.

3. Up to 40% one-inch chopped glass fiber can be incorporated into the SMUC formulation to enhance physical properties, and as much as 40% filler can be used for improved surface appearance and economics. The single-component system can be processed on conventional SMC and compression molding equipment. Both the pot life of the premixture and the mold life of the SMC processed material appear to be adequate for reasonable production schedules, with adequate allowance for variations in stability, depending upon filler and glass content.

4. The mechanical properties of the molded SMUC system were excellent and were enhanced by the addition of glass fiber. The combination of good flexural modulus properties and excellent impact resistance properties over a wide temperature range was particularly impressive.

5. In view of its promising potential, the SMUC system should fill an important gap between conventional RIM and SMC systems, particularly in new areas of application where current materials have been found to be deficient in mechanical properties or lacking in favorable strength-to-weight ratios or corrosion resistance.

Future Work

It should be emphasized that this work was quite preliminary in nature and considerable optimization studies need to be undertaken. In particular, formulation and molding parameters need to be optimized, and additional mechanical properties, surface paintability, and weatherability need to be determined.

Other work already in progress at Eastman is concerned with modification of the basic polyurethane resin formulation by the addition of other components for the purpose of developing a new composition which also contains an unsaturated polyester cross-linked with a vinyl monomer as in conventional SMC processing technology.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of personnel at Owens-Corning Fiberglas Corporation, who assisted in evaluating the effects of glass fiber reinforcement and were helpful in establishing certain formulation parameters.

Table I

FLEXURAL MODULUS[a] VALUES OF SMUC SYSTEMS

Temperature	Wt. % Filler	Flexural Modulus (psi X 10^5)			
		Wt. % Glass			
		0	20	30	40
−20°F	0	0.60	1.70	2.68	3.79
	20	–[b]	1.20	1.85	2.73
	30	–	1.65	2.13	5.33
72°F	0	0.28	1.33	1.71	2.99
	20	–	1.35	1.59	5.39
	30	–	1.34	3.22	3.20
158°F	0	0.18	0.71	1.62	2.43
	20	–	0.70	1.1	1.92
	30	–	0.42	1.27	0.93
258°F	0	0.08	0.36	1.02	1.40
	20	–	0.23	0.74	0.91
	30	–	0.32	0.69	0.63

[a]ASTM D 790.
[b]Values not determined.

Table II

FLEXURAL STRENGTH[a] VALUES OF SMUC SYSTEMS

Temperature	Wt. % Filler	Flexural Strength (psi)			
		Wt. % Glass			
		0	20	30	40
−20°F	0	3000	8700	12,400	15,700
	20	–[b]	4800	8000	12,000
	30	–	7100	9600	19,100
72°F	0	1400	4700	5200	7200
	20	–	4100	4700	11,200
	30	–	4700	9100	7600
158°F	0	900	2300	3600	2900
	20	–	2100	3000	4100
	30	–	1600	3000	2500
258°F	0	400	900	2000	2900
	20	–	700	1500	1800
	30	–	900	1600	1500

[a]ASTM D 790.
[b]Values not determined.

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1. H. W. Cox and S. A. Iobst, "The Injection Molding of One-Component Thermosetting Polyurethanes," Research Publication GMR-2595, Polymers Department, General Motors Research Laboratories, November 1977.

2. S. A. Iobst and H. W. Cox, "Thermoset Polyurethanes Containing Hydroquinone Di-(beta-hydroxyethyl) Ether," Research Publication GMR-2594, Polymers Department, General Motors Research Laboratories, December 1977.

3. U. S. Patent 4,119,594, S. A. Iobst and H. W. Cox (to General Motors Corporation), October 10, 1978.

APPENDIX

Suppliers of Raw Materials and Equipment

Hydroquinone Di-(beta-hydroxyethyl) Ether (HQEE Chain Extender)	EASTMAN CHEMICAL PRODUCTS, INC.
PLURACOL 581 Polyol	BASF WYANDOTTE CORP.
ISONATE 181 Diisocyanate	THE UPJOHN COMPANY
OCF Type 433 Glass Fiber	OWENS-CORNING FIBERGLAS CORP.
COWLES Dissolver	MOREHOUSE INDUSTRIES, INC.
BAKER PERKINS Mixer	BAKER PERKINS, INC.
SMC Process Machine	FINN AND FRAM, INC.
Verticle FARREL Compression Press	FARREL COMPANY DIVISION OF USM CORP.

Figure 1

TENSILE STRENGTH[a] (PSI) AND PERCENT ELONGATION OF MOLDED SMUC SYSTEMS[b]

Wt. % FILLER \ Wt. % GLASS	0	10	20	30	40
0	2400 (200)		4700 (8)	5100 (5)	13,100 (4)
10		2200 (15)			
20			3300 (5)	4100 (6)	13,500 (4)
30			2800 (6)	5800 (4)	6300 (5)
40				6300 (4)	

[a]ASTM D 638 – Elongation values (%) are shown in parentheses below values for tensile strength at fracture.
[b]Compositions represented by squares without numerical values were not tested.

Figure 2

TEAR RESISTANCE[a] OF SMUC SYSTEMS
(Pounds Per Linear Inch)

Wt. % FILLER \ Wt. % GLASS	0	10	20	30	40
0	600		1100	1500	1700
10		800			
20			1400	1500	1700
30			900	1600	2300
40				1300	

[a]ASTM D 624, Die C.

Figure 3

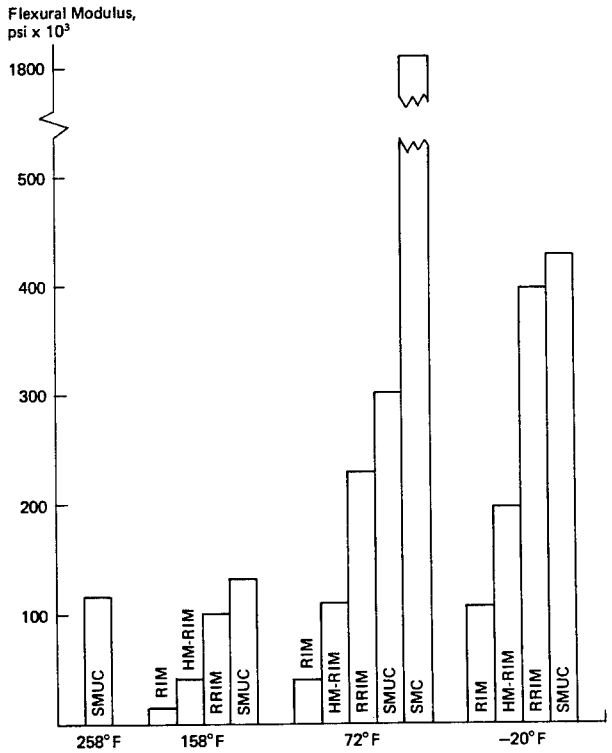
IZOD IMPACT RESISTANCE[a] OF SMUC SYSTEMS
(Foot-Pounds Per Inch of Notch at −20°F)

Wt. % FILLER \ Wt. % GLASS	0	10	20	30	40
0	10		22	20	24
10		11			
20			11	14	23
30			9	16	18
40				12	

[a]ASTM D 256

Figure 4

COMPARISON OF FLEXURAL MODULUS
FOR VARIOUS MOLDED SYSTEMS[a,b]

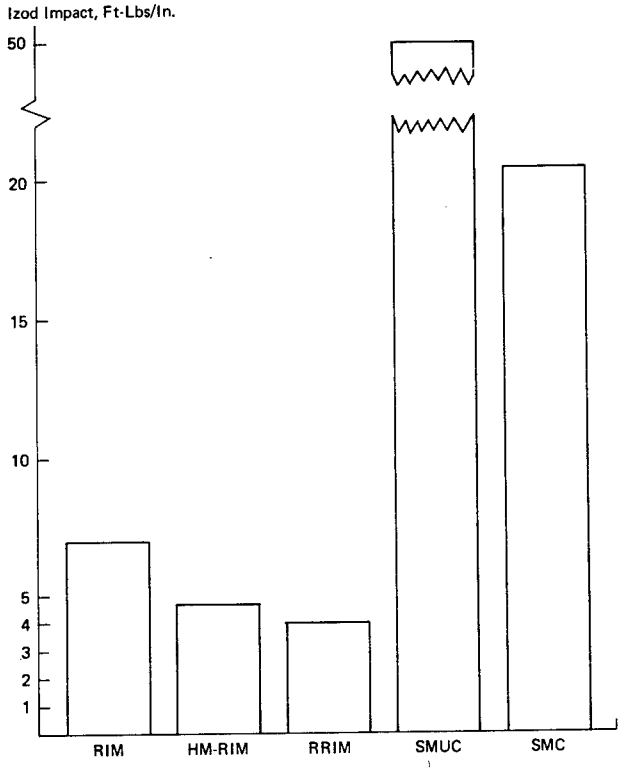


[a]RIM Conventional Reaction Injection Molding
HM-RIM High Modulus RIM System
RRIM 20% 1/16" Milled Glass Fiber in HM-RIM
SMUC 30% 1" Chopped Glass Fiber in Sheet Molding Urethane Compound
SMC Sheet Molding Compound

[b]The graphs shown above are based on a compilation of data obtained from personal communications and published sources.

Figure 5

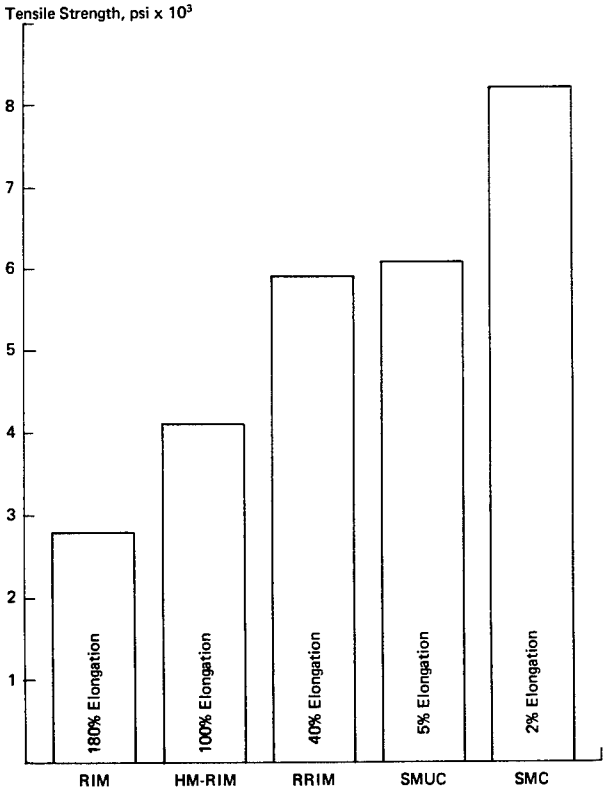
COMPARISON OF IZOD IMPACT RESISTANCE OF MOLDED SYSTEMS[a]
(Ambient Temperature)



[a]See Footnotes to Figure 4 for Identification of Molded Systems and Source of Data.

Figure 6

COMPARISON OF TENSILE PROPERTIES
OF MOLDED SYSTEMS[a]



[a]See Footnotes to Figure 4 for Identification of Molded Systems and Source of Data.

METALLIZING SMC

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INTRODUCTION

The metallizing of thermoplastics is an established science. It was determined during our investigation of the state of the art that the metallization of SMC demands new metallizing processes and new related materials. Automotive designers and engineers are turning more to sheet molding compound to solve problems of weight and corrosion. The ability to metallize SMC could open up many new automotive applications. Two metallizing techniques which are showing promise are sputter coating and electroplating. These two systems are undergoing vast change because of new technology and availability of new substrates such as compression molded SMC.

SHEET MOLDING COMPOUND (SMC)

One of the significant breakthroughs in fiber glass reinforced plastics (FRP) technology in recent years has been the development of sheet molding compound (SMC). SMC is now used in innumerable high volume applications involving large complex parts. It has proven to be highly effective for automotive exterior components, appliance parts and other large components requiring a highly refined surface finish, design complexity and outstanding mechanical properties.

SMC can now be compounded for new structural type applications such as crossmembers, radius arms, even bumpers and wheels. Some of these applications might need a metal coating to maximize their acceptance.

SMC is an integrated fiber glass reinforced resin composite that can be manufactured by an automated continuous process (see Figure I (1)). Fiber glass roving is chopped into desired lengths ranging up to two inches (5.08 cm) or introduced in continuous form, or both, and deposited onto a layer of polyester resin-filler paste traveling on a carrier film together with a second carrier film, which also has resin-paste. The two sheets join together as a continuous composite of chopped glass, continuous glass and resin-filler paste. This is compacted and rolled under controlled tension into standard package-sized rolls at the wind-up stage of the machine. The technique used to form SMC is compression molding. A typical formulation of the SMC substrate is shown in Table 1.

SPUTTER COATING PROCESS

The first metallizing technique which will be discussed is sputter coating. Conventional sputter coating, which is applied in a vacuum, has been around for a long time. Figure II (2) shows how conventional sputtering is performed. Conventional sputtering can be sustained only at relatively high working pressures, where a high density of argon collision targets is provided for the primary electrons.

The sputtering rate can be effectively increased at a given voltage by increasing the argon pressure. However, if the pressure is too high, the deposition rate starts to decrease since significant numbers of the sputtered atoms cannot get through the dense working gas atmosphere and are deflected back to the cathode by collisions with gas atoms. These conflicting requirements cause an optimum operating pressure for producing the maximum deposition rate in the chamber.

The recent development of high performance magnetron sputtering permits increased deposition rates, reduced substrate heating and deposition over large substrate areas.

This process is performed in a vacuum of 10^{-5} torr, it is then backfilled with argon gas to 10^{-3} torr. Argon atoms are then electrically charged and accelerated toward the metal target, causing severe atomic collisions. This is accomplished within electric and magnetic fields. These severe collisions "chip off" a few metal atoms, which then traverse through space in a line of sight manner onto the SMC surface. Post (cylindrical) or planar configurations of the magnetron are shown in Figures III (3) and IV (4).

In magnetron sputtering, the majority of the secondary electrons leaving the cathode are prevented from reaching the substrates by the optimized geometry of the magnetic and electric fields, and are captured at the anode. The electron-capturing feature minimizes electron bombardment heating of the substrates, even at the highest sputtering rates. The magnetic field makes it possible to generate a current density an order of magnitude greater than DC or RF planar diode sputtering systems. The higher current density thus causes greater bombardment of the cathode surfaces. This results in proportionately higher sputtering rates. Neither sputter coating nor vacuum metallizing can produce a deposit having mechanical and physical properties approaching those of electroplating. Typical electroplated parts are plated to thicknesses of 1.5 to 2.0 mils.

Sputter coating has unique advantages when compared with conventional vacuum metallizing systems. Almost any metal or alloy can be deposited when sputter coating. In automotive applications, the metal of primary interest is a high chrome alloy because of its appearance and corrosion resistance.

Though alloys can be laid down by conventional vacuum metallizing, such as electron-beam fired evaporation or resistance fired evaporation, in practice, the vapor deposition may be substantially different in composition than the source alloy. As the alloy is consumed, the different vapor pressures of the constituent alloying elements cause them to vaporize at different rates. As a result, the original alloy composition is changed and with it, the physical properties of the metal coating. This preferential vaporation does not occur in sputtering because the source alloy is mechanically "chipped away," not melted.

Another plus for sputtering results from the higher kinetic energy of the metal ions, estimated from 10 to 100 times that of conventional vacuum metallizing. Higher kinetic energy means higher impact energy. The metal atoms do produce a denser and brighter coating on the part, and some investigators claim better adhesion.

However, some disadvantages of sputter coatings include a much greater tendency to show cracks and iridescence. Also, the metallic sputter coatings are so thin, as low as approximately 600 angstroms, they replicate the surface which they cover. In addition, they wear off almost immediately upon abrasion. In order to minimize these problems, two additional coatings are necessary - a leveling basecoat and a protecting topcoat.

A smooth leveling basecoat is necessary to cover substrate defects and level surface roughness. Below is a list of basic requirements for a satisfactory basecoat:

1. Good leveling ability.
2. Good adhesion to substrate and to metal film.
3. UV stability.
4. Clear for depth and color.

The topcoat must satisfy the following important functions.

1. Good clarity and UV stability.
2. Good mar and scratch resistance.
3. Good chemical resistance and inertness.
4. Good weather resistance.
5. Good adhesion.

The final proof of any system is its ability to consistently produce a surface which looks like chrome and is stable enough to remain as such for an extended period of time.

PERFORMANCE REQUIREMENTS

We have developed some performance requirements of metallized coatings for SMC. These performance requirements were established after discussions with companies in the transportation industry. The performance requirements involve appearance, adhesion, humidity, gravelometer, cass corrosion, thermal cycle, thermocycle, salt spray, topcoat crack cycle test, accelerated weathering, abrasion and resistance to thermal shock. The testing methods are presented in Table 2. These test methods are geared more towards sputter coating because the industry has standards for electroplating. The test performances of electroplating SMC or thermoset substrate needs to be re-evaluated because the thermoset substrate is more stable than a thermoplastic. This is reaffirmed in Table 3, which lists coefficients of linear thermal expansion.

Adhesion is a major concern with thermoplastic substrates. Presently, the industry is very concerned about initial adhesion because it predicts the potential performance of the part. The most critical performance requirement in Table 2 is adhesion. Adhesion is the determining performance factor in the performance of five of nine tests. The technique used to check adhesion is dictated by the method of metallizing. Sputter coating is measured as presented in Table 2. Electroplating adhesion is measured by a peel test. The environmental testing in Table 2 is valid whether testing sputter coating or electroplating.

SPUTTER COATING RESULTS

Several major, closely interrelated defects were often observed when sputter coating SMC. These were iridescence, visible microcracking, poor adhesion, poor image clarity and highlighted paint defects.

Iridescence is the whitish, hazy appearance of the metallized surface. It is usually caused by a microwaviness phenomenon which occurs in the metal layer.

Visible microcracking is caused by the inability of the metal layer to cope with thermal expansion, flexibility and mobility of the coating and substrate systems. Since the metal cannot match these properties, stresses build up until either the metal fractures or stress is relieved in some other manner.

Poor adhesion can occur from any number of ordinary organic coating problems, but it can also occur in the metal film through internal or interfacial metal fractures. Internal loss of adhesion occurs when the metal itself loses cohesion and divides internally. Interfacial loss of adhesion results when the metal loses its bond to the organic coating.

Poor image clarity most commonly occurs because the substrate has an initially poor surface finish. The basecoat cannot completely smooth over microwaving. Initial roughness also tends to cause unequal surface stress distributions, thus results in a greater tendency toward microcracking and iridescence. Normal basecoat-topcoat defects often become major coating problems in metallizing because they are intensified. The clear topcoats and highly reflective metals act very much like a magnifying glass, bringing dirt, runs and sags to clear visibility.

Causes of defects in sputter coating can be broken down into the following components:

1. SMC Substrate
2. Basecoat
3. Metal Film
4. Topcoat

In each of these components, various phenomena can disrupt the total appearance of the final coating.

SMC substrate related disruptions are dirt and other foreign surface matter statically attached to the surface due to the nonconductivity of the plastic. Also, problems occur related to linear coefficient of thermal expansion. Table 3 shows the linear coefficients of thermal expansion of various SMC compositions and of some common thermoplastics.

Basecoat related problems arise mostly from the inability of basecoats to retain thermal stability. Common paint problems also cause great difficulty due to the highlighting effect of the metallized coat.

Metal coating difficulties arise when the metal coating cannot cope with the properties of the adjacent organic coatings and organic substrate. Its coefficient of thermal expansion are decidedly different from the organic substrates, although SMC systems are more similar to metal coatings than thermoplastics.

The main topcoat problem is one of stability. U.V. degradation causes color changes, loss of adhesion and erosion of the coating. New systems have been developed which have overcome these deficiencies.

Some typical sputter coating (600 angstrom-1000 angstrom) results we have achieved using these performance tests with Red Spot basecoat (X303) and topcoat (ET4) on a polyester based SMC substrate were as follows:

Thermal Cycle - There was not metal or topcoat cracking or other appearance change after four cycles and an adhesion rating of 3B-4B.

Thermocycle - There were no cracks, crazing, blistering, corrosion or other obvious appearance changes and an adhesion rate of 4B.

Accelerated Weathering Test - There was no evidence of chalking, cracking, checking, blistering or peeling after 1000 hours in the weatherometer.

Humidity Test - There was an adhesion rating of 3B with no blistering or other appearance change after 96 hours exposure at 100°F and 100% relative humidity.

ELECTROPLATING PROCESS

As with sputter coating, the electroplating of SMC has become very complicated because each resin seems to demand its own electroplating process. For this reason, chemical suppliers to the electroplating industry can no longer rely on selling products, but must depend on selling processes. These processes provide the electroplating chemicals and the instructions relating to time and temperature. When electroplating SMC, a plater should have a basic understanding of the resin system and of the total composition of the SMC.

When sputter coating, minor differences were noticed between vinyl ester and polyester resin based SMC's, but they were not critical. This was not the case with electroplating. The electroplaters involved were able to develop better processes for plating vinyl ester than polyester resin based SMC's.

The pertinent points of electroplating SMC's can be narrowed to the preplating process. The preplating process involves seven steps. These seven steps are:

a. Clean
b. Etch
c. Neutralize
d. Condition
e. Activate
f. Accelerate
g. Electroless Plate

The electroplating process which will now be presented might really be considered a guide to a process since the time, temperature and rinses will not be given. These considerations would be based on the chemicals you use, and would be proprietary information of the specific chemical company.

Electroplating Process

Clean
Etch
Neutralize
Condition
Activate
Accelerate
Electroless System
Watts Nickel Strike
Acid Dip
Bright Acid Copper
Acid Dip
Semi Bright Nickel
Bright Nickel
Chrome Predip
Chrome Plate

ELECTROPLATING RESULTS

When we tested the preplating process for ABS on SMC, then followed with a standard electroplating system, we had total failure. The type failure we achieved was no metal deposition.

The best etch process for SMC was the Ronason gas etch process supplied by Lea Ronal. The Ronason process is a proprietary, non-chromic etch system. The process is described in U.S. Patent 4,039,714 and licensed exclusively to Lea Ronal, Inc. Equipment implementing this step is presently in commercial operation in the United States. Lea Ronal has successfully electroplated numerous SMC compression molded plaques and parts, using the Ronason process.

The thermal cycle test is one of the most critical tests in electroplating plastics. It was the test we used most to measure the new systems. The initial measurement of the test was appearance, then they were tested for adhesion. The peel test was the technique used to measure adhesion. Once a system had achieved a satisfactory adhesion performance in pretesting, we never had a failure in the thermal cycle test. We evaluated a number of systems of various companies which passed this thermal test.

SUMMARY

This presentation covered two techniques which can be used to metallize SMC. The degree of success consummated in sputter coating was only possible with the organic coating suppliers newly developed coatings, and with the sputter coating equipment suppliers systems for metallizing SMC. Together they have achieved a metallized coating which can be used to coat compression molded SMC.

The performance requirements which were established after discussions with companies in the transportation industry can be considered a base for future development of sputter coatings.

The electroplating chemical suppliers have developed systems which now can be used not only to electroplate fiber glass reinforced thermosets, but can be used through systems designed for thermoplastics.

With the cultivation of new applications utilizing new improved structural resins, these newly developed metallizing techniques will support the creating of new applications. There are systems being developed today which were not touched upon that will open up additional new opportunities.

ACKNOWLEDGEMENTS

The author greatly appreciates the suggestions of colleagues Dr. Richard Gaertner, Dr. Robert Beck, Jeri Clark and Ralph Jutte at the Granville Technical Center regarding the preparation of this paper. The author introduces the metallizing techniques which were developed by the metallizing industry. Appreciation is also extended for the permission by Owens-Corning Fiberglas to present this paper.

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1. Structural SMC - Material, Process and Performance Review, Ralph B. Jutte, 33rd Annual Conference, Society of Plastics Industry, February 7-10, 1978.

2,3,4. Recent Development in Sputtering - Magnetron Sputtering, John A. Thornton, 21st Annual Technical Conference of Vacuum Coaters, May 25-26, 1978.

TABLE 1

SMC-R50

Ingredient		Percent
Polyester Resin (OCF)	E 980	32.282
Inhibitor	pQuinone	0.015
Catalyst	TBPB	0.320
Mold Release	Zinc Stearate	0.809
Filler	Calcium Carbonate	16.144
Thickener	Mag Oxide	0.430
Fiber Glass (OCF)	433 glass 1" (2.54 cm)	50.000
		100.000

TABLE 2

TENTATIVE DURABILITY REQUIREMENTS FOR METALLIZED

SYSTEMS ON OCF RIGID SUBSTRATE

APPEARANCE:

There shall be no visible metal cracks, rainbows or sags.

Distinctness of image (DOI) shall be to be determined (tbd).

Color as measured in Hunterlab L, a, and b units or equivalent must be in the following range:

L = tbd to _____

a = tbd to _____

b = tbd to _____

ADHESION:

No loss when tested per ASTM D-3359-74.

HUMIDITY TEST:

No loss of adhesion, blistering or other appearance change after 96 hours exposure at 100°F and 100% relative humidity per ASTM D2247.

After a maximum 10 minute recovery period, the system must exhibit a "3" rating for adhesion when tested according to tape adhesion test ASTM-3359-74.

GRAVELOMETER TEST:

When tested at -10°F per ASTM D-3170-74, samples must exhibit a minimum rating of "6."

CASS CORROSION TEST:

After exposure to a copper-accelerated acetic salt spray test for 22 hours, the system shall not show any signs of failure by cracks, crazing, blistering, corrosion or adhesion. ASTMB-368.

THERMAL CYCLE:

There shall be no metal or topcoat cracking or other appearance change after 4 cycles as follows:

2 hours @ 175°F in an air circulating oven

16 hours humidity @ 100°F, 100% RH

2 hours @ room temperature

2 hours @ -10°F in a cold box

2 hours @ room temperature

After test the sample shall have good adhesion per ASTM D-3359-74.

THERMOCYCLE TEST:

Samples shall be subjected to three temperature cycles where each cycle consists of:

175° for 20 hours in an air circulating oven
70° for 4 hours
-20°F for 20 hours
70°F for 4 hours

There will be no failure by cracks, crazing, blistering, corrosion, adhesion or any other obvious appearance changes. Also, following a 24 hour recovery period at room temperature, the metallized system must exhibit tape adhesion per ASTM D-3359-74 equivalent to initial adhesion.

SALT SPRAY:

After exposure to neutral salt spray for 336 hours the system shall show no evidence of blistering or corrosion in unscribed areas and no creepage or loss of adhesion from a line scribed to substrate prior to exposure. Test with and without topcoat.

TOPCOAT CRACK CYCLE TEST:

Samples with a clear topcoat as part of the system shall be subject to 15 cycles which consist of:

24 hours of humidity @ 100°F, 100% RH

20 hours @ -10°F

4 hours @ room temperature

TOPCOAT CRACK CYCLE TEST:

Samples shall not exhibit metal cracking, topcoat cracking, blistering or significant gloss change per ASTM D-2246.

ACCELERATED WEATHERING TEST:

1000 hours in weatherometer or QUV cycle ultraviolet cabinet with no evidence of chalking, cracking, checking, blistering or peeling.

ABRASION TEST:

Test I. No noticeable wear after 800 cycles with Taber abrader, using CS-10 wheels with 500 gram load.

Test II. The coating shall not be worn through after 15 back and forth rubs with 600 grit sandpaper using moderate finger pressure and a one inch stroke.

RESISTANCE TO THERMAL SHOCK:

No blistering or loss of adhesion on the scribed surface, after 4 hours water immersion @ 90°F, 4 hours @ -20°F and direct steam blast at 45° angle 2 to 3 inches away from scribe for 15 seconds.

TABLE 3

COEFFICIENT OF LINEAR THERMAL EXPANSION

MATERIAL SYSTEM	Temperature Range -30°C to 25°C ΔT = 55°C		-30°C to 100°C ΔT = 130°C		-30°C to 150°C ΔT = 180°C	
	in/in/°C X 10^{-5}	in/in/°F X 10^{-6}	in/in/°C X 10^{-5}	in/in/°F X 10^{-6}	in/in/°C X 10^{-5}	in/in/°F X 10^{-6}
SMC-R40 E980/E573/433	1.53	8.5	1.46	8.1	1.41	7.8
SMC-R50 E980/433	1.22	6.8	1.47	8.2	1.36	7.6
SMC-R50 E980/S-2(433)	.993	5.5	1.14	6.3	1.06	5.9
SMC-R50 XD9013.02/433	.993	5.5	1.04	5.8	.86	4.8
SMC-R65 E980/433	1.16	6.4	1.13	6.6	1.05	5.8
SMC-R65 E980/S-2(433)	.964	5.3	.994	5.5	.892	4.9
SMC-R30 Low Profile(Typical)	1.17	6.5				

	-30°C to 30°C ΔT = 60°C
	in/in/°C X 10^{-5}
Polysulfone	3.1
ABS	3.9-9.5

SUPPLIERS

Listed below are companies which have been involved in the development of metallizing SMC. Some will be more qualified than others based on their continued development work. All will be knowledgeable of compression molded SMC.

Basecoat and Topcoat Suppliers

Red Spot Pain and Varnish Company
Evansville, Indiana

Bee Chemical
2700 East 170th Street
Lansing, IL 60438

Sputter Coating Equipment Suppliers

Telic Corporation
1631 Colorado Avenue
Santa Monica, CA 90404

Varian Associates
611 Hansen Way
Palo Alto, CA 94303

Electroplating Chemical Suppliers

Lea Ronal, Inc.
272 Buffalo Avenue
Freeport, NY 11520

Oxy Metal Industries Corporation
21441 Hoover Road
Warren, MI 48089

MacDermid, Inc.
50 Brookside Road
Waterbury, CN 06720

Richardson
29111 Milford Road
New Hudson, MI 48165

Shipley Company
2300 Washington Street
Newton, MA 02162

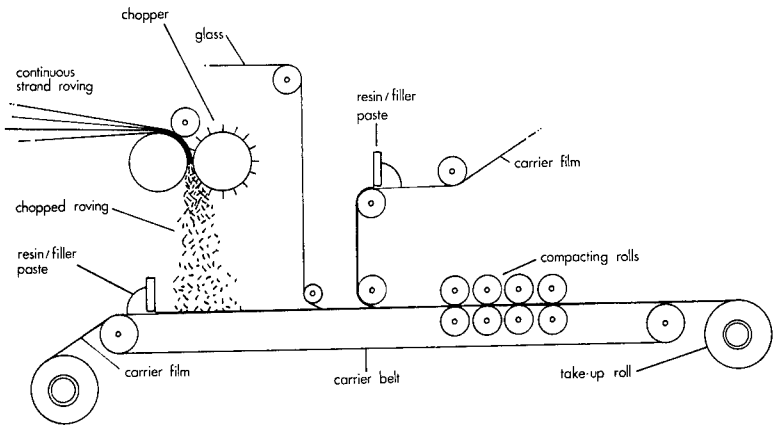
Enthone, Inc.
Frontage Road
West Haven, CN 06516

TABLE 4

Measurements

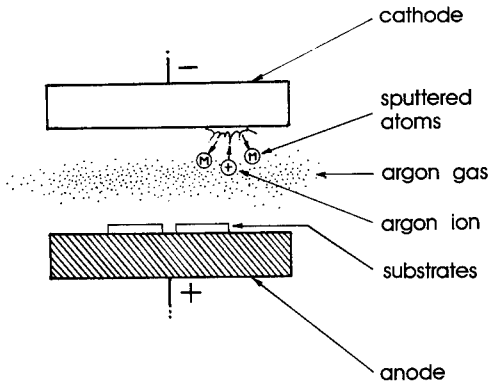
ANGSTROM	=	10^{-8} cm
cm	=	0.3937 INCH
cm	=	393.7 MILS
INCH	=	2.54 cm
MIL	=	0.00254 cm
MIL	=	254,000 ANGSTROM
20,000 ANGSTROM	=	0.079 MIL
1,000 ANGSTROM	=	0.0039 MIL
600 ANGSTROM	=	0.0024 MIL

FIGURE I



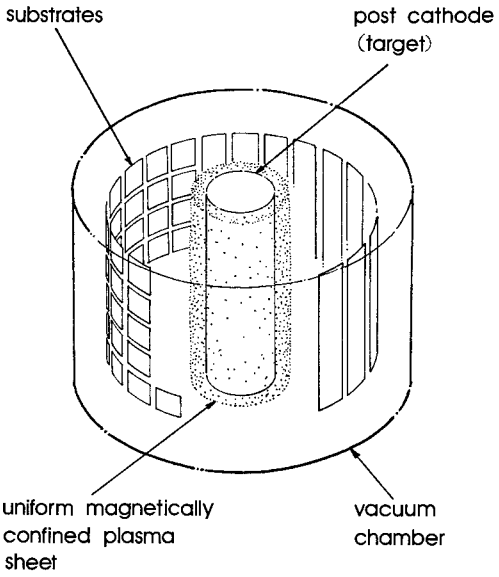
Continuous belt, SMC machine

FIGURE II



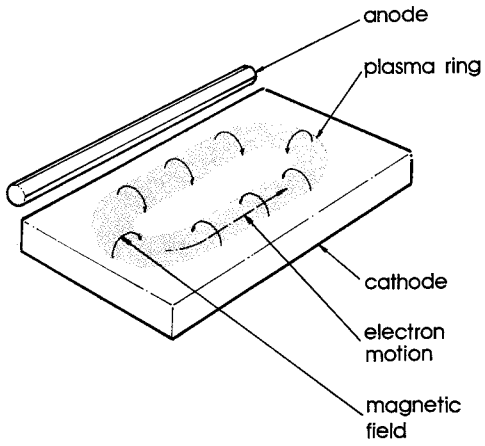
Conventional sputtering

FIGURE III



Telic cylindrical magnetron sputtering apparatus

FIGURE IV



Magnetron with magnetic end confinement

STATUS OF SPUTTERING ON RIGID AND FLEXIBLE SUBSTRATES

Charles D. Storms

President
Red Spot Paint & Varnish Co., Inc.

I. INTRODUCTION

Exterior Vacuum Metallizing (EVM) by sputtering is a reality in the automotive industry for rigid and flexible parts. The program offers 30-50% cost savings, 10% weight savings, a solution to water pollution regulations, improved overlay adhesion, and is the only process available for three dimensional flexible substrates. Current automotive applications include upper and lower grilles, both flexible and rigid. Other applications include light bezels, nameplates, mirror housings, flexible rocker and filler panels, door and window handles, hub caps, hood ornaments, flexible bumper guards, and end caps. Non-automotive applications requiring corrosion resistant metals might include appliance parts, plumbing fixtures, marine hardware, and exterior light fixtures. First generation coatings have performed satisfactorily. More durable abrasion, mar resistant, and flexible coatings will be required if the process is to be widely adopted.

II. HISTORY

A. Metals and Firing Techniques

As early as 1966 a topcoat of exterior quality was developed in conjunction with resistance fired aluminum. After field and laboratory tests (primarily CASS Test) aluminum was discarded as being inherently corrosion susceptible regardless of the topcoat. Electron beam fired Antimony was selected as the most likely candidate in late 1973 primarily due to color but also CASS test performance. Field testing showed Antimony to be marginally acceptable. Exterior exposure showed severe disappearance of the Antimony. Stainless steel did not disappear but was too dark in color. In early 1975 work began on sputtered chrome and was used for 1976 production. Metal cracking developed on exterior exposure, so a chrome alloy (80% Cr, 15% Fe, 5% Ti:) was developed and adopted for 1977 production.

B. Sputtering Process

Sputtering is performed in a high vacuum atmosphere. Chrome alloy targets are electromagnetically bombarded by excited Argon ions that dislodge or "knock off" metal atoms and are deposited on the parts that are passed by the target. The current process is line of sight, although rotation is possible using alloys and proper basecoats.

C. Past Production

Production has included:

1976	500,000	Chevy Caprice Lower Grilles
1977	600,000	Chevy Caprice Lower Grilles
	30,000	Chevy Caprice Upper Grilles
	5,000	Chevy Impala Upper Grilles (Service Parts)
	635,000	
1978	600,000	Caprice Lower Grilles
	95,000	Chevette Upper Grilles
	15,300	1977 Cheville Service Grilles
	8,200	1976 Cheville Service Grilles
	718,500	
1979	600,000	Caprice Lower Grilles
	90,000	Nova Upper Grilles
	65,000	Camero Upper Grilles
	65,000	Camero Lower Grilles (TPU)
	220,000	Chevette Upper Grilles
	167,000	X body Upper Grilles
	1,207,000	

Past production has performed at an acceptable level. While the applications were carefully chosen for protection from abrasion and exposure, field failures have been minimal. More durable topcoats will be required for more abrasive applications.

D. Substrates and Coatings

1. Substrate

For rigid applications general painting grade ABS and electroplating grade ABS are used.

Flexible parts use thermoplastic urethane (TPU) and flexible polyesters. B. F. Goodrich 58130 and UpJohn 8014-50D cause least problems among the TPU's from plasticizer migration.

2. Basecoat

On ABS a modified nitrocellulose lacquer basecoat is applied by flowcoating. Flowcoating lacquers presents problems in maintaining the proper solvent balance to not attack the plastic and to keep the coating in solution, resin stability, adequate solids and stress cracking of metal as related to basecoat formulation.

The current TPU flexible system uses no basecoat. The substrate is thermo reflowed by heating the parts to 1200°F (649°C) to give the part a glossy surface for bright plating.

Flexible polyesters use two package urethane coatings.

3. Topcoat

The topcoat is an acrylic lacquer applied by flowcoating. For flexible parts a urethane topcoat is required which is sprayed.

III. COST SAVINGS

Cost savings have been the motivating factor for EVM although 10% weight savings are also realized for grilles.

General cost savings of 30-50% over electroplating depending on part size, configuration, and whether electroplating is currently done in house or is purchased. Frankly cost is not a factor for flexibles because bright work cannot be accomplished any other way.

Economic considerations are as follows:

1. Capital investment is less with sputtering than for a conventional copper-nickel-chrome EP system.

2. Energy costs are 10-20 per cent of electroplating useage. Future utility costs will rise 10-15 per cent annually 1978-1985.

3. Electroplating chemical costs will increase 6-10 per cent annually through 1981 and 10 per cent 1982-1985.

4. EPA

The Water Pollution Control Act of 1972 is as follows:

1977 Best practical

1983 Closed loop no discharge of pollutants

1985 No discharge whatever

To meet the 1977 regulations, treatment systems cost 30-200 per cent of the cost of the plating system they serve.

5. Specific parts affect cost.

a. If significant surface ratio is high, sputtering provides a greater cost savings.

b. Sputtering is an advantage where the part is solid or honeycombed like a grille. The advantage is less with an open part such as a headlight bezel.

c. Line of sight coverage with sputtering could be a problem. Perhaps rotation firing could help.

IV. SPECIFICATIONS

A. Representative specification for sputtered exterior finishes is as follows:

1. Initial Crosshatch Adhesion - Use 3M#710 tape.

2. Abrasion

a. Sandpaper wear to failure - Use 600 grit sandpaper.

b. RCA Wear.

c. See Exhibit II.

3. 100 Hrs. Humidity (100°F @ 100% RH) - Crosshatch adhesion.

4. Three temperature resist cycles - 1 cycle =

20 Hrs. @ 175°F)
4 Hrs. @ RT) Crosshatch
20 Hrs. @ -20°F) Adhesion
4 Hrs. @ RT)

5. 336 Hrs. Salt Spray - Crosshatch adhesion.

6. 22 and 48 Hrs. CASS Test - Crosshatch Adhesion.

7. 1200 and 1600 Hrs. QUV -
120°F UV - 8 Hrs.
100°F Condensation - 4 Hrs.

8. 100 Hrs. Heat Stability @ 175°F - Crosshatch Adhesion.

9. Gravelometer (SAE J 400) - 0°F pass med (5) fair.

10. Cleanability - 5 cycles.

11. Flexibility - 1" Mandrel @ -20°F, direct and reverse flex.

12. 336 Hrs. Accelerated QUV -
8 Hrs. UV @ 160°F
4 Hrs. Condensation @ 120oF

13. 336 Hrs. Accelerated QUV + 96 Hrs. Humidity 100°F @ 100%.

14. Florida Exposure 5° D.I. South.

a. 3 months.

b. 3 months + 96 Hrs. Humidity.

c. 3 months + 15 Acrylic Crack Cycles.

1 cycle = 24 Hrs. Humidity
20 Hrs. @ -10°F
4 Hrs. Room Temperature

d. 6 months.

e. 12 months.

f. 24 months.

V. MARKET POTENTIAL

The attached chart is the market potential at one automotive company. (See Exhibit I.) Projecting this to world wide useage of exterior vacuum metallizing the number of parts could be several hundred million.

VI. CURRENT PROBLEMS AND POTENTIAL SOLUTIONS

A. Rigid Substrates

1. Mar and abrasion resistant topcoats.

For the market potential to be achieved, more abrasion and mar resistant topcoats will be required so that parts with wider bars will perform well. Field and laboratory testing is underway with two component systems which give greater abrasion resistance. Primary topcoats as well as clear overlay on the leading edges over the standard topcoat are being evaluated. Comparative wear evaluations are given in Exhibit II.

2. Metal Stress Cracking

Metal stress cracking is similar to an alligator appearance. Metal stress cracking

can be controlled by basecoat resin formulations, topcoat solvents, firing techniques, humidity control, alloys, and film thickness. On ABS 600 A^{O} is the maximum.

3. Basecoats

Resin systems that can be flowcoated with greater build are desired. Faster curing systems will be desired also. Basecoats for other plastics such as nylon, Noryl, and Polycarbonate are available where the engineering properties of heat distortion or impact are required. Perhaps higher heat distortion temperatures would allow coatings with greater properties. However, urethane topcoats which may be cured at lower temperatures appear to perform satisfactorily in abrasion testing.

4. Overlays

Because the overlay is organic coating to organic coating interface, overlay adhesion is excellent compared to the monumental problem of overlay adhesion to electroplated chrome.

B. Flexible Substrates

1. Basecoat Flexibility

Closely related but working contrary to metal stress cracking is basecoat flexibility. In general, the more flexible the basecoat, the worse the stress cracking and visa versa. Therefore, the basecoat must be optimized in both areas. Basecoat flexibility is tested by room temperature and cold temperature ($-20^{O}F$ ($+10^{O}F$ considered now by some)) bending over a 1" mandrel.

The current system passes tension (convex) bending but not compressive (concave) bending. The basecoat wrinkles in appearance but does not loose adhesion.

2. Metal Flexibility

Certain alloys are more susceptible to cracking in the plating process and upon flexing. One of the keys to successful flexible substrates will be the use of special alloys.

Basecoating is the preferred process to the thermo-reflow method being faster and less energy consumptive. The purpose of the basecoat is to provide adequate build to smooth rough surface for maximum brilliance and to provide adhesion and lamination of the metallic film.

3. Topcoat Flexibility

The topcoat must not crack on bending. (Same test as for basecoat.) This again is a compromise between flexibility and hardness/abrasion resistance.

4. Florida Exposure

Early submissions passed appearance-wise but the basecoats became brittle upon flexing after Florida exposure. The failure is typical of exterior varnish failure typified by checking. Field tests were not nearly as bad as Florida exposure due to the part being on the lower area of the car.

300-400 A^{O} of sputtered chrome does not give an adequate UV screen. Pigmenting the basecoat to provide a UV screen and UV absorbers are being studied.

One year Florida exposure on the topcoat on flexible substrates is complete with no loss of gloss, hazing, or cracking of the topcoat.

5. Wetting of the Substrate

TPU is difficult to wet by the basecoat. This condition is accentuated since one basecoat under evaluation is waterbased. Water based coatings inherently do not wet plastics as well as solvent types.

Parts could be power washed in detergent or solvents to remove oils and mold release. Work being done with wetting agents and solvent type basecoats.

6. Exudation of Interval Lubricants

Exudation of interval lubricants into basecoat causes dulling of metal film. This resembles iridescence. The solution is to select proper substrates such as 8014-50D, B. F. Goodrich 38130 (TPU), RIM, or flexible polyesters.

VII. CONCLUSION

All of us involved in the exterior vacuum metallizing project feel like we are in a poker game that takes three of a kind to win. Each hand we draw a pair and have to ante up some more. Some of us have drawn two pairs at times--but it takes three of a kind to win. All of us have so much at stake none can drop out. Soon we'll draw three of a kind. Fortunately in this game all of us can win - equipment suppliers, coating suppliers, processors, and the automotive industry.

ACKNOWLEDGEMENTS

1. David M. Lindsey, Chevrolet Motor Division, General Motors Corporation, 30003 Van Dyke Avenue, Warren, Michigan 48090.

2. Canby Willson and Rick Sorg, Guide Division, General Motors Corporation, P. O. Box 1090, Anderson, Indiana 46015.

EXHIBIT I

POSSIBLE CHEVROLET USAGE OF ALTERNATIVES TO CONVENTIONAL CHROME PLATED PLASTICS

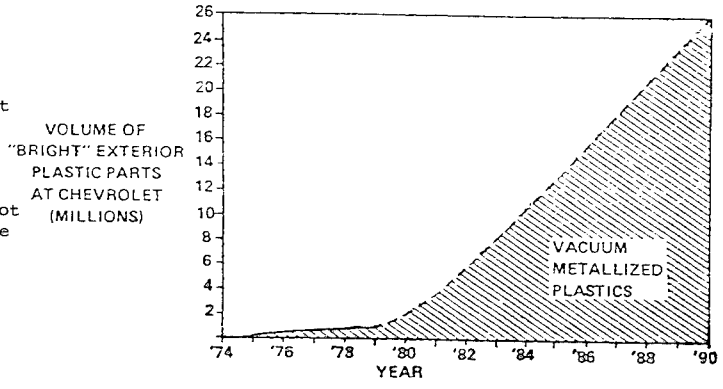


EXHIBIT II

COMPARATIVE EVM TOPCOAT WEAR EVALUATIONS

	Standard System	Standard System	Abrasion System	Flexible System	Clear Overlay
Film Thickness[1]	.4 mil	1.0 mil	1 mil	1 mil	1 mil
Sandpaper	37	92	195	209	131
Scrub Test[2]	306	766	3322	3220	
Gravelometer	6 Fair	6 Fair	6 Fair	6 Fair	7 Good
Tabor Wear	294	735	1135	809	
Zenith Eraser	133	333	811	610	
RCA Wear	5	12	403	100	75
TOTAL POINTS	775	1938	5866	4948	
Wear Index	1.00	2.50	7.57	6.38	4.43

1 All test results were corrected to reflect 1 mil film thickness. In production flowcoat applications .4 mil is practice.

2 Test uses Gardner Washability Machine Model M-105A using a 5% Lava Soap solution.

ABS AND ABS ALLOYS FOR AUTOMOTIVE EXTERIOR BRIGHTWORK

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ABSTRACT

Corporate Average Fuel Economy (CAFE) requirements have dictated that the American automobile lose weight. Part of this weight reduction is being accomplished by an industry-wide downsizing. Additional weight can be removed by prudent material substitutions. Obviously, substitutions must at least maintain existing quality and preferably improve quality at little or no cost penalty.

ABS is an industry recognized standard of excellence as the substrate for exterior automotive brightwork. ABS offers an unquestionable balance of cost and performance. Electroplated ABS radiator grilles dominate the industry. Recently with the emergence of vacuum metallizing of exterior automotive brightwork as a viable production process, the industry has once again recognized the inherent quality of ABS by making it the substrate of choice for sputtering.

ABS, like all materials, is not without certain limitations. Resistance to warping or deformation at elevated temperatures is one limitation. An ABS/polycarbonate alloy with improved warp resistance, good processability and platability has been developed to address this limitation.

One example of a significant opportunity for material substitution is rearview mirror housings. A substitution of ABS/PC alloy for diecast zinc allows a weight reduction of up to four pounds (1.8 Kg) per vehicle. Test data on these housings will be exhibited.

Wheel covers represent another application where the ABS/polycarbonate alloy can offer not only a cost/weight effective alternate to metal but also allow the engineer greater design freedom. With the increased demand for even smaller cars it will become even more desirable to utilize trim to retain the individuality of the various automobiles. The design freedom of thermoplastics in general, and the high performance ABS/polycarbonate alloy in particular, make this possible.

CHROME PLATEABLE NYLON 6

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INTRODUCTION

Two plateable nylon grades have previously been commercially available. Both were reported to have poor adhesion. In addition, the literature describes a few processes for plating polyamides. Jacob[1] plated nylon fibers and fabrics by immersion in a multiple action bath. Iodine treatment was reported to improve adhesion[2]. Both nylon and phenolic resins were plated by first activating in trihydroxymethylphosphine[3] whereas ionization of the amide groups with a reducing acid was claimed to promote better adhesion[4]. Chemical modifications of polyamides were also described. Additives such as phenylmethyl silicone oil; polypropylene glycol, or cetyl alcohol to polyamide substrates were reported to promote plating[5]. In all or most of these examples, modifications of materials or plating chemicals were found necessary in order to minimize the side reactions to which nylon is sensitive under the plating conditions.

This paper will describe a special grade of mineral filled nylon which has the versatility to accept mild etch conditions and can be plated using a variety of commercial plating chemicals. It will also describe some of the numerous applications for which this material was found suitable under an environment too stringent for ABS or polypropylene.

RESULTS AND DISCUSSIONS

A. Polyamide Chemistry:

Nylon 6 is a polyamide. It owes its properties to hydrogen bonding between amide groups as well as to the polarity of these groups. Its high level of crystallinity, high modulus, solvent and creep resistance are governed by the chain order which, in turn, is regulated by the amide groups.

It is known, however, that amide groups are sensitive to acids or bases. The rate of attack of these chemicals on the amide groups is controlled by the pK value of the medium, temperature, time and the level of crystallinity of the polyamide substrate. The selection of plating chemicals should be dictated by these criteria.

Since polyamides, like other organic polymers, areelectrically non-conductive, a means must be found to increase their surface conductivity. The following considerations were taken into account when the plan to produce plating grade nylon 6 was implemented:

(1) The composition should qualify for new applicatons for which plated ABS is unsatisfactory.

(2) To assure commercial viability, molded nylon parts must be accomodated in commercially existing plating lines, at least initially, with as little modification as possible.

(3) The aesthetics of plated nylon 6 parts should be comparable to metal or ABS.

B. Etch Systems:

(1) Chromic Acid:

The crucial step in plating polyamides was found to be the surface etching. In order to promote good adhesion and surface aesthetics, etching must be done without grossly distorting the surface, yet a sufficient number of active sites must be generated to promote the lock-and-key mechanism with the metal substrate which is required for high adhesion. Also, chemical degradation of polymeric chains will weaken the mechanical strength of the surface layers. Thus, although a good etch pattern may be obtained, a low molecular weight nylon layer will produce weak adhesion.

Conventional chromic/sulfuric acid etch solutions produced extensive surface degradation leading to poor adhesion and substandard appearance. The etch pattern obtained is shown in Figure 1. A high degree of erosion is evident and the surface lacks the required sites known to promote mechanical interlocking with the metal substrate.

Hexavalent chrome, used in these solutions, requires a neutralizaton step and, most often, an extensive hot water rinse because residues of chrome 6 left on the substrate will inhibit the redox process needed to deposit the palladium catalyst in the subsequent electroless steps. Nylon has a large affinity for complex formation with hexavalent chrome. It was found necessary in many cases to use a reducing agent, such as stannous salts, to reduce chrome 6 to chrome 3 which forms a weaker complex with the amide groups and are thus removable. The magnitude of chromium absorption was found to depend on the concentration and bath temperature of the etch solution. "High chrome" etch baths tend to exasperate this difficulty. Also, the prolonged exposure of the plating article to numerous chemical treatments, which is required with chromic acid etch, often leads to a high level of water absorption and a noticeably weak surface. Adhesion under these circumstances could improve only after oven baking of the plated article.

(2) Hydrochloric Acid Etch:

A mineral filled nylon 6 composition was especially formulated for mild etch conditions. Mineral acid solutions, such as 3N hydrochloric acid maintained at 40°C, produce an etch pattern closely resembling that of ABS. Figure 3 shows the etch of a plaque by HCL as viewed by scanning electron microscope at 45°C angle. Under similar conditions, the surface of an unfilled nylon 6 plaque had been left virtually unchanged, as is shown in Figure 4.

Hydrochloric acid etch solution is especially compatible with the commercially available catalyst solutions, most of which utilize 3N HCl. Colloidal Pd/Sn^{+2} activators in conjunction with acid/salt or fluoroboric acids are preferred although the classical $SnCl_2/PdCl_2$ two step activation is also adequate. Parts etched in the 3N HCl and subsequently activated by the Pd/Sn^{+2} colloidal catalysts are capable of accepting either electroless copper or electroless nickel and give peel strengths of 6-8 lbs/in immediately after plating without requiring oven baking. In fact, the adhesion does not increase on samples left at room temperature for over a month.

The entire electroless plating cycle for the mineral filled nylon 6 using the aqueous mineral acid solutions is sufficiently simplified that it requires some 12-25 minutes for completion compared to about one hour for ABS. Scheme 1 outlines a typical sequence for such a cycle.

Scheme 1
Electroless Cycle for CPN-1030

	Minutes
1. Etch: 3N HCl, 40°C	3-5
2. Activator, Pd/Sn Colloid, 27-30°C	1-4
3. Cold water rinse	1-2
4. Accelerator, 50°C	1-2
5. Cold water rinse	1-2
6. Electoless copper or nickel	5-8
7. Cold water rinse	1-2
Total time, minutes	13-25

It is worthwhile to stress that water rinse after the HCl etch bath is not required nor recommended. Most of the commercially available activators function in 3N HCl solution in order to maintain the acidity of the catalyst bath.

As is expected with filled polymers, debris tends to accumulate in the etch bath. Polyamides also contain low molecular weight oligomers which are leached into the etch solution. The bath life time can be extended and star dusting reduced by installing continuous filtration. Carbon pack is also desirable to remove the soluble organics.

C. Plating Chemicals:

As was stated earlier, commercially available plating chemicals were found, generally, to be compatible with the mineral filled nylon 6 especially when the non-chromic mineral acid etch solutions were employed. Tables 1 and 2 summarize some of these chemicals and the conditions under which they were applied.

The appearance of plated parts obtained under the conditions outlined in Tables 1 and 2 was excellent with adhesions varying between 6 and 8 lbs/in. Parts were thermally cycled and found to successfully pass the automotive specifications.

The water content of plated parts was found to vary depending on the geometry of the part in question. A truck assist handle contained 0.25% moisture after plating and remained unchanged after one year standing at room temperature, unprotected by a moisture barrier container. Auto window regulators, because of ribs and contours in the part, picked up higher water levels up to 0.45-0.5%. The highest level of water pick up was found in an auto exterior mirror housing, amounting to 1.0%. It would seem that water pick up during plating is a function of the surface-to-volume ratio of the part. The startling point, however, is that such high water levels in the plated parts did not cause blistering or cracking upon thermal cycling. This would indicate that the adhesion between the metal substrate and the plastic surface was sufficient to overcome the combined forces of thermal expansion of the plastic as well as the internal water vapor pressure generated during oven cycling.

D. Mechanism of Adhesion:

Unfilled nylon 6 plaques, etched and plated under conditions similar to those used for the mineral filled nylon 6, produced peel strengths of 1-1.5 lbs/in. As was stated earlier, the surface topography of unfilled nylon 6 did change when subjected to the etch conditions outlined in Scheme 1. One would, therefore, conclude that this adhesion is most likely produced as a result of the static or dipole-dipole forces between the polar amide groups and the metal substrate. Similar results were obtained when polyamides containing non-etchable minerals were used.

Mineral filled nylon 6, on the other hand, produces peel strengths of 6-8 lbs/in. Of this, presumably 1-1.5 lbs/in is due to the forces described above and the remainder 5-6 lbs/in. adhesion is most probably from the mechanical interlocking which occurs in the minute cavities generated in the surface of the plastic substrate. Since the etch solution used is non-oxidizing, the possibility of chemical bonds existing such as sigma bond or a coordination bond, is remote.

E. Molding of Mineral Filled Nylon:

(1) Molding Analysis:

A properly designed mold cavity produces stress-free parts under a wide range of molding parameters. Improper molds, such as those with a small gate or unbalanced cavities tend to narrow the "molding window". In certain severe cases stress-free parts cannot be produced under any molding condition. ABS molding technology was subject to the same degree of uncertainty until the glacial acetic acid stress analysis procedure was introduced. Mineral filled nylon 6 molded parts can now be readily scrutinized using a recently discovered "Plateability Analysis Solution". This solution will visibly project any potential trouble section of the molded part and will assist the molder in varying his molding conditions to minimize or eliminate these difficulties within minutes. The Plateability Analysis Solution can then be used intermittently to assure stable conditions on the molding press. Furthermore, parts that have been subjected to some of the solutions can subsequently be plated without detriment.

The Plateability Analysis Solutions are aqueous colored chemicals of critical chemical structure. They should be maintained at 40-70°C when in use. A molded part is dipped into one of these solutions for a few seconds, normally 10-30 seconds at 60-70°C, removed and rinsed with water. The analyzed part should acquire a uniform color intensity throughout indicating acceptable conditions. Parts that behave in this manner can be plated uniformly without skips and should pass thermal cycling and corrosion tests. Non-uniform color pick-up indicates potential problems in the lighter sections. These sections will either cause plating skips or, if covered, will most likely produce blisters. Figures 5 & 6 show an excellent correlation between the solution analysis and performance of plated parts.

A scanning electron micrograph shown in Figure 7 for a lightly stained, stressed section, indicates virtually no etch in that section.

This technique is not only useful for the molder but also for the mold designer who can detect flaws prior to finalizing the mold.

(2) Molding Conditions:

Mineral filled nylon 6 can be molded at high melt temperature and fast injection speed in order to produce high gloss finish. Table 3 outlines some of the conditions which are most suited for plating surfaces.

F. Properties of Mineral Filled Nylon 6:

Mineral filled nylon 6 is an engineering thermoplastic with properties suitable to replace metals, such as zinc die cast, in a variety of applications. It is particularly suitable for the auto, appliances and marine hardware industries. These are the applications from which ABS or polypropylene were excluded for either poor creep, low heat distortion temperature or low flexural modulus. Figures 8 & 9 demonstrate some of these potential applications.

III. REFERENCES

(1) Jacob, G., US Patent 3,733213, May 15, 1973.

(2) Abu-Isa, Ismat A., J. Appl. Polymer Sci., 15, 2865.

(3) Menikheim, Virginia, C., US Patent 3,686,017, August 22, 1972.

(4) Miller, G. T. and A. N. Dey, US Patent 3,629,922 December 28, 1971.

(5) VanAsperen, P. J. and J. L. M. VanderLoos, US Patent 3,674,658, July 4, 1972.

(6) Private Communication, The Enthone Co., West Haven, CT.

Table 1
Plating Chemicals for CPN-1030

	MacDermid(a)			Enthone(b)			Udylite(c)		
	Chem.	Temp	Time	Chem	Temp	Time	Chem.	Temp	Time
Activator	D-34	27	1-2	442	35	4	878	40	4
Accelerator	D-45	50	2	PA491	50	2	886	50	2
or	9338	50	2						
Electroless Cu.	9387	60	7	07297	25	7	820	60	10
Electroless Ni	9340	30	7				891	35	10
Adhesion, lb/in	6-8			6-8			6-8		

Temperature in °C
Time in minutes

Table 2
Mixed Plating Chemicals for CPN-1030

	Mixed Chem.	Temp	Time	Mixed Chem.	Temp	Time	Mixed Chem.	Temp	Time
Activator	442[b]	35	4	9F[d]	25	3	DriCat[e]	27	1.5
Accelerator	D-45[a]	45	2	964[d]	55	1.5	886[c]	50	3
Electroless Ni	414[b]	25	7	891[c]	27	7	891[c]	27	10

Temp. - °C
Time - minutes

(a) MacDermid
(b) Enthone
(c) Udylite
(d) Shipley
(e) McGean

Table 3
Injection Molding Conditions for CPN-1030

Cylinder setting, of

____ Rear Zone	480-520
____ Center Zone	500-540
____ Front Zone	540-560
____ Nozzle	540-560
Melt Temperature, °F	540-560
Mold Temperature, °F	180-200
Screw Back Pressure, PSI	100
Injection Pressure, PSI	6,000-15,000

Table 4
Properties of Capron® CPN-1030

	ASTM Method	Unplated	Plated*
Specific Gravity, g/cc	D-729	1.47	
Tensile Strength, psi	D-638	13,000	12,000
Elongation, %	D-638		
Flexural Strength, psi	D-790		
-1/4" Bar		20,000	20,000
-1/8" Bar		20,000	23,000
Flexural Modulus, psi			
-1/4" Bar	D-790	800,000	1,300,000
-1/8" Bar		800,000	1,700,000
No Notch Izod Impact ft.lb./in.	D-256	30	
Tensile Creep Strain, % @4000 psi, 1000 hrs. 181°F		10.5	
Deflection Temperature, °F under 264, psi	D-648	240	
Coefficient of Thermal Expansion, x 10, in./in./°F	D-696	2.8	

* 1.5 mils metal thickness

Figure-1 SEM of a surface etched by a conventional chromic/sulfuric acid etch system

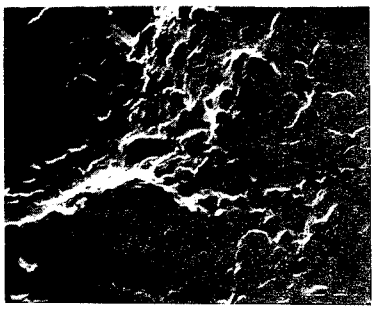

Figure-2 SEM of a surface etched by a modified chromic/sulfuric acid mixture

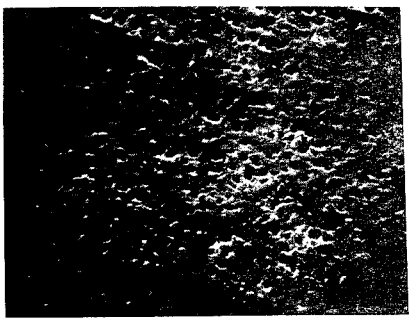

Figure-3 SEM of a surface etched by 3N HCl solution at 40°C

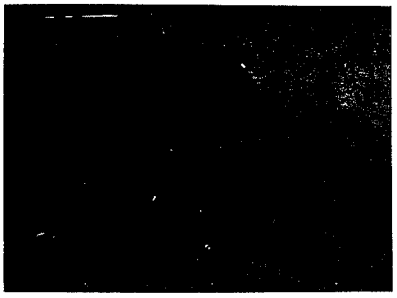

Figure-4 SEM of unfilled Nylon 6 surface etched by 3N HCl at 40°C

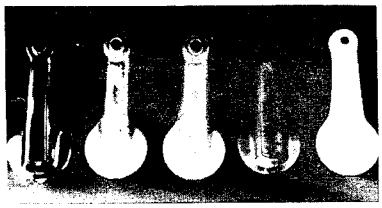

Figure-5 Stress-free auto window regulators show no blisters

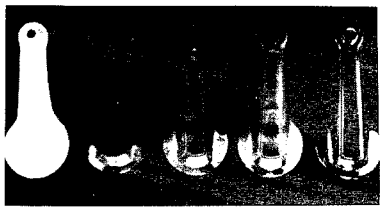

Figure-6 Stressed auto window regulators showing blisters after thermal cycling

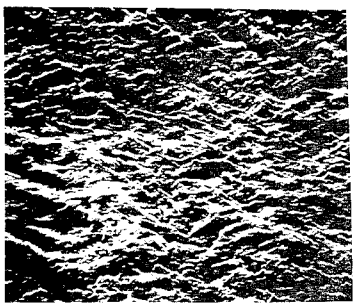

Figure-7 SEM of HCl-etched stressed section showing no etch pattern

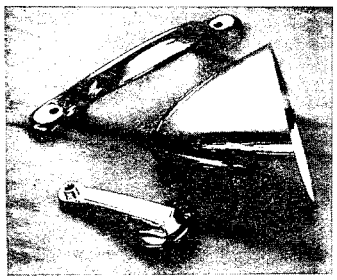

Figure-8 Plated truck assist handle, car exterior mirror housing, and car window crank

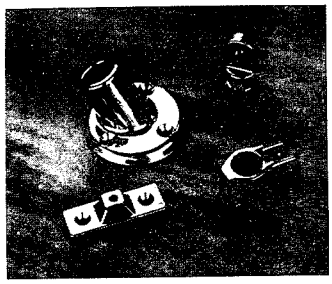

Figure-9 Plated marine hardware

THE NEWEST GROWTH "INDUSTRY": REGULATION

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THE NEWEST GROWTH "INDUSTRY": REGULATION

The cost of operating federal regulatory agencies is growing faster than the national budget, faster than the American population and faster than the Gross National Product. There are now 41 governmental regulatory agencies. Their expenditures are estimated to increase by 115 percent, to $4.8 billion over the five-year period ending in fiscal year 1979. But the regulatory agency cost is a very small part of the total. The really big cost is the cost imposed on industry.

Private industry spends 143 million manhours a year filling out the 4,400 different federal forms required by the government. The Commission on Federal Paperwork says the total cost of federal paperwork imposed on private industry ranges from $25 billion to $32 billion annually.

But paperwork is just the start. The Chase Manhattan Bank has estimated the total impact on industry. According to its research, the total cost resulting from government regulation in 1977 was almost $100 billion (Slide 1). Of that:

- More than $5 billion was for administrative costs to keep the bureacracy operating at the federal, state and local levels.
- About $85 billion was for compliance costs - the price of responding to regulation.
- And $13 billion was for lost opportunity costs - the loss of income caused by the need to invest in non-productive rather than productive products.

The grand total - governmental agencies plus industry, is well over $100 billion per year. Cost is up 40% since 1976.

In the final analysis, the public pays these costs, in higher taxes and higher consumer prices.

Federal, state and local regulations, for example, are adding between $1,500 and $2,500 to the cost of a typical new home. Automobile equipment requirements mandated by the federal government have increased the price of the average passenger car by $666.

We have progressed now to the point of forcing a conflict between further progress toward environmental goals and the other major war against inflation.

The argument is not over whether we should keep our environmental gains, or even whether we should continue to clean up. The conflict exists because too many regulations now go beyond what is needed, and are based on poor science or misinterpretation of scientific studies and ignore economics and technologic feasibility.

This outlook has a very real and direct impact on the chemicals and plastics industry.

For example, a study of air pollution control by industrial consultants Booz, Allen & Hamilton reveals the way cleanup costs increase with the degree of cleanup. They surveyed 712 chemical plants in 64 companies to determine steps which could be taken to clean up the air along with the cost of cleanup (Slide 2). Costs are fairly low for the first 60 to 70% of the cleanup. This is where we now stand. Progress has been made without the target well founded or scientifically based. But the costs increase expotentially as we approach the last 5 to 10% of cleanup. Industry stands ready to spend whatever is needed to protect health and welfare, but at these levels of costs, the target should be well founded and based on a balance of health risks, costs and benefits.

We agree with the general objectives of many of the statutes and regulations. All of us, for example, share concern for the public health and welfare goals. With few exceptions, we all want to keep our air and water clean.

And progress to date has been substantial. The environmental battle has many successes. Numerically, NYC enjoyed 216 days of acceptable air last year compared with only 100 in the mid-'60's.

San Francisco's air improved from about 60 satisfactory days per year to 250.

And automobile pollution will be reduced by 97% from 1970 to 1981. New cars, with older cars retiring, will continue to improve air quality.

These are just examples and the victory is certainly not complete. But real progress is evident and momentum underway will carry us further.

Let's look at the Clean Air Act with this in mind. Pollution is defined in terms of ambient air standards for air content of (A) nitrogen oxides, (B) carbon monoxide, (C) sulfur dioxide, (d) particulates (or dust), and (E) ozone. The heart of the cost of the problem is the level of the standard itself - to protect public health and welfare. If the standard is set more stringent than needed, the costs can skyrocket.

For example, in 1979, the EPA announced an ambient air standard of .08 parts per million of ozone, well below the level of existing air quality in 102 out of 105 urban areas in the country.

In February of this year, EPA, in announcing the new ozone standard of 0.12 ppm, stated that adverse health effects could be seen in very sensitive people at ozone concentrations in air of as little as 0.15 or 0.18 ppm.

And yet here is what the President's Regulatory Analysis Review Group in CWPS has to say:

> "The evidence for human health effects below 0.25 ppm is quite sparse, and the evidence of significant adverse effects below this level is even weaker. Put another way, the evidence does not appear to support the claim that significant human health effects have been clearly demonstrated or are virtually certain at 0.15 ppm or even 0.20 ppm. In addition, it is important to note that all of the ozone-related health effects that have so far been measured appear to be short-term and reversible."

Does this new ozone standard sound like a wise expenditure of $12 to $15 billion of our societal resources? Could we obtain greater public health benefits by spending these resources in other areas? These are questions which demand answers. Again, risk/benefit/cost analysis might avoid a lot of unnecessary and unwise expenditure.

There are other examples such as the Toxic Substances Control Act regulations which can seriously impact innovation or the OSHA Generic Carcinogen standard or RCRA, etc., etc. But identification of the problems associated with regulation, the costs and the impact are only part of the equation. Faced with the situation, one might ask: "What is the solution?"

The key lies largely with the public and its attitudes toward business and government.

Proposition 13 was clearly a signal of growing unrest over high taxes and government inefficiency.

President Carter, in his anti-inflation message, took note of the costs of regulation and pledged to do something about it.

This lead to the formation of the Regulatory Council, chaired by Douglas Costle of EPA, to better manage regulatory economics impacts and to hold all agencies accountable for the results of their decisions. Costle, writing in Pollution Engineering, says that:

> "There is a very serious commitment throughout this administration to make regulation more effective; to eliminate unnecessary economic and administrative burdens; to do away with duplication..."

These are encouraging developments and welcome words. They indicate an opportunity for the business community.

The stage is set for a constructive dialogue on the whole issue of regulation. Business should make every effort to contribute to this debate in a reasonable and informative way.

Business can start by informing the public on its vested interest in a strong economy and the private enterprise system

which makes it strong. Too few people seem to understand the connection between economic vitality and their own personal welfare.

Business should continue to speak out about the cost of regulation and the dangers of over-regulation and to stress that it is a cost ultimately borne by the consumer and the taxpayer.

The time is right to tell our story to the American people. We can convince them, through our words and actions, that our present regulatory system is in itself sorely in need of control.

SLIDE 1

TOTAL COST

GOVERNMENT REGULATION

$ BILLION	
5	ADMINISTRATION
85	COMPLIANCE
13	OPPORTUNITY LOSS
103	

SLIDE 2

CAPITAL COST OF REDUCING HYDROCARBON EMISSIONS IN CHEMICAL INDUSTRY

EMISSIONS CONTROLLED %	CAPITAL COST $ BILLION
60	0.4
82	0.9
88	1.3
90	2.0
95	3.5

AUTOMOTIVE FUEL ECONOMY— A MANUFACTURER'S VIEW

Gerald F. Stofflet
General Motors Corp.

It is probably safe to say that virtually everybody is concerned, in one way or another, about the energy pinch. Many people believe it is a manufactured crisis, but even the unbelievers have to pay attention to it.

Because of the close relationship between the energy supply and the auto industry, automotive fuel economy has become especially vital. The public has been generally conscious of the difficulties in petroleum distribution and the threatened real shortage ever since the Arab oil embargo of 1973-74. The sudden drastic price increases and the long lines at filling stations made an impression that has not faded. In contrast, before the embargo the general population was oblivious of the energy situation.

GM ECONOMY MEASURES

General Motors, whose well-being depends on the availability of fuel, recognized the situation much earlier, and took compensating measures. In the preceding years, compromises in spark and carburetor settings for emission control had reduced GM's new car average fuel economy to 12.0 miles per gallon (mpg) in 1974. Adoption of a new emission control system made possible engine operating improvements that brought average fuel economy up to 15.3 mpg in 1975. The reason was that the use of the oxidizing catalyst to remove most of the hydrocarbons (HC) and carbon monoxide (CO) after the exhaust gases have left the engine enabled us to recalibrate ignition and carburetion nearer to their optimum settings. Each year thereafter has seen further increase in our fuel economy, so the GM sales-weighted average for 1979 is estimated at 19.0 mpg, an improvement of almost 60% since 1974.

Well before the oil boycott, GM had begun plans for a broad program to reduce car weights. Congress was also concerned about the energy situation and in 1975 passed the Energy Policy and Conservation Act, calling for Corporate Average Fuel Economy (CAFE) of 18, 19, and 20 miles per gallon (mpg) for 1978, 1979 and 1980, respectively, and then set the CAFE at 27.5 mpg for 1985. The Department of Transportation was authorized to establish standards for 1981-84 and set a very stringent "front-loaded" schedule at 22, 24, 26 and 27 mpg for 1981 through 1984.

As you are aware, GM's program to develop lighter weight cars has been evident for several years. By 1976 the Chevette was on the road; the program produced new full-sized vehicles for the 1977 model year, intermediate cars for 1978, the front-wheel-drive luxury cars for 1979, and the 1980 compact X Body cars, completely new front wheel drive cars that came out in the spring of 1979.

This method of improving fuel economy--by weight reduction--is among the most basic approaches. Weight reduction of almost all of our series over the past four years has averaged about 700 pounds per car, and has been responsible for average improvement of about 2.3 miles per gallon for the new car CAFE. In the case of our 1980 X cars it may be as great as 5-6 mpg.

The fleet average fuel economy improvements already accomplished by GM, while largely attributable to weight saving, have been achieved while the passenger space was retained. Further weight reductions are going to be necessary, and the difficulty of achieving them can be expected to increase. Up to now, the cost of the massive weight-saving program has been about a billion dollars for each half mile per gallon improvement in CAFE. Future improvements will probably cost us a billion dollars for each two-tenths of an mpg, as each additional increment becomes more difficult.

By 1980, GM will have redesigned almost all of its cars. The fat has been trimmed from the vehicles, and getting 27.5 mpg is going to take a series of new technologies, none of which can be expected to give us the mpg gain we got from the catalytic converter.

OTHER MODIFICATIONS

In addition to weight reduction, other technologies also are being investigated to improve fuel economy, some of which are related to weight saving. For instance, when car weight is decreased, engine size also can be reduced. Improvements in basic engine efficiency are constantly being sought in research programs that are never considered really ended. Engine efficiency will be further improved by increasing use of electronic engine controls, to decrease emissions and offset much of the fuel economy penalty resulting from emission control. Despite these improvements, the general decrease in engine displacement will lead to some compromise in performance, which we will all have to live with.

Improvements in transmissions are being developed, which should further help our fuel economy. A torque converter clutch for automatic transmissions, which eliminates slipping in the converter once up to speed, is one of the more promising measures. The increased economy from all the transmission improvements may be as high as 9 to 11%.

Aerodynamic improvements are planned, and one of our principal tools to help in this area is a wind tunnel now being constructed at the GM Technical Center. Complete full-sized vehicles have had to undergo aerodynamic tests at a remote location in the past. As fast "turnaround" is made possible by the new facility, we will be able to conduct our aerodynamic development programs more efficiently. The wind tunnel is expected to be operational late this year. We hope to gain 3 to 4 percent in this area.

Related to aerodynamic improvements are current projects designed to help reduce friction. In this area we are also working with oil companies as they develop new low-friction lubricants. We hope to reduce engine and powertrain friction enough to help fuel economy about 2 percent. Tire rolling resistance also is being decreased by work our company does with the tire manufacturers; savings here might be 3 percent.

It has been a well established fact that the diesel engine is superior to the gasoline engine in fuel economy, and GM introduced a diesel engine as an option for its full-sized Oldsmobile in 1978. Its use later was expanded to make it available for the Cadillac Seville and in some Chevrolet and GMC light trucks. For comparable performance, the diesel gives upwards of 25 percent better fuel economy than the gasoline engine, and if we can overcome the negative effect of tightening emission standards, we expect to apply the diesel to a greater number of our vehicles, further improving our CAFE. Current indications are that up to 15 percent of our production will be diesel driven by 1985, which in that year would add about 0.8 mpg to our fleet fuel economy average. The diesel is one of the most useful tools we can use to meet the fuel economy requirements of the Energy Policy and Conservation Act while still offering cars that can carry a family of six members.

DIESEL DIFFICULTIES WITH EMISSION STANDARDS

The diesel has excellent reliability, and it is basically clean with respect to HC and CO, without any aftertreatment. Emissions could be a problem when a particulate standard is established, and when the NOx requirement goes below 1.5 g/mi. With the HC standard at 0.41 g/mi in 1980, even the HC standard is hard to meet.

The NOx standard is scheduled to become 1.0 g/mi in 1980 in California and one year later in the other 49 states. For diesel engines, a provision of the law allows EPA to waive this Federal standard through 1984, allowing diesels an NOx standard of 1.5 for those four years. GM has requested that the waiver be granted. As the NOx standard becomes very stringent, exhaust gas recirculation must be applied to control the NOx. In the diesel, this increases the formation of particulates, some of which would get into the engine oil and could cause wear of engine parts, mainly the valve train and piston rings.

The particulate standard also could be an obstacle. EPA has proposed a standard of 0.6 g/mi in 1981 and 0.2 g/mi in 1983. GM believes a standard of 1.0 g/mi would be more realistic, and it would be attainable if the NOx waiver also was granted. An alternate plan suggested by GM would set up a fleet average particulate emission standard, analogous to the CAFE. It could be given a similar designation--CAPS, for Corporate Average Particulate Standard. Such a scheme would allow us to build diesels while we are working on the technology for close control of particulates, and average fuel economy could continue to improve. Without concessions by EPA in the NOx and particulate standards, our plans for extensive use of the diesel might be jeopardized. This, in turn, would seriously affect our campaign to improve fuel economy.

EMISSION STANDARDS PENALIZE ECONOMY

While we are meeting the 1980 fuel economy standard, which is 20 miles per gallon, we also have to overcome a penalty estimated at up to 5 percent imposed by the increased stringency of the 1980 emission standards. In 1981, when the Corporate Average Fuel Economy must be 22 mpg, another increase in emission control severity imposes an estimated 3 percent penalty on fuel economy as compared with 1979. Introduction of the new GM C-4 emission control system in 1981 will prevent this loss from being larger. EPA also has made achievement of fuel economy standards more difficult by changes to the fuel economy test procedure, causing a loss in GM's CAFE amounting to about 0.6 mpg.

MATERIAL USAGE CHANGES

Our 1980 compact line--the new front wheel drive X car--is a good example of techniques to be used in continuing to save weight in new car designs. New suspension, transmission, steering, and other chassis systems had to be developed, and weight saving was a consideration in all the development projects. Careful space planning also has helped in retaining practicality when the car size was reduced.

Changes in material usage already have played a part, and will continue to be very important in our weight saving during the coming years. One of the principal changes will be a decrease in iron and steel usage and substitution of aluminum and plastics where practical. High Strength Low Alloy (HSLA) steel also will become more widely used, competing in some areas with aluminum, but total iron and steel use will decline by about 600 pounds in a composite GM car, from over 2600 pounds in a composite GM car of 1979.

Although aluminum offers promise because of its low weight, the extent of its application can't be forecast with confidence because of its high cost.

Some materials, like rubber and glass, will be used in smaller amounts just because cars in general will be getting smaller, but use of plastic will definitely increase. At present, the average GM car contains about 200 pounds of plastic, as compared with about 175 pounds in 1975.

In addition to light weight, plastics have the following advantages:

- o freedom from rust
- o resistance to dents
- o cost effectiveness
- o fewer fabricating steps
- o simplified assembly operations
- o reduced tooling costs
- o capability of consolidating components.

Our current forecast is that plastic usage will be about 255 pounds per car in 1985, but it could reach as much as 300 pounds if certain technological problems can be overcome. Among the areas of difficulty are

- o surface quality of sheet molding compound
- o elastic modulus and fatigue properties of fiber-reinforced plastic
- o production rates
- o recyclability.

Plastic materials in today's car are applied mostly to decorative panels and other nonstructural components, and the extent to which plastics can be used in more demanding functions depends on the success of our engineers and scientists in developing their mechanical properties. The strength of fiberglass-reinforced plastic can be equivalent to that of steel, but the elastic modulus is considerably less. As the necessary characteristics are developed, plastics can be used for such components as leaf springs, transmission supports, and drive shafts. Graphite fibers in reinforced plastics impart excellent stiffness and strength, but extremely high cost has so far prevented the use of graphite fiber-reinforced plastic in any GM cars. There is hope that the price will decline enough in the next few years to make the use of graphite fibers practical.

A few structural uses of plastic already are being evaluated; one example is an experimental radiator support made of sheet molded compound with high fiberglass content. Seven metal parts are replaced by a single molded panel, with a weight saving of 12 pounds.

A station wagon tailgate being developed also saves several pieces, with two pieces of sheet molded compound taking the place of seven steel parts. Here the weight saving is 16 pounds. Fiberglass leaf springs have been successfully evaluated. These composite springs achieve a weight saving of 30 pounds, or 75 percent, compared with conventional leaf springs.

Petroleum is used as a feedstock for making plastics, and so the oil dilemma has led to some concern about whether the manufacture of plastics is a wise use of petroleum resources. At current rates of plastics manufactured in this country, the plastic feedstocks use only 1.5 percent of the oil used in the United States, and plastics in cars constitute only 0.1 percent of total U.S. oil usage. Plastics also have low manufacturing energy content relative to other materials, and the reduction in car weight effected by the use of plastics helps to save fuel during vehicle operation. There actually is an energy advantage, therefore, in the application of plastics to auto manufacture.

As an example, if a sheet steel part weighing 13 pounds was replaced by aluminum, the aluminum part would weigh 5 pounds. Made of plastic, the part would weigh 6 pounds. In producing the raw materials and manufacturing the part from steel, an energy equivalent of 3 gallons of gasoline is used; one-third more energy, equivalent to 4 gallons of gasoline, is required to make the part of aluminum, and one third less--equal to 2 gallons of gasoline--is needed to produce the plastic part. Adding to these quantities of energy the amount consumed in carrying this part around assembled in a vehicle for 100,000 miles, we arrive at an energy total equivalent to 14 gallons of gasoline for the steel part, 8 gallons for aluminum, and 7 gallons for the plastic part. Rather than shy away from plastics because they are made from petroleum, therefore, we can wholeheartedly seek to find new applications, saving energy in two ways.

The energy saving methods we have mentioned will enable our new vehicles to meet higher fuel economy standards. As they enter the automobile population, replacing older, less economical vehicles, total fuel consumption will begin to decrease, even though the total of vehicles in operation increases. The total fuel consumption by passenger cars for 1979 is estimated at 82.9 billion gallons. By 1985, an 11 percent decline in usage is anticipated, to 73.5 billion gallons.

Illustrations

1. A Car or B Car dimensional pic
2. X Body Car
3. Wind Tunnel
4. Emission Standards 1980 and future, including particulate & CAPS proposal, table.
5. Material usage past & present, table
6. Plastic Parts

Federal Passenger Car Exhaust Emission Standards (Grams Per Mile)

	HC	CO	NO_x	Particulates		
					GM Proposal	
				EPA Proposal	CAPS † Level	Estimated Diesel Requirement
1979	1.5	15	2.0	—	—	—
1980	0.41	7.0	2.0	—	—	—
1981	0.41	3.4*	1.0 +	0.6	0.2	1.0
1982	0.41	3.4*	1.0 +	0.6	0.2	1.0
1983	0.41	3.4	1.0 +	0.2	0.1	1.0
1985	0.41	3.4	1.0	0.2	0.07	0.5
1987	0.41	3.4	1.0	0.2	0.05	0.2

* *Possible 1981- 82 waiver to 7.0 g/mi*

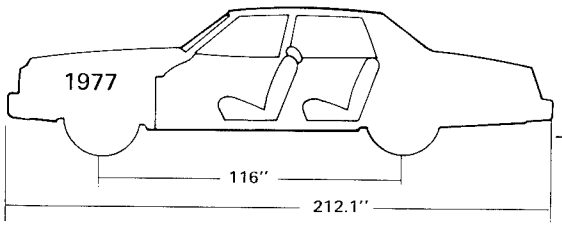
\+ *Possible 1981- 84 waiver to 1.5 g/mi for innovative technology or diesel*

† *Corporate Average Particulate Standard (sales-weighted average of all new cars sold by a given manufacturer)*

Materials in the Composite General Motors Car

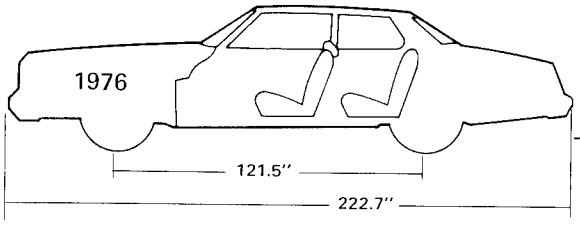
Material	LB (Net)		
	1975	1979	1985 (Est.)
Iron	643	585	310
Steel	2347	2050	1735
Aluminum	56	110	175 - 235
Lead	26	22	22
Copper	26	31	29
Zinc	39	15	9
Glass	99	92	79
Rubber	125	97	84
Plastics	175	191	235 - 300
Other	254	227	189
Total *(Avg. Shipping Wt.)*	**3790**	**3420**	**2867-2992**

CHEVROLET IMPALA 4-DOOR SEDAN 1977 VS. 1976



	HEAD ROOM	SHOULDER ROOM	LEG ROOM	TRUNK SPACE
F	39.0"	60.8"	42.2"	
R	38.2"	60.8"	39.5"	20.2 cu ft

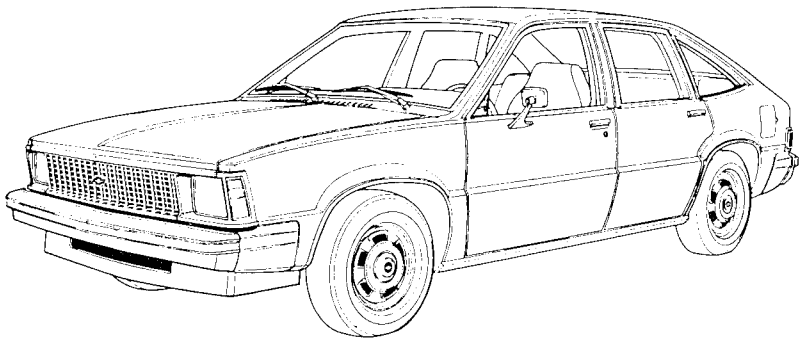
Fuel Economy 17.9 mpg



	HEAD ROOM	SHOULDER ROOM	LEG ROOM	TRUNK SPACE
F	38.5"	64.0"	42.6"	
R	37.8"	63.1"	38.5"	18.9 cu ft

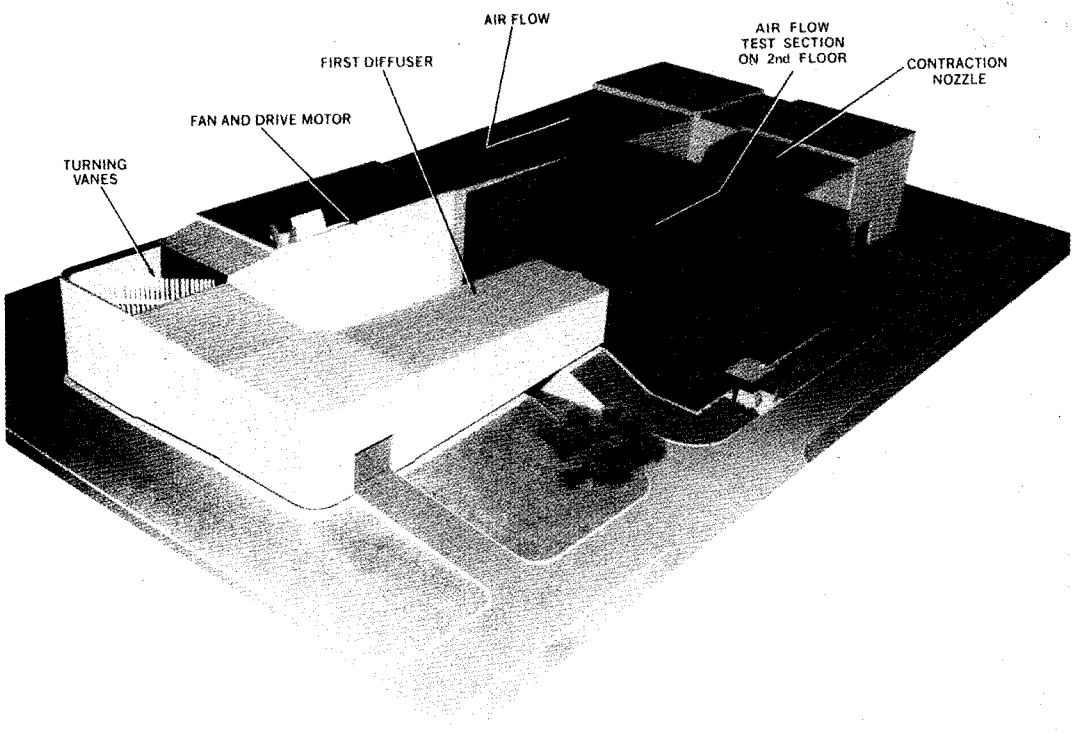
Fuel Economy 14.7 mpg

Full-sized cars were reduced in weight and outside dimensions in 1977. Average weight reduction was about 700 pounds.

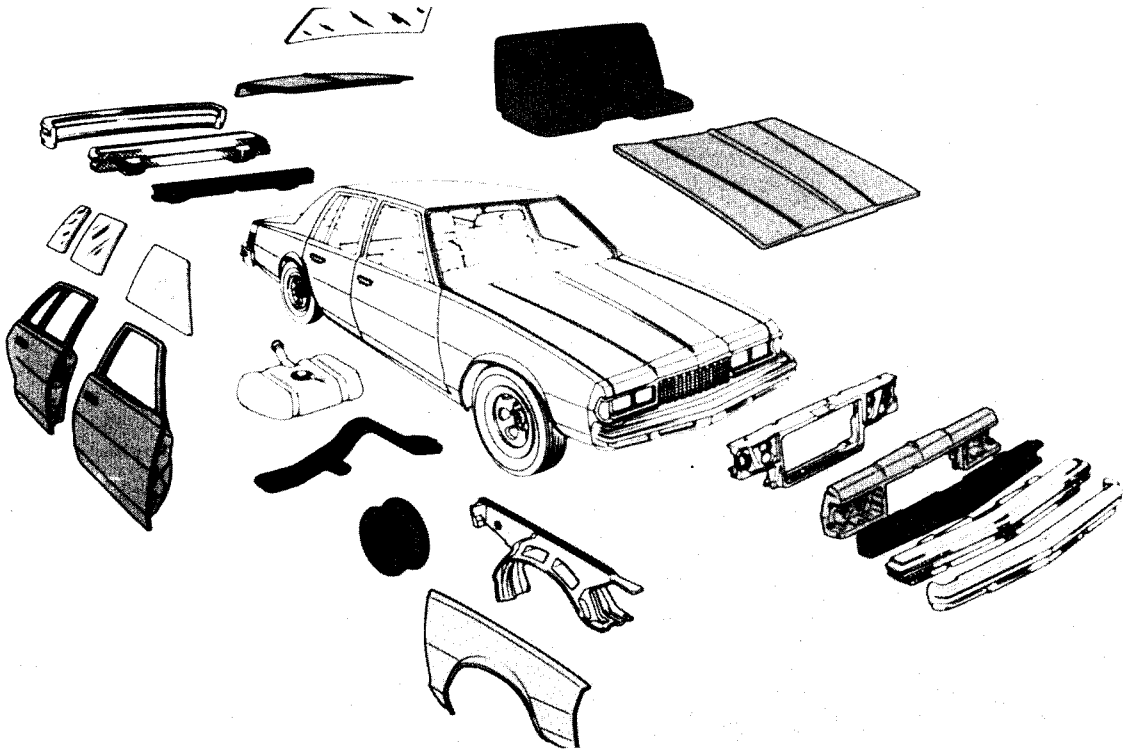


1980 "X Body"

The completely new 1980 "X Body" cars are about 750 pounds lighter than the 1979 cars they succeed.



The new wind tunnel at the GM Tech Center will expedite improvement in aerodynamic qualities of new vehicles.



Parts shown have the potential for large volume use in the future. Both appearance parts and structural components are included.

ENERGY AND RAW MATERIALS IN TRANSITION: CONFLICT AND COMPROMISE

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ENERGY AND RAW MATERIALS IN TRANSITION:

CONFLICT AND COMPROMISE

Engineers, marketing consultants, and industry analysts have all predicted a strong demand for plastics in the transportation industry in the 1980's. We can readily understand the basis for this prediction; plastics, with their combination of light weight and high strength, make it possible for automobiles to reach the improved gasoline mileage goals demanded both by legislation and by the public and at the same time to meet the legislatively mandated standards for greater safety. For the petrochemical industry -- the suppliers of plastics -- this would seem to indicate a highly favorable outlook. As a result, I was asked to discuss with you the anticipated petrochemical feedstock/energy relationship, and to "assure you" of the continuing availability of raw materials for this plastics growth.

I'd like to be able to do that, but I must instead suggest that while the demand for plastics is strong, serious questions about the supply and price of raw materials are creating much uncertainty in the plastics market. To understand this uncertainty, we need to put the outlook for plastics in a broad framework by considering the influence of energy, environmental, and economic policies on feedstocks. Once we do, it becomes apparent that there are several problems that must be solved if the petrochemical industry is to satisfactorily meet this important plastics demand. At the heart of the problem lies a compelling paradox which cries out for resolution.

All of you are familiar with paradoxes and logical fallacies -- those puzzling applications (or misapplications) of logic which surprise and bewilder us. The eccentric English philosopher Bertrand Russell loved logical fallacies, and he frequently told a story to entertain and test the wisdom of visitors. The point of the story was to prove that he had a cat with ten tails. He argued as follows:

> No cat has nine tails.
> My cat has one tail more than no cat.
> Therefore, my cat has ten tails.

Like many paradoxes, this logical fallacy flouts conventional logic -- and common sense to boot.

Unfortunately, the plastics industry faces a more serious paradox, which shares all too much in common with the story of the ten-tailed cat.

Our paradox concerns aromatics. These substances -- benzene, toluene, and xylene (BTX) -- are used both in improving the performance characteristics of gasoline (or as they say in the trade, "raising its octane rating"), and in making lightweight plastic parts for automobiles. To understand the paradox, it's necessary to look at the competing applications for these versatile substances. On the one hand, they are increasingly used as gasoline blending components to improve octane ratings, since the emissions requirements for today's new cars necessitate the use of high performance unleaded gasoline. On the other hand, lightweight plastics, many also derived from aromatics, are essential in trimming down automobile weight to meet the still stricter gasoline mileage requirements for tomorrow's cars, due to reach a fleet-averaged 27.5 miles per gallon by 1985. A vast quantity of hydrocarbons can be saved by driving cars incorporating lightweight plastics -- vastly more hydrocarbons, in fact, than are used to produce those same plastics.

The demand for aromatics in gasoline is now so great that we in the petrochemical industry are having increasing trouble obtaining sufficient supplies of feedstocks at acceptable prices. The paradox, then, is that fuel emission and performance requirements are creating pressures to burn aromatics now rather than using them in plastics that will help us save gasoline in the future.

Why is this happening? A number of factors are responsible, including the public's driving habits, government regulations, and the use of the catalytic converter to meet the emission standards for new cars. Let me highlight these last two factors. Catalytic converters lower fuel efficiency and this requires the use of greater quantities of gasoline -- which must be high-octane unleaded gasoline. The catalytic converter in turn was designed as a response to the rigorous clean air standards of the Environmental Protection Agency. So to maintain engine performance while meeting EPA regulations, refiners have had to raise the percentage of high-performance hydrocarbons in their gasoline. Together, the catalytic converter and the EPA regulations require the use of enormous quantities of BTX as fuel.

Conventional projections suggest that U.S. gasoline consumption will peak in the early 1980's and then decline, as a result of increasingly fuel efficient cars. But without a resolution of our paradox, this is unlikely; high raw material costs could reduce the use of lightweight plastic parts and that would hinder the gasoline conservation efforts that serve as a basis for these projections. The country can -- and must -- resolve this paradox.

The paradox itself is complex, but it is no accident. Federal regulations governing petroleum are now in a period of transition, a time of change from old to new, a time of conflict and readjustment. And the roots of the paradox lie in the recent past.

Much, though not all, of our current regulatory environment was shaped by a preconception which is now out of date: namely, that petroleum was available in quantities sufficient for all our needs. Since supply did not appear to be a problem, we could turn our attention to other ambitious goals, such as establishing strict new auto emissions timetables and putting a ceiling on oil prices.

Now we are faced with a new set of circumstances, not entirely of our own choosing, marked by fuel shortages, strict conservation measures, high prices for petroleum products -- and by the increased use of plastic products in automobiles. It is a new era in energy and in transportation.

The regulations and environmental timetables laid out in earlier years, however, are still with us and are hindering our progress in this new era. Here is the essence of our present conflict between old and new.

Fortunately, this conflict ought to be only temporary since the new fuel efficiency requirements now being phased in will significantly curb our nation's demand for gasoline, including aromatics. The conflict is likely to be most severe between 1979 and 1982, but should move toward resolution after that. As this happens, we should be able to make still further progress on other important national goals like cleaner air.

Before going into the feedstock situation in more detail, let me step back for a moment and discuss Union Carbide's stake in the feedstock/fuel conflict. We are a major

supplier of raw materials used in making plastic automobile parts. Many of these are available now, and others will be soon:

- Urethane elastomers used in RIM -- Reaction Injection Molding -- were first used in 1975 model cars and have now reached a significant commercial volume. This material is used for the fascia, bumpers, sight shields, air spoilers, and fender flares of cars. Use of RIM parts can result in weight savings of up to 60% as compared with the metal they replace.
- Deep foam urethane, now being used to make car seating, combines the necessary qualities of light weight and comfort.
- Urethane also has another important use -- carpet backings made by Union Carbide's new NIAX process. Here again important weight savings can be achieved, and the carpets also have valuable cushioning and noise suppression qualities.
- Another plastics material, SMC -- Sheet Molding Compound -- is used in making grill opening panels.

All of these materials are derived in part from aromatics.

New uses of other plastics, now in the experimental stage, are expected to make them even more attractive to automobile manufacturers.

Carbon fiber products also have strong potential for use in cars since they, like plastics, have the needed combination of low weight and high strength.

- Union Carbide's THORNEL brand of carbon components, now being evaluated for use in automobiles, has potential for use in support systems, drive shafts, leaf springs, and side door intrusion beams. For example, a carbon fiber/glass fiber transmission support for passenger cars weighs only 6-8 pounds, compared with the 20 pound steel component it is designed to replace. And carbon fibers can also be used for radio interference suppression.

If one adds together all the Union Carbide products designed for use in automobiles, our stake in resolving the feedstock problem is clear.

As a major producer of plastics, we are enthusiastic about the strong market demand for these products in automobiles. The average 1978 automobile in the U.S. used 165 pounds of plastics, supplied by us and by other plastics producers. Yet this required a surprisingly small percentage of our country's overall petroleum usage: considerably less than 1%. Some of the petroleum used was aromatics. Since many plastics have unique combinations of properties, the amount of plastic used in automobiles is expected to more than double by 1985 (to about 350 pounds per car), growing at the rate of about 11% per year.

The amount of aromatics used today in the petrochemical industry is quite small relative to the amount used in gasoline (a ratio of 1 to 9), but for petrochemicals these aromatics are virtually indispensable. As important as our present levels of use, however, is the projected demand for aromatics and other petrochemical feedstocks in the future. This demand for both automotive and non-automotive purposes will grow by about 6% per year between 1978 and 1985. During this same time however, the overall use of oil in our country will grow by only about 2.0 - 2.5% per year. Although only about 5% of the petroleum used in America goes to petrochemical feedstocks, even this small share will be difficult to acquire if a higher priority is given to directing petroleum supplies to fuel consumption. The overall petroleum supply problem is intensified of course because of the declining availability of domestically produced oil and the nation's need to avoid still greater dependence on oil imports.

I would like to be able to tell you precisely what plastics will cost in the next decade, but that is difficult to do. It used to be that the only certainties about human existence were death and taxes. But I'm afraid that in the 1970's and 1980's we need to add a third certainty: inflation. A number of factors make it highly likely that the cost of plastics will rise: inflation throughout the economy as a whole, the strong oil position of the OPEC nations, the dwindling availability of readily accessible domestic oil, and the high cost of oil alternatives. From this combination, it seems clear that plastics prices will rise faster than the rate of increase of prices in the economy as a whole, though it is impossible to say precisely how fast.

Our chemicals and plastics feedstocks unit cost is now over seven times what it was in the pre-oil shortage year of 1972. During the same period, our total purchased material cost index rose "only" about half as much, and in that same period construction costs doubled. We expect that these general relationships will continue into the 1980's, with feedstock and energy costs rising faster than average. This increase not only has to be reflected in plastics prices, but must also be taken into account in assessing their future markets.

Increased prices are of course a result of high demand, brought on by the competition between fuel and feedstock needs. If appropriate action isn't taken, these price increases could reach prohibitively high levels, making much-needed plastics less attractive to automobile manufacturers. These pressures are already strong. The price of naphtha -- the basic material used in making BTX and other plastics building blocks -- more than doubled in the year from June, 1978 to June, 1979. If continued, such increases could have a serious negative impact on our nation's automotive efficiency goals in the 1980's. Moreover, price is not the only factor determining the allocation of tight supplies. Hard-pressed refiners may be tempted to maximize high-octane, lead-free gasoline production by diverting some of the BTX which has traditionally gone to petrochemical feedstocks. The motivation for this action would not be price but public pressure from irate, gasoline-short motorists. Thus spot shortages of BTX are a possibility.

The petroleum shortage is, of course, a critical national problem. But there is no shortage of complex government policies -- both economic and strategic -- which further complicate the situation. These policies include our nation's commitment to holding down inflation, to lessening our reliance on imported oil, and to increasing our national security.

Each of these policies has substantial public support and each is aimed at a worthwhile objective. However, too little has been done to cut through and resolve the conflicts which inevitably arise between them. And this points to a more basic problem: as a nation we have established no clear sense of priorities. Each policy is pursued singlemindedly, often in response to pressure by narrow interest groups. We can improve on this approach, first by agreeing on basic priorities, and then pursuing our policies in a more balanced way. If all of us -- the public, the Congress, and the federal agencies -- took such a broader view, and if we all were committed to solving problems rather than allowing them to continue, difficulties like those surrounding plastics feedstocks should not be impossible to eliminate.

Once we adopt a broader outlook, several key perspectives become clear. Most basic is the importance of national security considerations. Our present dependence on imported oil, much of it from the politically unstable Middle East, is an Achilles Heel for our nation, both strategically and economically. Despite much rhetoric to the contrary, our nation's dependence on imported oil has almost doubled from 4.76 million barrels per day in 1972 to an estimated 8.88 million barrels per day in 1979. We must reduce this dependence, and conservation is one good way to do it.

An important step is already being taken: phased decontrol of domestic crude oil prices, gradually allowing the U.S. price to rise to the world level. This should allow market forces to be more active in stimulating increased petroleum supplies and determining levels of use -- and that would represent a decided improvement. We supported President Carter's decision on decontrol last April, and we believe it will in time help to alleviate our over-dependence on oil imports.

The nation also needs to take steps to increase refining incentives for the production of high-octane gasoline. Present price controls on motor gasoline simply don't allow for the recovery of a reasonable return on new process investments. These controls need to be eliminated if we are to have adequate supplies of high octane gasoline -- as well as feedstocks.

An equally important short-term measure is for EPA to reevaluate the use of octane-boosting additives in gasoline. As the President has recognized, we need more flexibility in scheduling lead phaseout. That is why his administration wisely postponed for a year any further reduction in lead use. The administration also allowed the use of one other octane-boosting additive, MMT, but only for the summer months. We need to examine the need for these measures for a longer duration (i.e., two to three years), to help assure that both the petrochemical industry and the motorist get the BTX each needs during the transitional period of the early 1980's.

One program aimed at holding down the consumption of gasoline should be escalated: promoting diesel usage. Diesel engines run more efficiently than the conventional internal combustion engine, and diesel fuel consumes no light aromatics. But since diesel engines emit more particulates and oxides of nitrogen than conventional engines, their full-scale promotion is now in abeyance pending the development of pertinent air quality standards and criteria by EPA.

We at Union Carbide -- like you -- favor cleaner air, and my company, like most of yours, has followed through on that commitment with substantial anti-pollution expenditures. A clean air policy, however, must be pursued in a measured way, recognizing that much has already been accomplished and that future progress must be made in conjunction with progress on other national goals. Specifically, we must be aware of the effects of our clean air policy on the economy, on oil import levels, on fuel conservation efforts, and on feedstock supplies.

Let me suggest one final strategy, this one longer term. It is to begin the commercial synthesis of quality transportation fuels from coal and oil shale. Abundant domestic sources of these raw materials are available for fuel synthesis, and we should stimulate their use, preferably by providing stronger investment incentives. Technology is not the limiting factor; it's economic motivation.

This list seems to us to contain the most important solutions to our feedstock supply problem. But as you go over it, the individual steps underline the need for all of us to take a broader perspective as we rethink, reformulate, and refine our public policy goals for the 1980's.

One legacy of the 1960's that is still at work today has led to regulations which in effect say, "do this!" with scarcely a second thought about costs, conflicts, or feasibility. This approach results from the conviction, so common in the sixties, that virtually any problem, once discovered, could be easily solved. And this conviction has directed much of our energy and environmental policy.

But the paradox facing the automotive industry -- as well as its suppliers and its customers -- points out that not all problems can be solved simultaneously by regulatory fiat. Rather, regulations which treat problems in isolation can lead to an impasse -- and in the case of transportation policy, they are doing just that. As we have seen, some problems can even be made worse by narrowly focused solutions to other problems.

I firmly believe that we Americans can resolve this difficulty. We can meet the transportation challenges of the 1980's, while still making economic and environmental gains. But whether we will -- in a timely, rational way -- is another question. To do so, we must more carefully weigh and balance our many policy goals. We must assess costs and benefits, establish priorities, and evaluate the risks where there is the potential for conflict.

Unless we do this, unless the present course is changed, it is likely that increased automotive efficiency goals will be extremely difficult to meet and that feedstocks for plastics will be unbelievably expensive over the next several years. With a tightening crude oil situation, with no domestic supply alternatives, with insufficient incentives for the production of aromatics, with unrealistic gasoline price controls, and with an understandable desire to restrain inflation, our current environmental and automotive fuel conservation timetables are simply incompatible.

Resolution of this impasse rests largely on action by the federal agencies involved: the Department of Energy, the Department of Transportation, and the Environmental Protection Administration. The problems are not principally technical; they are institutional and political. And only in a changed regulatory climate where there is a reasonable equilibrium between gasoline supply and demand and a realistic set of environmental expectations -- only then will the necessary supplies of feedstocks be obtainable at an affordable price.

Until then, necessary business and investment decisions by refiners, plastics producers, and automobile manufacturers will be delayed by regulatory conflict and uncertainty, extending this difficult transitional period.

Since the resolution of this problem is institutional and political, it does not rest solely with others. It's up to you and me to express ourselves individually and through our companies and associations in this important policy debate. We must share our concerns with our neighbors, our legislators, and with the regulators. Our regulatory system can respond, if we make our concerns clear. Only in this way will we strike a compromise among conflicting policies. And only in this way can we free the plastics industry to play the key role it must in meeting the energy and transportation needs of the 1980's.

SPECIALTY URETHANES FOR AUTOMOTIVE APPLICATIONS

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Peabody, Massachusetts

INTRODUCTION

This paper discusses the present and future uses for urethanes in automotive applications. The paper has three parts: Urethanes for Automotive Upholstery, Radiation Curable Urethane Coatings, and Urethane Powders. For each of these topics, there is a brief discussion of the general chemical structure, properties, methods of fabrication or application, and automotive uses.

URETHANES FOR AUTOMOTIVE UPHOLSTERY

At present, virtually all automotive upholstery is either genuine leather or a coated fabric which is made to look, and feel, as much like leather as possible.

Of course, genuine leather is an excellent upholstery material combining all the comfort and aesthetics traditionally associated with leather together with physical properties to insure durability and wear. Genuine leather is and will remain the symbol of elegance in upholstery.

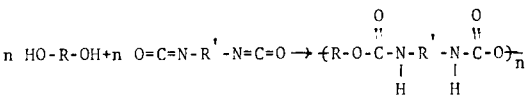
Plasticized vinyl has been the workhorse of the automotive industry for the past 30 years and through continuing advances in art and technology has shown itself to be an excellent performer in automotive use over a long period of time.

In recent years much development has been done on a new upholstery material, namely urethane coated fabric, which has evolved through a continuing 7 year research and development effort to become a viable candidate for the upholstery market. The guidelines for the development have been to emulate the successful features of genuine leather and vinyl coated fabrics, and utilize these guidelines together with the unique strengths of urethane chemistry to produce a product which has the feel, look, and comfort of leather and the properties and durability of vinyl coated fabric. Urethane chemistry has enabled the production of a light weight product with an infinite variety of grains wherein the material does not retain the heat of summer or the cold of the winter, and yet performs well in both high and low temperatures. A unique characteristic of the new urethane upholstery materials is the ability to be produced in soft drapey forms with good break and a variety of surface gloss and feel. The chemistry of the urethanes which was developed to satisfy the automotive requirements enables the use of thin urethane coatings, which in turn enhance the comfort factor. This chemistry was developed because of the drawbacks of conventional urethanes which were not suitable because of poor hydrolytic stability and poor oxidation resistance.

The Permuthane Company has developed urethane coatings specifically for automotive upholstery. This urethane upholstery system has three main components; a urethane skin coat, an adhesive layer, and a backing. The skin coat is approximately 0.002 inches thick, and it is textured and pigmented to resemble leather. The adhesive layer is also urethane; it bonds the skin coat to the backing. The backing can be either a non-woven material or a woven fabric such as nylon, polyester, etc. The entire construction is built up by first casting a film of pigmented urethane polymer, in solvent solution, onto an appropriately textured release paper. After the solvent has evaporated, a film of adhesive solution is cast onto the skin coat, and immediately the fabric backing is laid into the wet adhesive. After the solvent of the adhesive layer has evaporated, the paper is stripped from the construction, revealing the textured surface of the coated fabric.

Often, a thin layer (approximately 0.002 inches) of a flexible, high density urethane foam is cast between the skin coat and the adhesive layer. This foam layer gives the overall construction a more leather-like consistency and feel.

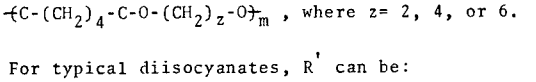
The basic chemistry of these urethane materials is as follows:



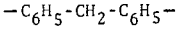
diol diisocyanate polyurethane

For typical diols, R can be:

or



For typical diisocyanates, R' can be:



or

Numerous urethane polymers were tried as skincoat, foam, and adhesive materials. All were rejected because they failed to meet the specifications for automotive upholstery, especially resistance to hydrolysis and resistance to oxidation. In order to meet all of the automotive upholstery standards, fundamentally new urethane polymers had to be synthesized. These new urethane polymers, still proprietary with Permuthane, meet all of the specifications for automotive upholstery, including light weight (10 oz. per sq. yd.), abrasion resistance, resistance to hydrolysis and to oxidation, flame retardancy, and low temperature flexability.

RADIATION CURABLE URETHANE COATINGS

In order to meet EPA requirements, a great deal of effort is going into developing solventless coatings. One such effort is the development of radiation cured urethane coatings. These coatings are produced by using radiation to cure liquid oligomers, forming crosslinked coatings from liquids which are 100% solids in composition. The radiation can be either a beam of electrons or ultraviolet light. Such radiation cured urethanes have been used to coat fabrics, to cover

flooring with a wear layer, and to put a protective finish on metals, plastics, woods, etc.

Radiation curable coatings have several economic advantages:

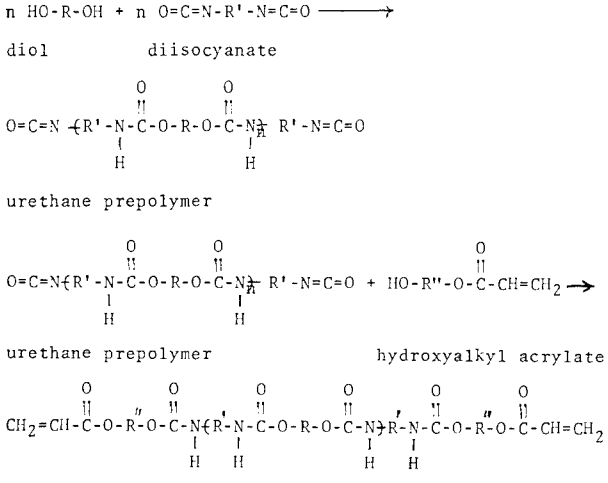
1. No solvent to evaporate, and no equipment for solvent recovery.

2. Increased rates of production, because of the very fast rate of cure.

3. Radiation curing equipment requires far less floor space than conventional coating equipment.

4. While the initial cost for radiation curing equipment is higher than for conventional equipment, the costs for energy usage is much lower; at current prices, electron beam curing uses approximately $2.00 of energy per hour, ultraviolet curing uses approximately $4.00 of energy per hour, while conventional thermal curing uses approximately $8.00 of energy per hour.

The chemistry of radiation curable coatings requires building low molecular weight urethane polymers with terminal double bonds, such as urethane acrylates.



diol diisocyanate

urethane prepolymer

urethane prepolymer hydroxyalkyl acrylate

urethane acrylate

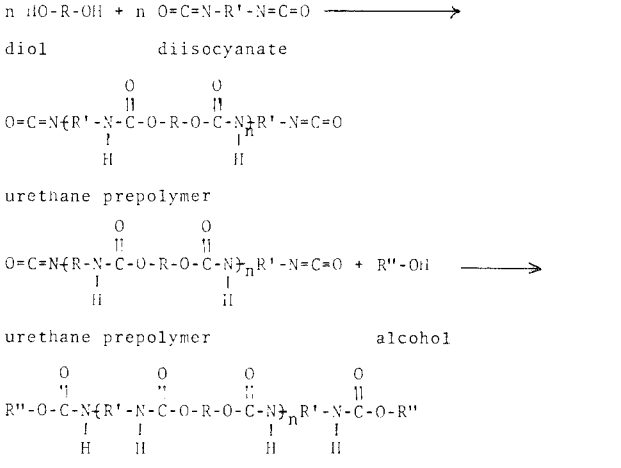
These low molecular weight polymers are coated or sprayed onto the substrate, and exposed to radiation which causes further polymerization via the carbon-carbon double bonds.

Automotive uses for radiation cured coatings include undercoatings for auto carpeting, and abrasion resistant coatings for complex surfaces, such as dashboards, headliners, etc.

URETHANE POWDERS

Permuthane has developed a line of 100% solids, urethane powders. These powders are not ground urethanes; rather, the urethane is actually polymerized into the form of very small particles. Typically, particle sizes are approximately 0.006 inch. At this time, we have produced about a dozen different urethane naterials in this form. These materials can be used as solventless coatings and as additives to other polymeric materials.

The chemistry of these urethane powders is as follows:



diol diisocyanate

urethane prepolymer

urethane prepolymer alcohol

polyurethane

Thus, the present materials are totally reacted, thermoplastic urethanes. It is anticipated that in the future we will develop urethane powders which will be cross-linkable, and, therefore, thermoset.

As would be expected, the properties of these various urethane materials vary with chemical composition, molecular weight, etc. For example, softening points vary from one product which softens at 125°C (257°F) to another which softens at 225°C (437°F). All of these materials are characterized by a high degree of toughness; elongation at break ranging from 250% to 700%.

A number of application techniques can be used to convert these powders to a urethane film or coating:

1. Electrostatic spraying; followed by heat to fuse the particles, forming a coating.

2. Electrostatic fluidized bed coating; again, followed by heat.

3. Calendering the powder into sheet stock.

4. Extrusion and blowing, to form a urethane film.

5. Dissolving the powder in a suitable solvent, applying the solution as a wet layer, and evaporating the solvent away, usually with the aid of heat.

6. Plasma arc spraying coats the substrate with molten urethane; there is no need to subject the coated object to oven heat.

There are also several techniques wherein urethane powders can be used to produce items other than coatings: injection molding, compression molding, rotational molding, and extrusion of profiles. In addition, urethane powders have been utilized as hot melt materials, and as toughening additives in other polymeric materials.

There are numerous examples of the use of urethane powders in automotive applications; such as corrosion resistant coatings on the underside of vehicles, as hot melt adhesives, as abrasion resistant coatings on foam rubber window gasketing and on FRP parts, and as impact modifing additives in prime and top coats.

HIGH MELT STRENGTH COPOLYESTER ELASTOMERS

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INTRODUCTION

As a class of materials, thermoplastic elastomers combine many of the characteristics of rubber with the economies of thermoplastic part fabrication techniques, i.e. high speed processing and reusable scrap. The HYTREL® family of copolyester elastomers, available from the Elastomer Chemicals Department of Du Pont are characterized as high performance thermoplastic elastomers with properties intermediate between rubber and engineering plastics.

The purpose of this paper is to describe the properties of copolyester elastomers, cite commercial applications, and describe recent developments in high melt strength grades suitable for extrusion blow molding applications.

STRUCTURE & PROPERTIES

HYTREL® copolyester elastomers exhibit the generalized chemical structure shown in Figure 1. Based on 1,4 butanediol, terephthalic acid and polytetramethylene ether glycol these high molecular weight thermoplastics contain intrapolymerized butyleneterephthalate hard segments and polytetramethylene ether therphthalate soft segments the relative proportions of which determine the hardness or stiffness of the family member. The hard crystalline blocks contribute to strength while the soft amorphous segments account for the flexible elastomeric nature of the polymer.

Copolyester elastomers are not, as is frequently thought, derived from or related to the urethane family. Isocyanates are not used in the manufacture of HYTREL®. These resins are made by chemistry similar to that which is used to produce such products are MYLAR®, DACRON® and REMAY®.

Because the properties of copolyester elastomers are essentially intermediate between rubber and engineering plastics, appropriate data comparisons will be made with both classes of materials.

Figure 2 shows the hardness range of materials from soft rubber to hard engineering plastics. Note that copolyester elastomers span the range from hard rubber at 40 Durometer D to tough elastoplastics at 72 Durometer D. Whereas surface hardness may adequately describe many of the properties of conventional thermoset elastomers i.e. we speak of a 60A Durometer rubber, this is not necessarly true when applied to thermoplastic elastomers. The flexural modulus of a rubber for example does not change greatly with changes in hardness. Figure 3 shows the change in flexural modulus with change in hardness for a typical rubber and a typical copolyester. As the hardness changes from 40 Durometer D to 72 Durometer D the flexural modulus of the copolyester ranges from 48 MPa (7000 psi) which is about twice that of most thermoset rubbers, to about 515 MPa (75000 psi) which is comparable to low density polyethylene. This large change in flexural modulus with relatively small changes in hardness is characteristic of many thermoplastic elastomers. Thus care should be taken when comparing elastomers of the same hardness, since they might not be of the same stiffness.

As you would expect from the flexural modulus, other properties of copolyester elastomers are intermediate between those of thermoset rubber and harder engineering plastics. Figure 4 shows the relative position of copolyester elastomers in stress-strain vs rubber and nylon. The high load bearing capacity of the copolyesters is suggested by the relatively high tensile stress while their elastomeric nature is exempilified by a high ultimate elongation. The useful elastic limit of copolyester elastomers is shown in Figure 5 which expands the scale of the previous figure and shows tensile stress at low strain. Copolyesters will exhibit recoverable deformation up to about 20% elongation. At this recoverable strain the material will withstand repeated loads of up to 2800 psi with almost complete recovery.

The compressive properties of these polymers shows the same sort of intermediate position between rubber and plastic as the tensile properties. Fundamentally, these characteristics translate into an elastoplastic with good spring like behavior. Under such dynamic condition the copolyester elastomers exhibit low hysteresis. Heat buildup is lower than thermoset rubber and comparable to harder engineering plastics. In addition, resistance to flex cut growth is very good. Figure 6 compares the flex cut growth of copolyester elastomers with thermoplastic urethanes.

Compression set is a standard test for rubber and test conditions can be either constant load, Method A or constant deflection, Method B. Under the constant load conditions the copolyester elastomers exhibit lower compression set than that seen for most thermoset rubbers and comparable values to that of thermoplastic urethanes. This is not true under the constant deflection condition where the elastic limit of the copolyester is exceeded and the material exhibits higher set.

Under long term exposure to even low levels of stress, most materials will experience some nonrecoverable deformation known as creep. The copolyester elastomers show good resistance to this type of deformation. Figure 7 shows the effect of stress and temperature on creep strain.

The effect of temperature on other properties of copolyester elastomers can be described in terms of tests used for conventional rubbers and plastics. The heat resistance of rubber is usually related to the time and temperature required to cause functional failure in the material.

Using this criterion for performance, Figure 8 compares copolyester elastomers with conventional thermoset materials as HYPALON® chlorosulfonated polyethylene and nitrile rubber. Note that standard grades of copolyester elastomers show very good heat aging resistance and heat stabilized grades can extend this range if necessary.

The heat resistance of plastics is often described in terms of retention of physical properties. Figure 9 illustrates the effect of temperature on tensile strength and modulus of copolyester elastomers. Note that at 150°C (302°F) this material retains almost half of its room temperature properties. The maximum continuous service temperature is 121°C, (250°F)

however these polymers can withstand short excursions above 150°C (302°F) such as in paint repair ovens without deleterious effects.

Low temperature properties of copolyester elastomers are excellent as evidenced by low torsional modulus, small change in modulus with temperature and good low temperature impact resistance. The change in flexural modulus as temperature decreases is less than that noted for many thermoplastics and at -40°C the copolyester is 2-6 times as flexible as a urethane. Data comparing the torsional modulus of these materials in shown in Figure 10. This flexibility at low temperature is the property which provides low temperature impact resistance.

In summary, the mechanical properties of copolyester elastomers are intermediate between thermoset rubber and engineering plastics. Compared with rubber the copolyester elastomers have a higher surface hardness and tensile and flexural moduli. At strain below 20% elongation however the copolyester elastomers are truly elastic, exhibiting spring-like characteristics with exceptional resistance to creep and low heat buildup under flexing conditions. This combination of resilience with the exceptionally high load bearing capability under tensile or compression load and the retention of these properties at low and high temperatures makes these thermoplastic copolyester elastomers a truly unique family of materials.

The subject of environmental chemical and fluid resistance is a lengthy one and cannot be treated in adequate detail in this paper. However, we will briefly comment on several generalizations in this area.

The copolyester family of elastomers are generally resistant to polar materials up to about 70°C (158°F) and to hydrocarbons such as oils and greases, up to temperatures as high as 121°C (250°F). While the copolyesters are used commercially in applications requiring constant exposures to lubricating oils, hydraulic fluids, grease, transmission fluids, gasolines and alcohol it should be noted that proprietary additives particularly in lubricants, can have a significant effect on compatability of the copolyester elastomer with the lubricant. End use tests using the proprietary lubricant are suggested to verify the suitability of the copolyester materials in a particular application.

Commercial applications where chemical and fluid resistance are issues include hydraulic hose, seals, and gasoline tanks, where copolyesters have replaced high quality thermoset rubber or engineering plastics.

Other commercial applications which take advantage of the unique physical properties of the copolyester elastomers include retractable wire for telephones, automotive uses such as seat belt retractor mechanisms, vacuum tubing and a variety of gears and bushings.

PROCESSING

HYTREL© copolyester elastomers are true thermoplastic polymers and can be processed by most conventional thermoplastic techniques. They are characterized by relatively sharp melt points, by viscosities sensitive to temperature change and by rapid crystallization.

Copolyester elastomers enjoy wide acceptance in standard injection molding and extrusion techniques using general purpose screws of the type used for polyethylene.

BLOW MOLDABLE COPOLYESTER ELASTOMER

Blow molding is a thermoplastic technique that requires a material with special rheological characteristics. Early evaluations of standard copolyester elastomers in blow molding were not successful because of low melt viscosity and low melt strength.

Research efforts have resulted in a blow molding grade meeting those requirements while retaining the physical properties normally associated with the standard lower viscosity counterparts. This new resin has moderately high die swell with correspondingly low melt index and parison sag. These characteristics are similar to other commercial blow molding resins. A comparison of this polymer and several commercial blow molding resins is shown in Figure 11.

The blow molding grade has been extensively evaluated in extrusion blow molding. Typical conditions used in this process are shown in Figure 12. Satisfactory products have been made by this technique. Surface finish and other mold details have been good in all parts and release from the blow mold has been possible without the need for release agents. Mold uniformity has also been good and parisons of up to 18" in length have been processed without extensive sag. Melt viscosity and melt strength were found to be sensitive to melt processing temperatures. This has not proven to be a problem in evaluations and satisfactory parts have been made consistently, once machine conditions had been equilibrated.

The blow moldable copolyster resin has rubber like properties similar to those exhibited by the standard grade of copolyester elastomers. Figure 13 shows typical properties of this new polymer.

Properties associated with toughness such as tear strength, abrasion resistance, and impact resistance are very good. Resistance to flexural fatigue and flex cut growth are excellent as exhibited by Ross flex test data. These characteristics together with high resilience and low heat buildup make this polymer particularly well suited for dynamic applications. Low brittleness temperature, high impact strength at low temperatures and relatively low flexural modulus at low temperature predict utility in subzero environments. VICAT softening point and stress-strain properties at 100°C (212°F) show good retention of functional strength at elevated temperatures. Overall chemical resistance, in particular resistance to oils and hydraulic fluids is good. These characteristics together with the relatively high load bearing characteristics that is normal to this family of copolyester elastomers results in material that can be utilized in a wide range of temperatures and environments.

Prior to the development of blow molding grades of copolyester elastomers, flexible bellows were made of conventional thermoset rubber materials such as neoprene. The parts were conventionally molded with an internal core and after molding the part would be stretched appreciably to remove it from the mold. Conventional thermoplastic elastomers are either too high in strength or too low in elongation to be demolded in this manner. Now that technology exists for blow molding copolyesters it is possible to produce these types of flexible hollow shapes, using fast thermoplastic processing techniques.

Many of these bellows applications demand a material with a high service temperature, good flex life and good resistance to grease and oils. This new blow moldable copolyester elastomer has met these requirements and is near commercial use in automotive chassis applications with expanded use predicted in the future.

Additionally, there are applications other than blow molding where a high melt viscosity and a high melt strengh would be desirable. The manufacturer of precise profile extrusions and relatively thick blown film are two examples which might take advantage of high melt strength and viscosity.

SUMMARY

The good overall physical properties and processing behavior of HYTREL© copolyester elastomers have enabled them to gain wide acceptance in the marketplace. Standard grades of copolyester elastomer compare favorably in properties and processing to other thermoplastic materials and new advances in polymer technology have introduced an alternative to conventional vulcanized elastomers.

BIOGRAPHY

Roger E. Barras received his MSME from University of Texas in 1969. He is employed as a Technical Representative, Elastomer Chemicals Department, E. I. du Pont de Nemours & Co., Inc. Recent assignments have included assisting in the commercialization of a blow moldable grade of copolyester elastomer.

FIGURE 1

Chemical Structure of Copolyester Elastomers

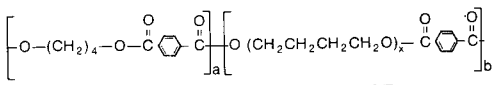

FIGURE 2

Hardness Scale

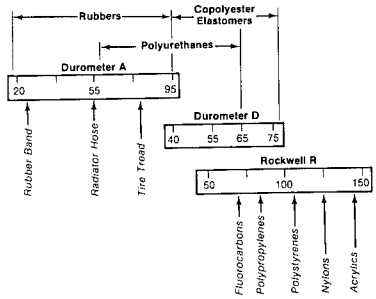

FIGURE 3

Flexural Modulus vs. Hardness

(Injection-molded test specimens)

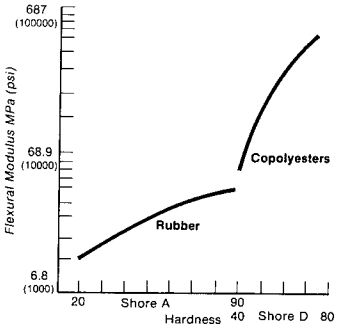

FIGURE 4

Tensile Properties

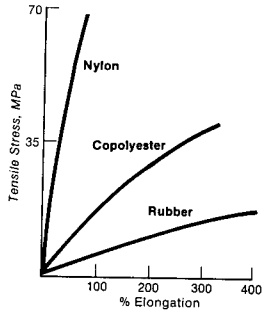

FIGURE 5

Tensile Stress at Low Strain

(Injection-molded test specimens)

(Strain rate: 1 in/min [25.4 mm/min])

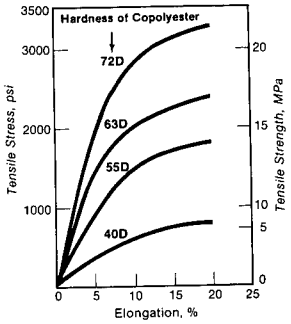

FIGURE 6

Flex Fatigue Resistance

	Hardness (ASTM D-2240)	De Mattia Flex, Pierced (ASTM D-813) Kilocycles to Failure 73°F [23°C]	250°F [121°C]	Ross Flex, Pierced (ASTM D-1052) Kilocycles to 5X Cut Growth 73°F [23°C]	-40°F [-40°C]
Copolyester	40D (92A)	216	108	>300[b]	>12[c]
TPU-ESTER	80A	1.5	1.5	30	Immediate
TPU-ESTER	91A	216	18	>300[c]	Immediate
TPU-ETHER	90A	3	Immediate	144	Immediate
Copolyester	55D	72	18	>300[b]	>12[d]
TPU-ESTER	55D	1.5	Immediate	84	Immediate
Copolyester	63D	—	—	280	Immediate

[b]No change in the length of the pierced area after 300 000 cycles.
[c]Test terminated after 3X cut growth.
[d]Test terminated after 4X cut growth.
Note: Properties were measured on injection-molded test specimens.

FIGURE 7

Effect of Temperature on Creep Strain at Various Stress Levels

(55D Copolyester)

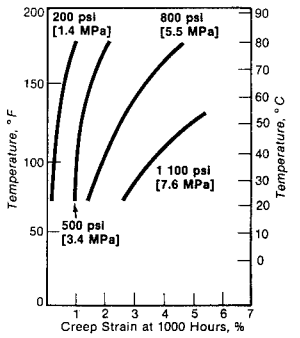

FIGURE 8

Heat Aging of Elastomers

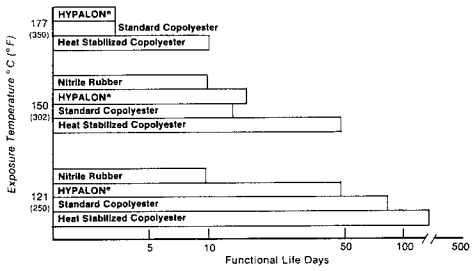

FIGURE 9

Tensile Strength and 100% Modulus vs. Temperature

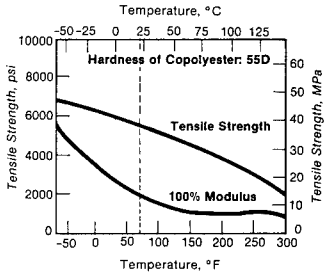

FIGURE 10

Low Temperature Flexibility

	Hardness (ASTM D-2240)	Apparent Modulus of Rigidity, Clash-Berg (ASTM D-1043), psi [MPa] -40°F [-40°C]	0°F [-18°C]	73°F [23°C]
Copolyester	40D (92A)	7 500 [51.7]	3 200 [22.1]	2 100 [14.5]
TPU-ESTER	91A	55 000 [379]	5 800 [40.0]	1 500 [10.3]
Copolyester	55D	18 000 [124]	11 000 [75.8]	8 800 [60.7]
TPU-ESTER	55D	40 000 [276]	20 000 [138]	5 000 [34.5]
Copolyester	63D	88 000 [607]	40 000 [276]	13 500 [93.1]
Plasticized Nylon II	65D	54 000 [372]	—	22 000 [192]
Copolyester	72D	94 000 [648]	—	19 000 [131]

Note: Properties were measured on injection-molded test specimens.

FIGURE 11

Blow Molding Characteristics

	Melt Index @ 2160 g & 230°C (dg/min)	Melt Viscosity @ 59 s⁻¹ & 225°C (Pa s)	Melt Tension @ 225°C (g)	Parison Sag @ 230°C (cm)	Die Swell @ 0.19 Pa @ 230°C (%)
Low Density Polyethylene	4.8	960	1.7	137	10
High Density Polyethylene Copolymer	0.4	2130	4.4	18	40
Polypropylene	3.4	930	1.0	71	34
Polystyrene	5.4	1060	1.5	69	26
Copolyester Elastomer	10.0	660	0.2	380	1
Blow Moldable Copolyester Elastomer	1.1	2790	3.1	255	43

FIGURE 12

Extrusion Blow Molding Copolyester Elastomer

Typical Conditions

Barrel Temperatures, °C
- Rear — 230
- Front — 220
- Head — 210

Die Bushing Temperature, °C — 215

Melt Temperature, °C — 215

Mold Temperature, °C — 45

Screw
- RPM — 100
- Back Pressure — Medium-High
- Injection (Melt) Pressure, MPa — 44.8-51.7

Blow Air Pressure, MPa — 0.55

Cycle, s
- Injection — 1-3
- Blow — 10
- Exhaust — 2-5

FIGURE 13

HTG-4275
Typical Physical Properties

Melting Point — 211°C

Melt Index — 412°F
- At 220°C/2160 g — 0.25 g/10 min
- At 230°C/2160 g — 1.1 g/10 min

Hardness, D Durometer — 56

Specific Gravity — 1.16

Tear Strength
- Die C @ R.T. (841 pli) — 147.2 kN/m
- @ 100°C (490 pli) — 85.8 kN/m
- Trouser @ R.T. (101 pli) — 17.7 kN/m
- @ 100°C (40 pli) — 7.0 kN/m

Abrasion Resistance, NBS, % of Standard 874 — 874

Compression Set: Method A
- After 70 Hrs. at 70°C 1% — 1%
- After 70 Hrs. at 100°C 3% — 3%

Ross Flex-Cut Growth
- Cycles to 5X Cut Growth — 678 000
- No Growth

Impact Resistance
- Notched Izod
  - At R.T. (16.7 ft-lb/in) — 890 J/m
  - At -40°C (4.6 ft-lb/in) — 245 J/m
- Gardner Impact, at -40°C
  - Avg. to 100% Failure (142 in-lbs) — 16.0 J

Brittleness Temperature -140°F — -60°C

Vicat Softening Point 140°C — 140°C
284°F

Flexural Modulus
- At R.T. (26 500 psi) — 182.7 MPa
- At 121°C (7 100 psi) — 49.0 MPa
- At -40°C (123 400 psi) — 850.8 MPa

PREDICTING PERFORMANCE OF OLEFINIC THERMOPLASTIC ELASTOMERS

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INTRODUCTION

Thermoelastic properties can be attained by direct synthesis of polymers (block or graft types), by blending of homopolymers or by alloying synthesized thermoelastics with homopolymers. Extension of these systems via incorporation of diluents and/or reinforcing materials is also possible to further expand property slates or simply to reduce materials costs.

Along with a product, the design engineer must have the right kind of performance information that enables him to make an intelligent selection of a particular material. Toward this end, both suppliers and users run exhaustive series of tests on each product submitted for approval at substantial cost to both.

The nature of thermoelastics in general and of olefinics in particular is such that it is not necessary to test a material fully each time a small change in component ratio or molecular weight, etc. is made to increase or decrease stiffness, or to improve or restrict flow, etc. In effect, families of polymers can be established wherein basic composition remains the same but where composition distribution and molecular manipulation are used to adjust the main and critical properties to meet a particular design requirement.

A method is offered and discussed here that provides a solution to the problem of material use limitations dictated by restrictive time factors and evaluation costs.

I. THE DESIGNED EXPERIMENT: SUBSTRATE PROPERTIES

A family of blended olefinic thermoelastics has been studied using statistical methods. A basic three variable central composite design was used to study the effect of hard segment component (polypropylene), soft segment viscosity (plasticizer/ethylene-propylene rubber mixture), and conductive component (carbon black) on basic physical and mechanical properties and performance of painted substrates.

STRUCTURE OF THE DESIGN The central composite design selected is shown schematically in Figure 1. It is a basic design for fitting a second-order model which Hunter[1] describes as "composed of center points, a 2^3 factorial design which provides the coordinates of the cube, plus the vertices of an octahedron". Center point replicates provide an independent estimate of the error variance. A total of twenty compositions are required to complete the experiment.

DESIGN VARIABLES The material design is keyed to flexural modulus or stiffness, flexural set or recovery and to surface conductivity level (required for successful use of commercial electrostatic topcoat application techniques), as the three basic parameters that would satisfy key performance and processing criteria developed for flexible automobile body components.

Secant flexural modulus (the ratio of stress to strain at any given point on the actual stress-strain curve) was controlled in the 35-415 MPa (5,000-60,000 psi) range by varying polypropylene content (23-60% PHC). Flexural set (recovery from a 180° bend) was controlled in the 10° to 25° range by varying plasticizer content (8-46 PHP). Conductivity was maintained between 10^{-6}/ and 10^{-12} siemens by varying carbon black content (1-75 PHP).

EXPERIMENTAL Each of the twenty compositions contained five (5) commercially available ingredients intensively mixed in a size 1 Banbury mixer.

Rubber	Ethylene Propylene, 54% Ethylene
Plastic	Polypropylene, 12 MFR
Plasticizer	Process Oil, 2900 SUS at 100°F
Filler	Carbon Black, N650 Furnace
Antioxidant	Hindered phenolic hydroxyl

To satisfy statistical requirements, a random order of batch mixing was used. However, each batch was mixed by the same procedure. A masterbatch of the EPDM rubber, carbon black and oil was prepared first. A twenty-four hour aging period followed, after which the final mix was completed.

A small fifteen ton reciprocating screw injection molding machine was used to prepare specimens for processing and physical and mechanical property testing. A larger, 350 ton machine was used to mold 10 X 30 cm plaques for painting and paint testing.

Processability was evaluated using four parameters. Moldability was assessed by measuring melt flow rate and spiral flow. The latter is the distance the material will flow in a 1/8" diameter half-round spiral die. Conductivity was measured to determine substrate sensitivity to electrostatic painting methods. A droop test at elevated temperatures was used as a measure of stability of materials that would be baked in ovens after painting.

Physical and mechanical properties were measured using ASTM methods wherever possible. Testing was done at -29°C, 23°C and 70°C, representing the practical temperature range in which such materials operate.

TEST RESULTS Processing and physical and mechanical property data are obtained and computer treated to determine appropriate regression coefficients. Predictor equations fitting the model shown here are subsequently developed.

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3$$

where X_1 = polypropylene content; X_2 + carbon black content; X_3 = oil content.

Predictor equations are solved via computer to provide two dimensional contour plots for all properties. One such plot is shown in Figure 2. Using several of these representing key properties, a series of overlays can be made to facilitate isolating a particular composition that gives a desired set of properties.

STRENGTH OF CORRELATIONS Qualitiative ratings of the strength of correlations have been made as follows. (Selected values are shown in Table I.)

% Variance Explained	Rating
95-100	Excellent
85-94	Good
75-84	Fair
74	Poor

Overall, good to excellent correlations were obtained for most processing, physical, and mechanical properties at each of the measurement temperatures: 23°C, 70°C and -29°C. A very poor tensile strength at break correlation represents inconsistencies in measurements of stress in the plastic phase of the materials attributable to their morphology, a subject beyond the scope of this paper. However, an excellent correlation of stress at yield

is obtained, indicating more precision in the measurement of elastic deformation.

No correlation was obtained for conductivity, gloss and color change after Weather-Ometer and South Florida exposure, and shrinkage after molding and painting. Failure to achieve correlations for conductivity are attributable to the need for a minimum amount of carbon black to reach a threshold value. Below this minimum level, materials are resistant and variations in conductivity are not measurable, hence design requirements are not satisfied to achieve correlation. Weathering performance and shrinkage data correlations will be discussed later in the section covering paintability and paint performance.

INFLUENCE OF INDEPENDENT VARIABLES Any analysis of the data obtained from the design requires an understanding of the influence of the three design components: polypropylene, oil, and carbon black content, individually on the dependent variables. Such effects are illustrated in Figures 3 and 4 for processing (MFR), stiffness (Flexural Modulus) and recovery (Flexural Set).

Carbon black (Figure 3) provides conductivity but at a significant sacrifice in flow rate, a very modest reduction in stiffness and a slight improvement in flexural set. Since the minimum amount of black required to provide conductivity provides marginal flow materials for processing, i.e. injection molding, some other composition adjustment is required to provide processable materials. Polypropylene or oil content can be increased (or a combination of both) to adjust flowability upward with a minimal affect on flexural modulus and flexural set.

Polypropylene concentration affects secant flexural modulus the most as shown by the steep slope from the appropriate curves in Figure 4. That the curve for the conductive material is close to that for the non-conductive is evidence of the small influence black content has on this property. Flexural set is affected less by the presence of polypropylene albeit significantly. It, too, shows a small carbon black dependency. MFR or flow can be improved by increasing polypropylene in either non-conductive or conductive materials. In the latter case, this would be a must to assure adequate processability. MFR can also be increased by lowering the viscosity of the blend by adding oil, and since these effects are additive both changes would be introduced commercially to effect maximum benefits with minimal changes in the product.

Benefits in MFR from a lowering of soft segment viscosity (adding oil) are accompanied by a lowering of secant flexural modulus again with little effect from a change in the material's conductivity. Flexural set of the conductive material is also lowered, but no influence is noted on the non-conductive materials.

Similar plots are made to study the dependency of the other properties tested on the three independent variables of the design. Users of the design data generally find them invaluable in determining how a change made to alter one property affects other important parameters.

MATERIALS DEVELOPMENT The design was first used to provide materials at two stiffness levels: 96 and 207 MPa (14,000 and 30,000 psi) secant flexural modulus. Both non-conductive and conductive materials were required.

SELECTION PROCESS To begin the composition selection process, a series of two dimensional contour plots of hard segment (polypropylene) vs conductivity (carbon black) range at a constant, median soft segment viscosity (oil) level was selected. An overlay of the 96 and 207 MPa contours was made from Figure 2. The overlay indicates a region of surface conductivity of 10^{-9} siemens or greater. Such materials can be successfully topcoated via commercial electrostatic application techniques.

Processability parameters were then checked to delineate regions of moldable compositions. Figure 5 shows the overlay covering the MFR plot. An area of marginal to poor processability is noted to the right of the 0.30 curve.

A rather wide range of non-conductive compositions can be selected at both the 96 MPa and 207 MPa psi flexural modulus levels. Fewer, yet many, conductive compositions are possible at 207 MPa psi flexural modulus. However, only a few processable 96 MPa materials are possible unless a lower viscosity (more oil) is used as shown in Figure 6. Here, a wide range of processable compositions are found for conductive 96 MPa material. And so, the process continues using many plots for all independent and dependent variables until the desired combination of properties is obtained.

VERIFICATION OF THE DESIGN Two such compositions were selected from the design and prepared: a 96 MPa flexural modulus conductive and a 207 MPa, non-conductive. Each was then tested to determine the predictive value of the design data. Results are shown in Table II.

In general, good agreement was found between predicted and actual values. A wide variation in tensile strength at break reflects the poor correlation already noted for this property. No such explanation satisfies the differences noted in flexural set. The design consistently predicts lower levels than actually found. At this time, some undetected change in preparation method is a suspected cause.

II. DESIGN MATERIALS AS PAINTABLE SUBSTRATES

All compositions tested for the design were also molded into plaques and coated with commercial elastomeric automotive finishes using commercial methods of surface treatment and application. A schematic of the painting design is shown in Figure 7.

EXPERIMENTAL Painted materials were evaluated using the following methods. Injection molded plaques were painted then aged a minimum of 72 hours before testing.

Performance Tests	Duration/Conditions
1. Adhesion	Tape, scribed lines 1/8" apart, at right angles and diagonally in one direction.
2. Thermal Shock	4 hrs water at 38°C, 4 hrs at -29°C, 30 seconds 100 psi wet steam blast on scribed panel.
3. Water Immersion	10 days, 32°C.
4. Humidity	Condensing 96 hrs/38°C, 100% RH.
5. Shrinkage	After molding, after painting.
6. Low Temperature Flexibility	-29°C, 1/2" mandrel, 180° bend.
7. Weather-Ometer	1,000 hours 63°C, 102 min light; 18 min light + spray
8. Outdoor Exposure	12 months South Florida 5° south, direct weathering inland.

An accurate record or history of performance of painted plaques during Weather-Ometer and outdoor exposure was kept using a Gardner XL10A tristimulus color meter and a Gardner 60° glossimeter. Both instruments are interfaced with an IBM 1130 computer.

The computer calculates a vector representing color change then qualifies the change by a series of letters: L or D for light-dark, G or R for green-red and B or Y for blue-yellow. The results are ultimately displayed in a bar graph plot as shown here in Figure 8. Bars represent 0, 3, 6, 9 and 12 months exposure. Gloss data is automatically recorded and conveniently tabulated to allow comparison of stepwise or total performance.

TEST RESULTS Painted design materials pass the specification requirements referenced above for adhesion, thermal shock, water immersion, humidity and low temperature performance. These tests are of the "go/no-go" variety and are treated qualitatively. Exposure and shrinkage tests, however, do provide data from which regression coefficients can be calculated.

Gloss and color measurements were made on the painted samples before and after Weather-Ometer and South Florida exposure intervals: each 200 hours to a total of 1,000 hours in the Weather-Ometer and each 3 months to a total of 12 months in South Florida. An analysis of the 60° gloss data after 12 months' exposure in South Florida indicates outstanding performance for the olefin based thermoelastic series coated with the Durethane 101 automotive finish. As shown in Table III, absolute changes in gloss are comparable to the coated metal control. Further, differences among samples are randomly fixed and not large enough to result in a meaningful correlation. Performance among the three test colors, red, metallic blue, white, is essentially the same. Gloss data from the series topcoated with Durethane 100 finish (Table IV) indicate more gloss loss after 12 months' exposure and more scatter in the data, especially for the red coated samples. However, differences among samples, although greater, are random and do not correlate.

Color change for each series follows a similar performance pattern as noted for gloss change. Red samples are affected most by exposure and changes are visible (vector magnitude greater than 5); Durethane 101 (Figure 8) appears to perform better than Durethane 100 (Figure 9), especially over the last 3 months of the test. Changes are smaller and not really visible on blue (Figure 10) and white samples.

Weather-Ometer exposure performance follows much the same pattern as that for the South Florida weathering. Durathane 101 retains gloss and color best and shows the least scatter in performance data. Differences among samples are again too small to enable satisfactory correlations.

Total shrinkage data (after molding and painting) for the samples has a mean value of $1.487 \pm .201$ at 95% confidence limits. At best, correlations are rated poor because differences among samples are not statistically significant. However, shrinkage values closely match the field experience level of 1.5%.

CONCLUSIONS A statistically designed experiment has been completed for a family of olefinic thermoelastics covering a broad range of processing, physical and mechanical properties. Overall, correlations for these parameters are excellent and contour plots of properties at all levels of composition considered have been drawn and used to provide materials meeting various specification requirements. Two compositions were constructed from the design, then prepared and tested. Excellent agreement of predicted and actual property levels was obtained.

Design materials are useful as paintable substrates for automotive and other uses as evidenced by excellent South Florida exposure and Weather-Ometer performance. Statistical analysis of gloss and color change vector data indicates that, within the limits of the design, composition has no effect on exposure performance. Molding and paint oven shrinkage levels also appear independent of composition.

Using the design discussed here and others that can be readily developed, extensive and costly materials qualification procedures can be streamlined considerably to facilitate their early commercial use.

ACKNOWLEDGEMENTS The author would like to thank Mr. J. H. Brillinger for his assistance in working up the exposure data and Messrs. C. B. Csernica and E. T. Kauchak for their assistance in sample preparation and testing

REFERENCE

(1) Hunter, J. S., "Some Applications of Statistics to Experimentation." Chemical Engineering Progress Symposium Series 31, 56 (1960).

TABLE I

STRENGTH OF CORRELATIONS

Property (Units)	% Variance Explained	Rating
MFR(1) (grams/10 minutes)	95	Excellent
Tensile Strength (MPa at Break)	37	Poor
Tensile Strength (MPa at Yield)	98	Excellent
100% Modulus (MPa)	98	Excellent
Tear Strength (kN/m)	88	Good
Secant Flexural Modulus		
(MPa, at 23C)	99	Excellent
(MPa, at -29C)	98	Excellent
(MPa, at 70C)	96	Excellent
Flexural Set (° After 5 Minutes Rest)	93	Good
Droop (cm at 121C)	84	Fair
Shrinkage After Paint Bake (%)	19	Poor

(1) Melt Flow Rate

TABLE II

VERIFICATION OF DESIGN

Predicted and Tested Performance Data

Selected Flexural Modulus	96 MPa		207 MPa	
	Design Prediction	Tested	Design Prediction	Tested
Melt Flow Rate g/10 minutes	0.15	0.27	3.6	2.8
Hardness, Shore D	26	22	33	28
100% Modulus, MPa				
at 23C	7.6	8.0	11.0	10.3
at 70C	4.1	4.8	4.1	4.9
at -29C	24.1	25.4	26.2	24.8
Tensile Strength, MPa				
at 23C (break)	13.1	8.7	12.4	11.8
at 70C (break)	3.8	5.3	8.3	8.3
at -29C (break)	26.7	25.8	22.7	22.0
Elongation, %				
at 23C	600	430	500	580
at 70C	600	970	1000	1160
Tear, kN/m				
at 23C	75.3	63.9	91	73.5
at 70C	29.8	29.8	43.8	38.5
Flexural Modulus, Secant				
at 23C	96.5	87.5	206.7	213.6
at 70C	41.3	28.9	72.3	76.5
at -29C	413.4	401.7	1171.3	916.4
Flexural Modulus, Tangent				
at 23C	110.2	110.2	254.9	250.8
at 70C	44.8	30.3	89.6	84.7
at -29C	516.8	426.5	1033.5	971.5
Flexural Set, °				
after 30 seconds	16.5	26	23	31
after 5 minutes	13	22	18.5	26
Droop, cm				
at 121C	2.4	1.5	0.6	0.6
at 132C	3.1	2.0	1.0	0.8

TABLE III

DESIGN MATERIALS AS PAINTABLE SUBSTRATES

ONE YEAR SOUTH FLORIDA EXPOSURE
DURETHANE 101 TOPCOATS
60° SPECULAR GLOSS

	Red (DSM 4330)		White (DSM 3967)		Met. Blue (DSM 4758)	
	Orig.	12 mo.	Orig.	12 mo.	Orig.	12 mo.
17-0	93	70	92	79	95	78
-1	92	65	93	76	92	72
-2	93	72	94	80	92	70
-3	92	72	93	73	91	76
-4	93	74	95	77	89	78
-5	92	74	93	74	91	74
-6	93	69	92	77	90	73
-7	91	68	94	75	89	67
-8	94	72	94	74	91	70
-9	92	71	93	74	90	75
18-0	93	74	93	73	91	81
-1	92	69	94	76	89	78
-2	92	69	93	76	91	71
-3	93	73	93	74	87	74
-4*	91	69	93	76	91	75
-5*	92	70	94	74	91	72
-6*	93	74	93	78	91	66
-7*	90	81	94	76	90	77
-8*	92	72	91	77	93	73
-9*	91	71	94	77	95	65
Mean	92.2	71.4	93.3	75.8	91.0	73.3
Std. Dev.	1.0	3.3	.9	1.9	1.9	4.3
Replicates						
Mean	91.5	72.8	93.2	76.3	91.8	71.3
Std. Dev.	1.0	4.4	1.2	1.4	1.8	4.8
Metal Control	89	74	92	71	90	73

*Replicates

TABLE IV

DESIGN MATERIALS AS PAINTABLE SUBSTRATES

ONE YEAR SOUTH FLORIDA EXPOSURE
BENZO/U.V. - DEM 33198 PRIMER - DURETHANE 100 TOPCOATS
60° SPECULAR GLOSS

	Red (DEM 71797)		White (DEM 889)		Met. Blue (DEM 14367)	
	Orig.	12 mo.	Orig.	12 mo.	Orig.	12 mo.
17-0	93	46	93	52	87	44
-1	91	47	93	58	86	35
-2	93	47	93	53	89	43
-3	92	43	93	41	87	39
-4	92	64	95	53	91	50
-5	92	34	94	66	87	45
-6	92	53	94	63	88	43
-7	92	9**	93	49	91	34
-8	96	19**	93	57	90	38
-9	92	54	93	51	90	37
18-0	92	54	92	44	86	53
-1	93	59	93	37	89	48
-2	92	55	94	66	89	43
-3	90	58	94	41	84	42
-4*	92	49	93	55	87	42
-5*	91	15**	93	36	87	44
-6*	92	38	94	58	88	36
-7*	92	35	93	54	88	38
-8*	92	35	95	64	91	41
-9*	93	50	95	47	88	52
Mean	92.2	48.3	93.5	52.3	88.2	42.4
Std. Dev.	1.2	9.0	.8	9.1	1.9	5.4
Replicates						
Mean	92.0	41.4	93.8	52.3	88.2	42.2
Std. Dev.	.6	7.5	1.0	9.7	1.5	5.6
Metal Control	86	72	91	74	89	57

*Replicates
**Not included in mean calculations.

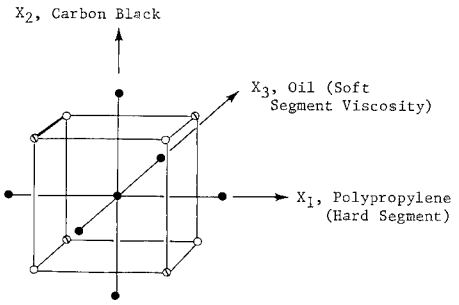


Fig. 1 - Central Composite Design in three Dimensions

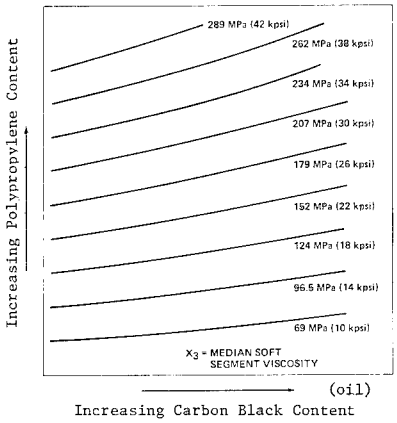


Fig. 2 - Effect of Independent Variables on Secant Flexural Modulus

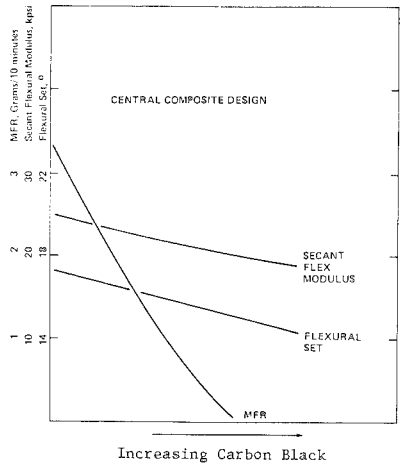


Fig. 3 - Change in Properties with Carbon Black content

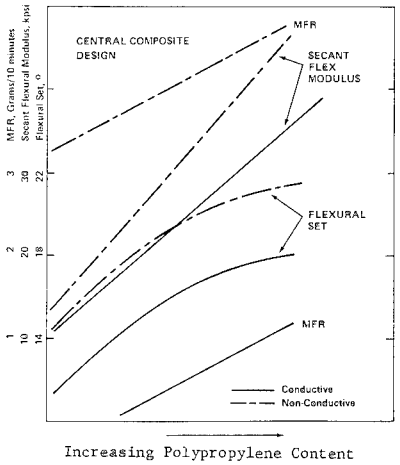


Fig. 4 - Change in Properties with Polypropylene content

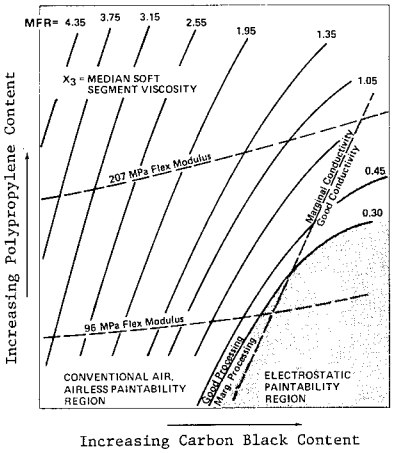


Fig. 5 - Materials Selection Process: Flow and Conductivity

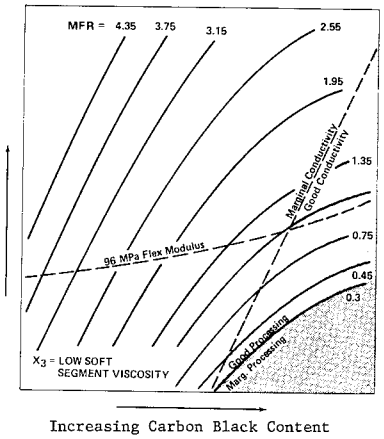


Fig. 6 - Materials Selection Process: Viscosity Adjustment

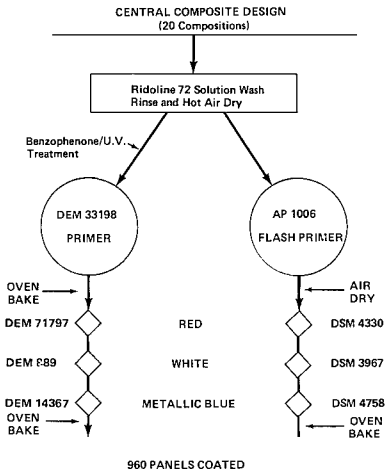


Fig. 7 - Painting of Design Materials

FIGURE 8

PLOT OF COLOR DIFFERENCE DURING SOUTH FLORIDA EXPOSURE RELATIVE TO ORIGINAL MEASUREMENT - S.N.'S 1505 1491 1502 1489 1497 1492 1493 1504
POINTS PLOTTED FOR EXPOSURE TIMES 0,3,6,9,12 MONTHS

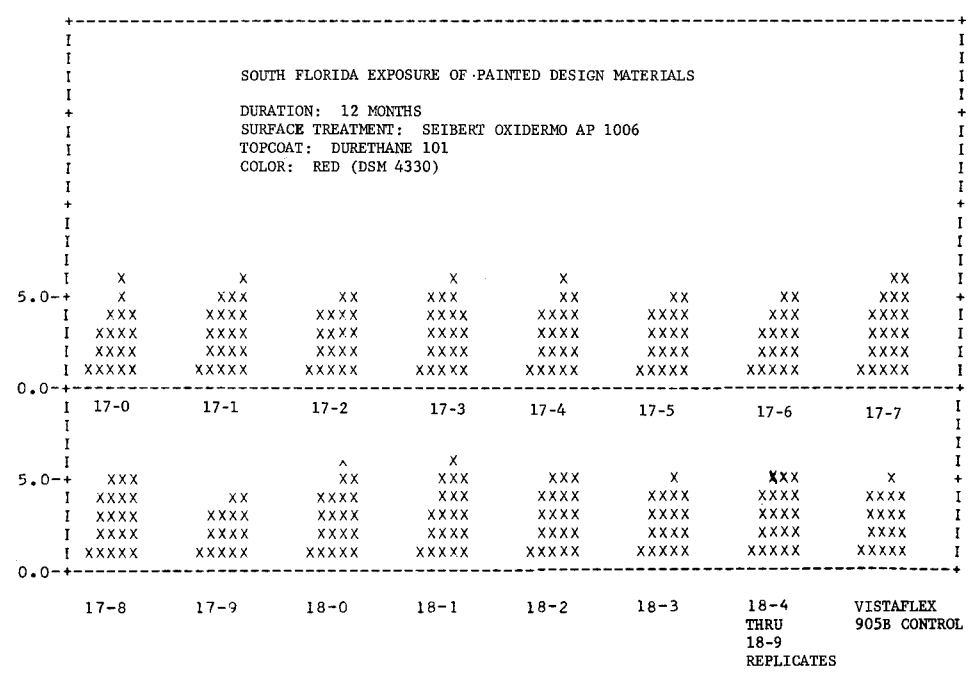


FIGURE 10

PLOT OF COLOR DIFFERENCE DURING SOUTH FLORIDA EXPOSURE RELATIVE TO ORIGINAL MEASUREMENT - S.N.'S 1557 1543 1554 1541 1549 1544 1545 1556
POINTS PLOTTED FOR EXPOSURE TIMES 0,3,6,9,12 MONTHS

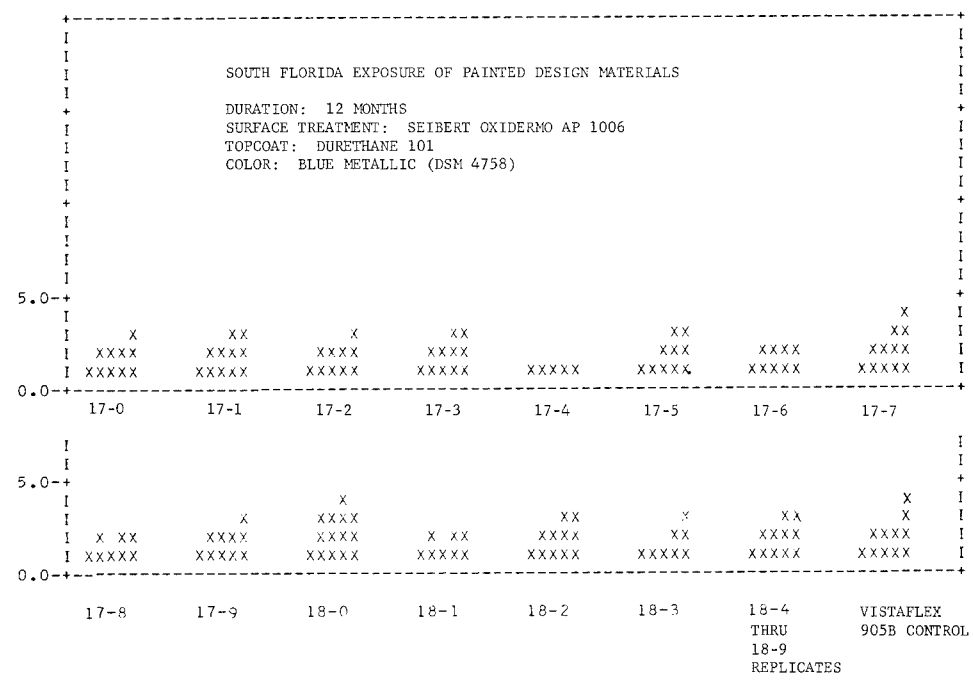
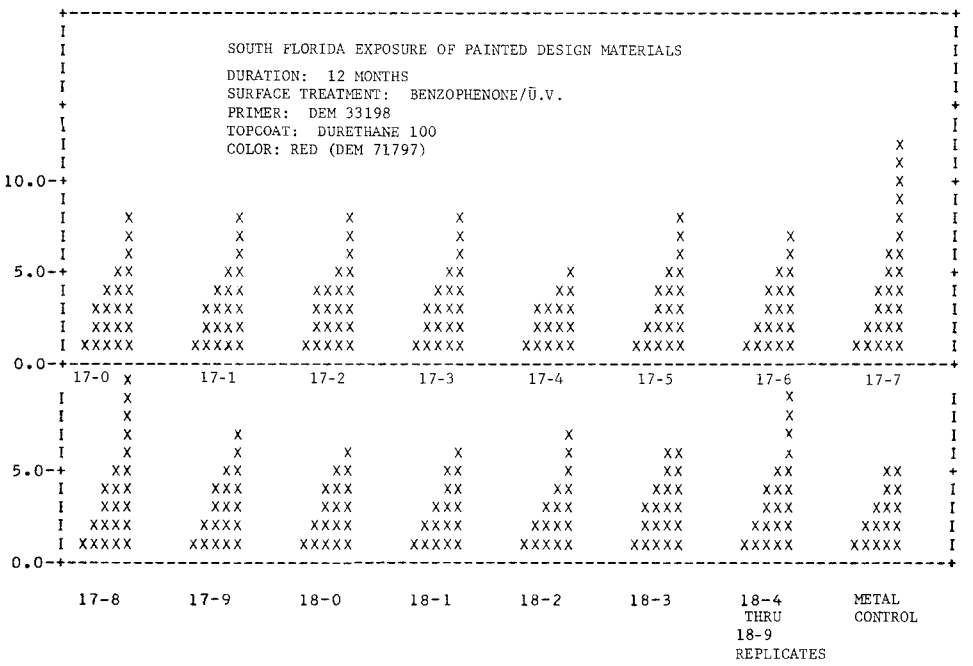


FIGURE 9

PLOT OF COLOR DIFFERENCE DURING SOUTH FLORIDA EXPOSURE RELATIVE TO ORIGINAL MEASUREMENT - S.N.'S 1584 1570 1581 1568 1576 1571 1572 1583
POINTS PLOTTED FOR EXPOSURE TIMES 0,3,6,9,12 MONTHS SEPT. 26, 1977



RECENT PRODUCT ADVANCES IN THERMOPLASTIC COMPOSITES

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INTRODUCTION

A brief review of recent developments in the field of thermoplastic composites and their significance to automotive designers will be presented. These composites include products to dissipate static charge, attenuate EMI/RFI, and a new family of glass bead and mineral reinforced thermoplastics for isotropic moldings.

MINERAL REINFORCED THERMOPLASTIC RESINS

Substantial development efforts have been directed toward the achievement of isotropic moldings while attempting to mitigate the expected drop in mechanical properties associated with the addition of a non-fibrous filler. A comprehensive study of the key properties of many minerals in nylon 6/6 was undertaken.

An examination of a comprehensive family of treated mineral reinforcements (Table II and Table III) at a 40% loading level in nylon 6/6 reveals treated mica to be the mineral offering the highest mechanical property profile and the lowest mold shrinkage values. Obviously, mica is the mineral of choice for isotropic moldings of reinforced composites.

Table III includes a series of mica/glass fiber composites in nylon 6/6, nylon 6 and PBT resins offering improved mechanical and thermal properties with the addition of reinforcing glass fibers.

The 40% aluminum trihydrate and 40% talc composites in nylon 6/6 offer the greatest flammability resistance because of water lost when exposed to the flame application during testing. All minerals in this series were treated with a sizing system to enhance wettability and mechanical properties.

STATICALLY CONDUCTIVE THERMOPLASTICS

Thermoplastics are replacing metals in many applications, offering the advantages of low cost, light weight parts, and flexibility in part design. They have until recently been slow to penetrate the electronic and high velocity conveyor system markets because of an inherent lack of electrical conductivity. Static charges are easily generated on the surfaces of poor electrical conductors on contact with electrically dissimilar materials; the resulting electrostatic charge must then be conducted to ground to avoid sparking and surface dust pick-up.

Static electricity results from an excess or deficiency of electrons on the surface of an insulating material. Accumulated surface charges can be dissipated by conduction within or along the surface of the material and gradual decay to the air. Conductive fillers such as carbon black powder, carbon fibers, and metallic fibers can be incorporated in insulating plastic systems to assist the charge dissipation process.

Metallic conductors (copper, aluminum) have surface resistivities ranging from 10^{-4} - 10^{-6} ohm; polymeric insulators have resistivities of 10^{14} - 10^{16} ohm. Bridging this conductance gap are the carbon fiber reinforced polymer systems with "conductive" compounds having 10^{0} - 10^{2} ohm resistivities and "anti-static" compounds with 10^{2} - 10^{6} ohm resistivity ranges.

A series of statically-conductive compounds based on nylon 6/6, polyacetal, polypropylene, polyphenylene oxide alloy, and polycarbonate with surface resistivity values of 10^{2} - 10^{5} ohm have been characterized on Table IV.

SHIELDING OF ELECTROMAGNETIC INTERFERENCE/RADIO FREQUENCY INTERFERENCE (EMI/RFI)

Aluminum fillers and graphite fibers have been evaluated (Table V) as conductive fillers imparting EMI/RFI attenuation. Tests were conducted on 1/8-inch thick injection-molded plaques, using a procedure that employs two shielded rooms with a 5-by-5 inch communicating aperture.

Most mechanical properties were retained; for instance, aluminum filled polycarbonate resin showed a tensile strength of 6,000 psi and flex modulus of 600,000 psi, but it yielded a notched Izod impact strength of only 1.2 ft-lb/inch. Respective figures for PBT were 8,000, 1,000,000 and 1.0; for nylon 6/6, 8,500, 1,000,000 and 1.1. The graphite fiber reinforced nylon 6/6 demonstrated much higher properties.

The next phase of the program will investigate addition of glass fibers to assess properties-improvement routes with the metallic filled composites.

TABLE I

MINERALS / PROPERTIES	MICA	CALCIUM CARBONATE	WOLLASTONITE	GLASS BEADS	ALUMINUM TRYHYDRATE	TALC	SILICA	FRANKLIN FIBER	CLAY
CHEMICAL FORMULA	$K_2(MgFe^{+2})_6$-$(Al_2Si_6O_{20})$. $(OH,Fe)_4$	$CaCO_3$	$CaSiO_3$	SiO_2 (72%) CaO,MgO Na_2O	$Al(OH)_3$	$3MgO.4SiO_2 \cdot H_2O$	SiO_2 (99%)	$CaSO_4$	SiO_2 (45%) Al(OH)
WATER CONTENT (%)	< 5%	< 2%	0.5%	-	34.6%	4.8%	< .1%	< 1%	13.8%
SPECIFIC GRAVITY (g/cc)	2.74-2.95	2.60-2.75	2.9	2.48	2.42	2.7 - 2.8	2.65	3.0	2.58
HARDNESS (MOHS)	2.4-3.0	3.0	4.5	5.5	2.5-3.5	1.0	7.0	~ 2	2
MELTING POINT	1300°C (d)	900°C (d)	1200°C(trans) 1540°C(mp)	1200°F (mp)	220-600°C loses 34.6% H_2O	Stable to 380°C	Stable to 573°C	-	1000°F loses 13.8% H_2O
INDEX OF REFRACTION	1.54-1.69	1.49	1.63	1.51	1.58	1.59	1.55	1.56	1.56
COLOR	gold-brown	white	white	color-less	white	gray-white	white	white	white

MINERAL FILLED NYLONS

LNP THERMOCOMP® DATA SHEET

TABLE I I

PROPERTY	ASTM METHOD	UNITS	THERMOCOMP NUMBER					
BASE RESIN			Nylon 6/6	Nylon 6/6	Nylon 6/6	Nylon 6/6	Nylon 6/6	Nylon 6/6
% by wt.		%	60	60	60	60	60	60
Filler A			Mica	$CaCO_3$	Wollastonite	Glass Beads	ATH	Clay
% by wt.		%	40	40	40	40	40	40
Filler B								
% by wt.								
Filler C								
% by wt.								
Filler D								
% by wt.								
Filler E								
% by wt.								
Specific Gravity	D792		1.50	1.48	1.51	1.46	1.45	1.47
Mold Shrinkage - 1/8"	D955	in./in.	.003	.012	.009	.011	.008	.004
Water Absorption - 24 hrs.	D570	%	0.6	0.5	0.5	0.6	0.7	0.4
Tensile Strength, Ultimate	D638	psi	15,260	10,480	10,480	9,780	9,200	10,850
Tensile Elongation, Ultimate	D638	%	2.7	2.9	3.0	3.2	2.8	2.5
Flexural Strength	D790	10^3 psi	26.0	16.5	17.7	15.8	14.7	23.7
Flexural Modulus	D790	10^3 psi	1540	660	790	615	645	1010
Impact - Notched 1/4"	D256	ft. lbs/in	0.6	0.5	0.6	0.4	0.5	0.3
Impact - Unnotched 1/4"	D256	ft. lbs/in	8.1	9.6	9.4	5.5	6.4	12.3
Heat Distortion 264 psi	D64	°F	460	388	430	407	396	391
Thermal Expansion	D696	10^{-5}/°F	2.2	2.8	2.3	2.8	3.0	2.6
Thermal Conductivity	C177	$\frac{BTU\text{-}ft.^2}{hr.\ in.\ °F}$	3.9	3.9	4.9	3.4	4.9	3.9
Oxygen Index		%	31	27	27	27	36	28
"K" Factor			230	180	715	460	560	1250

MINERAL FILLED COMPOSITES

LNP THERMOCOMP® DATA SHEET

TABLE III

PROPERTY	ASTM METHOD	UNITS	THERMOCOMP NUMBER					
BASE RESIN			Nylon 6/6	Nylon 6/6	Nylon 6/6	Nylon 6/6	Nylon 6	PBT
% by wt.		%	60	60	60	60	60	60
Filler A			Talc	Silica	Franklin Fiber	Mica	Mica	Mica
% by wt.		%	40	40	40	25	25	25
Filler B						FG	FG	FG
% by wt.						15	15	15
Filler C								
% by wt.								
Filler D								
% by wt.								
Filler E								
% by wt.								
Specific Gravity	D792		1.49	1.48	1.52	1.49	1.49	1.66
Mold Shrinkage - 1/8"	D955	in./in.	.008	.005	.005	.006	.0055	.0065
Water Absorption - 24 hrs.	D570	%	0.4	0.4	0.7			
Tensile Strength, Ultimate	D638	psi	8,980	13,040	12,240	20.500	20,400	14,500
Tensile Elongation, Ultimate	D638	%	2.0	6.4	2.9	3.4	3.8	3.1
Flexural Strength	D790	10^3 psi	15.3	21.2	18.6	28.5	36.6	21.5
Flexural Modulus	D790	10^3 psi	925	765	865	1450	1645	1400
Impact - Notched 1/4"	D256	ft. lbs/in	0.6	0.6	0.5	0.8	0.9	0.8
Impact - Unnotched 1/4"	D256	ft. lbs/in	5.1	31.0	9.3	15.0	11.5	11.0
Heat Distortion 264 psi	D64	°F	447	401	436	490	395	420
Thermal Expansion	D696	10^{-5}/°F	2.0	2.8	2.8	2.1	2.0	1.9
Thermal Conductivity	C177	$\frac{BTU\text{-}ft.^2}{hr.\ in.\ ^oF}$	4.1	5.3	4.7	3.7	3.6	3.5
Oxygen Index	D2863	%	34	26	26			
"K" Factor			3150	240	270			

TABLE IV

STATICALLY CONDUCTIVE THERMOPLASTICS

PROPERTY	METHOD	UNITS	Nylon	Poly-acetal	Polypro-pylene	Nylon 6/6 with 15% glass fiber	Poly-phenylene oxide alloy	Poly-carbonate with 30% glass fiber
GENERAL								
Specific Gravity	D792	-	1.11	1.43	0.94	1.29	1.12	1.47
MECHANICAL								
Tensile Strength	D638	psi	6,500	5,500	3,000	10,000	6,000	13,000
Tensile Elongation	D638	%	8.0	2.0	11.0	2.0	2.0	2.0
Flexural Strength	D790	psi	11,500	10,500	3,600	20,000	9,000	15,500
Flexural Modulus	D709	psi	325,000	420,000	110,000	850,000	420,000	1,040,000
Izod Impact Strength	D256	ft.lbs./in.						
Notched ¼"			1.5	0.4	3.2	1.0	0.3	1.2
Unnotched ¼"			15.0	2.5	25.0	3.5	2.3	4.2
THERMAL								
HDT @ 264 psi	D648	°F.	215	230	180	485	265	300
ELECTRICAL								
Surface Resistivity	D257	ohm	10^5	10^2	10^5	10^3	10^4	10^4

TABLE V

EMI ATTENUATION, 1/8" SECTION, DECIBELS

Base Resin	Shielding Component	10 KHz	100 KHz	1 MHz	10 MHz	100 MHz	1 GHz	10 GHz
PBT	Aluminum	45	40	35	40	30	30	30
Poly-carbonate	Aluminum	40	40	35	35	45	35	30
Nylon 6/6	Aluminum	65	60	55	50	35	40	35
Nylon 6/6	Carbon Fiber	80	80	90	75	40	40	55

TABLE VI

PHYSICAL AND MECHANICAL PROPERTIES

Base Resin	Shielding Component	Specific Gravity	Tensile Strength psi	Flexural Strength psi	Flexural Modulus psi	Notched Izod Impact Str. ft. lbs./in.	Unnotched Izod Impact Str. ft. lbs./in.
PBT	Aluminum	1.67	8,000	13,000	1,000,000	1.0	4-5
Poly-carbonate	Aluminum	1.56	6,000	12,000	600,000	1.2	4-5
Nylon 6/6	Aluminum	1.50	8,500	14,000	1,100,000	1.1	4-5
Nylon 6/6	Carbon Fiber	1.34	40,000	60,000	3,400,000	1.6	13.0

KAMAX™ MODIFIED POLYALIPHATIC IMIDE— A NEW FAMILY OF AMORPHOUS ENGINEERING THERMOPLASTIC MOLDING RESINS

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INTRODUCTION

Kamax compounds are a new family of high temperature resistant, high impact strength, modified amorphous polyaliphatic imide resins which can be easily molded in conventional injection molding equipment with fast cycle times.

The polyaliphatic imide structure provides chain stiffness which is essential to high heat resistance. It also contributes long-term thermal stability and excellent processability.

The service temperatures of Kamax compounds are lower than those of the aromatic condensation polyimides and amide imides, and they are not intended to compete for the same applications. Rather, they will be specified for molded parts when a balance of engineering properties at a reasonable price is required.

The key raw materials used in the manufacture of Kamax resin are acrylic monomers, of which Rohm and Haas is the world's largest producer.

AVAILABLE GRADES:

The basic polyimide polymer lends itself to the development of a family of amorphous compounds. The first two molding grades were introduced earlier this year. Kamax 201 is a general purpose grade. It offers a Vicat softening temperature of 148°C (298°F) and a deflection temperature under 264 psi load of 130°C (266°F). At 23°C (73°F), Izod notched impact strength is at least 5 ft.-lb./in.; a tensile yield strength of 7,500 psi is achieved with a tensile modulus of 305,000 psi. The dielectric strength at 1/8" thickness measures 460 volts/mil, and the arc tracking index is 117 seconds. (See Table I).

This general purpose grade is an off-white shade in its natural state. This allows the development of a spectrum of bright, glossy, and highly saturated colors. Kamax 201 resin is classified as 94 HB when tested in accordance with UL-94 flammability classification test.

Kamax 301 contains a flame retardant package and has been submitted to Underwriters Laboratory for characterization against UL subject 94.

Both grades are available in 1/8" cylindrical pellet form and have similar processing characteristics.

PROPERTY HIGHLIGHTS:

Rigidity vs. Temperature - Figure 1 shows the apparent modulus of rigidity of these compounds over a broad temperature range using Clash-Berg Torsional Modulus Test (ASTM D-1045, 2°C/min.). Both remain stiff and ductile up to 130°C (266°F). The modulus plot correlates well with values of the deflection temperatures under load and Vicat softening temperature.

At temperatures from 23-121°C (73-250°F), the resins remain rigid and tough (Example: Figure 2). Yield stress vs. temperature is plotted in Figure 3 and tensile modulus in Figure 4.

Impact Strength vs. Temperature - The practical toughness of both compounds over a wide range of temperatures is best shown in Figure 5, a plot of data obtained in the Gardner Variable Height Impact tester. This apparatus has demonstrated its usefulness in measuring the practical toughness of flat molded articles. Izod impact strength vs. temperature is shown in Figure 6. Kamax parts can be used continuously below -18°C (0°F) and retain adequate toughness unless notch sensitivity is of concern at such low temperatures because of design.

Electrical Properties vs. Temperature - Kamax resins maintain dielectric constant and dielectric strength virtually unchanged up to the practical softening temperature (140°C/284°F). They show a modest reduction in volume resistivity and an increase in dissipation factor with increased temperature (Figures 7 and 8).

Resistance to Flexing - Both resin grades retain unyielding integrity during continuous flexing up to 10^7 cycles. Figure 9 shows a working design level of 2000 psi is practical for Kamax 201 and 1500 psi is practical for Kamax 301. These are normal stress levels for amorphous plastics.

Creep Resistance - Creep may be expressed as the change in percent strain for a given stress over an extended period of time, but the change in either tensile or flexural modulus under load with time is preferred. Figure 10 plots change in flexural modulus after 1000 hours at room temperature and 1500 psi. Tests are continuing, but the plots have already leveled out and indicate that a modulus can be used directly in load-bearing calculations.

Thermal Stability - Oven tests are underway to establish an Underwriters Laboratory Recognized Component Continuous Use Thermal Index (Procedure UL 746B) for both compounds. The Thermal Index projects the continuous use temperature at which 50% of a property is retained after 100,000 hours (11.4 years). At the time this paper was prepared, 2520 hours of testing at 120°C (248°F) (tensile impact) and 130°C (266°F) (tensile strength) had elapsed. The time at which properties fell below 50% of the initial value had not been reached. Higher temperature tests were started. The general purpose grade is expected to have long term utility at temperatures in excess of 105°C (221°F). Kamax 301 is expected to be comparable to Kamax 201.

Chemical Resistance - These polymers are polar amorphous plastics. They are not chemically degraded by moisture, dilute aqueous acids or salt solutions. They are particularly resistant to fatty acids, high boiling esters, ethylene glycol, and glycerine. The surface of molded parts are dulled, but not crazed during brief contact with alcohols, naphtha, and carbon tetrachloride. They are chemically attacked by chlorinated hydrocarbons, aromatics, strong bases, low boiling esters, and ketones.

Molded parts absorb moisture without significant changes in strength, modulus, or toughness. Water does not have a plasticizing effect. After three months of immersion in distilled water at 82°C. (180°F), the modulus of elasticity remained essentially unchanged. Dimensional change will occur and must be allowed for if parts are exposed continuously to aqueous media.

Moisture absorption has a negligible effect on the basic electric insulating properties.

UV Stability - Simulated weathering programs carried out to date indicate that Kamax 201 will be stable in many exterior applications. Actual outdoor exposures are in progress at several locations in the United States.

SUGGESTED APPLICATIONS

These new resins offer a balance of beneficial properties including the maintenance of key mechanical properties at high temperature, inherent strength, and good electrical insulation. The attractive glossy surfaces and availability of bright highly saturated colors are also advantageous. Affinity to aqueous and hydrocarbon media along with high softening temperatures presents a broad range of decorating possibilities by painting, plating and hot-stamping, and for bonding.

Applications to be considered include appliance housings, mechanical parts, electrical/electronic parts, connectors, covers and internal parts for business machines, automotive electrical and decorative assemblies, and leisure products.

The large industrial market includes uses in process equipment, vending machines and photographic parts, to mention a few interesting possibilities.

PROCESSING AND RHEOLOGY

Kamax resins can be molded in all types of injection molding machines. Reciprocating screw machines are preferred because they are more versatile and deliver a more uniform melt. The machine size should be selected to give a shot size at least 40% of the machine capacity to prevent excessive thermal history.

Kamax resins are hygroscopic and should be dried thoroughly before molding. Drying for 2 to 4 hours at 121°C (250°F) should eliminate splay marks on molded surfaces. If drying is inadequate molded parts retain key physical properties because moisture does not react with the resin to decrease molecular weight.

Table II list typical start-up molding conditions.

Most gating techniques including sprue, edge, tab, fan, tunnel, ring, and diaphragm, as well as multigating, are suitable. The mold shrinkage of Kamax resins is 0.005 to 0.008 inches per inch.

Kamax resins have very good flow. Figure 11 shows the flow length as a function of melt temperature in a spiral flow mold 0.080 inch deep. Because of the thermal stability of Kamax molding resins over a wide range of temperatures range, difficult molds can be filled readily by increasing the melt temperatures, injection pressure, and fill speed.

The physical properties of molded parts are not sensitive to changes in barrel temperature. In the normal range of 271°C-316°C (520°F-600°F), Kamax resins are thermally stable and can be processed without difficulty. Figures 12 to 14 illustrate the minimal effects of melt temperature on tensile strength and toughness.

The excellent thermal stability of Kamax resins also minimizes the deterioration of physical properties when regrind is molded. Although 100% regrind could be used, the proportion should be kept below 25-30% to prevent the possibility of a decrease in physical properties in critical applications. When regrind material is not recycled as soon as produced, it should be dried before processing.

Rheological Properties - To obtain a simplistic comparison of Kamax 201 and 301 one can use melt flow rate (MFR) numbers indicating the weight of melted polymer that will flow through an orifice of given diameter and L/D ratio at a given temperature during a given time when a specified force is applied to the ram of the testing machine. For example, at 266°C (510°F) and a load of 18,700 grams the MFR's numbers are:

Kamax 201	12-15 grams/10 mins.
Kamax 301	20-24 grams/10 mins.

But MFR numbers are valid for comparisons under only one specific set of conditions which may or may not be related to performance in a molding machine. A more meaningful method of studying the response of a resin to changes in molding conditions is to examine the slope of flow curves made by plotting viscosity vs. shear rate at various temperatures and viscosity vs. temperature at various shear rates.

Practical experience has shown that Kamax 201 and Kamax 301 can be injection molded at melt temperatures from 271°C-316°C (520°F-600°F). In this range, fast injection rates greatly reduce the melt viscosity and thus allow molding these resins into thin sections and through small gates. Figures 15 and 16 show that this occurs because 10-15 fold reductions in viscosity can be obtained in standard molding machines which provide high injection pressures and shear rates well over 1000 $sec.^{-1}$.

By using measurements of apparent viscosity through a capillary of known geometry, relationships of viscosity, shear rate, and temperature can be plotted. By plotting log viscosity vs. the reciprocal of the absolute temperature, the viscosity at given shear rates forms a series of straight lines. This shear thinning effect makes these resins versatile molding compositions because the rate of flow is readily affected by changes in barrel temperature, screw speed, back pressure, injection rate, and to a lesser degree, mold temperature.

SUMMARY:

A new family of amorphous resins of unique chemical structure and properties has been introduced to specifiers. The first grades described in this paper offer an alternative to existing engineering thermoplastic molding resins. They are characterized by high heat resistance, excellent retention of key properties at high temperatures versus time, and good electrical properties. The surfaces of molded parts exhibit good gloss. Absorption of moisture does not plasticize parts or significantly affect the modulus. The chemical resistance is adequate for general purpose applications.

The resins process well with a broad molding range and fast cycles, and their sensitivity to shear allow excellent flow. They are supplied in pellet form.

ACKNOWLEDGEMENTS:

Dr. Evan H. Crook, Dr. Robert M. Graff, Dr. William F. Fischer, Miss Susan Liwak, Mr. Eric O. Teutsch, and Mr. William T. Freed were all part of the research team whose work made the development of these new polyimide compounds possible.

The physical measurement group at Rohm and Haas Company managed by Mr. R. W. Jans carried out most of the property testing. Mr. R. D. Cole prepared the graphs and slides for this presentation.

TABLE I: Physical Property Comparisons

Property	Units	ASTM Method	Kamax 201	Kamax 301
Specific Gravity		D792	1.16	1.30
Vicat Temp.	°C (°F)	D1525	148(298)	147(297)
Distortion Temp. 264 psi	°C (°F)	D648	130(266)	122(252)
Tensile (2% min. extension		D638		
Elongation at Break	%		34	32
Strength at yield	psi		7500	6300
Modulus of Elasticity	psi		305,000	265,000
Flexural (0.5"min./2" span)		D790		
Strength	psi		12,100	9400
Modulus of Elasticity	psi		365,000	273,000
Impact Strength				
Izod Notched	ft. lb./in.	D256	5.0	3.0
Gardner Var. Height	ft. lbs.	D20	9.0	15
Tensile Impact	ft. lbs./$in.^2$	D1822	140	150
Dielectric Strength	V/mil	D149		
1/16"			738	805
1/8"			460	504
Arc Resistance	sec.	D495	117	37

TABLE II: Start-Up Molding Conditions for Kamax Resins
Reciprocating Screw Machines - Part Thickness 0.125"

Barrel Temperatures	
Rear	450-470°F (232-243°C)
Center	470-490°F (243-254°C)
Front	500-510°F (260-266°C)
Nozzle	510-530°F (266-277°C)
Melt Temperature	530°F (277°C)
Mold Temperature	180°F (82°C)
Screw Speed	100 rpm
Injection Speed	2-4 seconds
Cycle Time	
Injection Forward	15-20 seconds
Cure	10-15 seconds
Mold Closed	25-35 seconds

FIGURE 1

APPARENT SHEAR MODULUS VS. TEMPERATURE
(CORRELATION WITH SOFTENING TEMPERATURE INDICES)

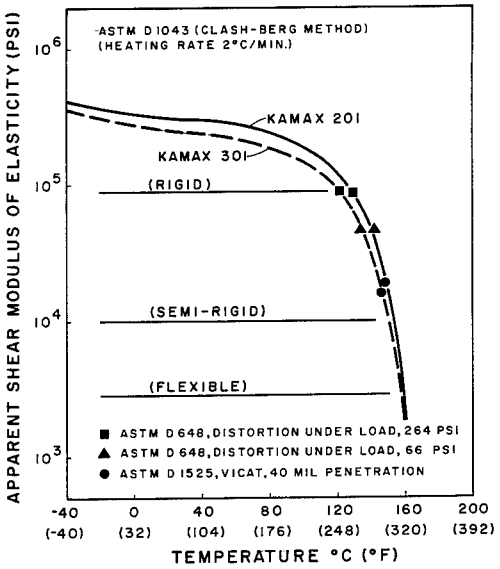


FIGURE 2

TENSILE STRESS VS. STRAIN AT VARIOUS TEMPERATURES

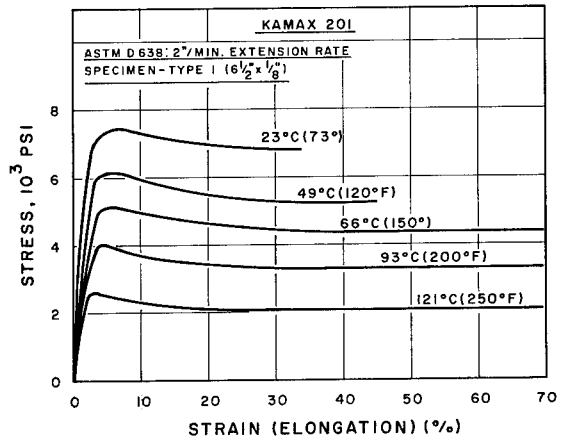


FIGURE 3

TENSILE YIELD STRESS VS. TEMPERATURE

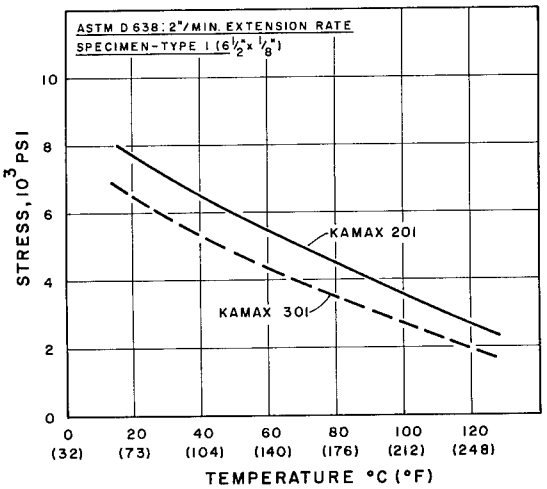


FIGURE 4

TENSILE MODULUS VS. TEMPERATURE

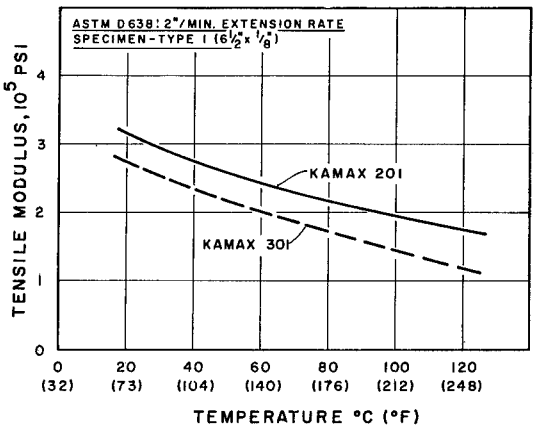


FIGURE 5

GARDNER VARIABLE HEIGHT IMPACT STRENGTH VS. TEMPERATURE (F50 VALUE)

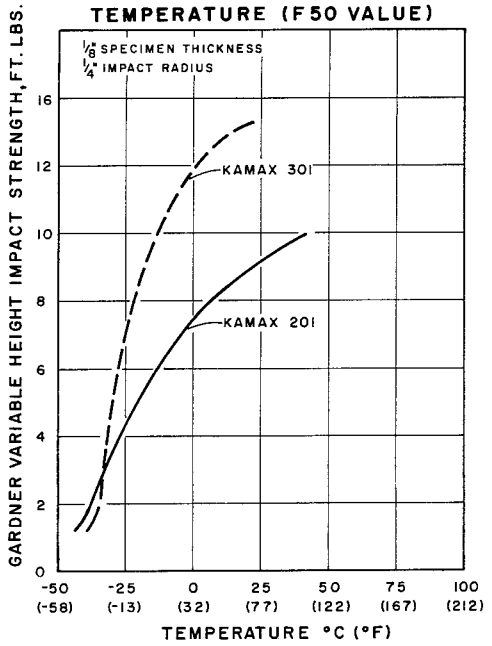


FIGURE 6

IZOD IMPACT STRENGTH VS. TEMPERATURE (MACHINED NOTCH)

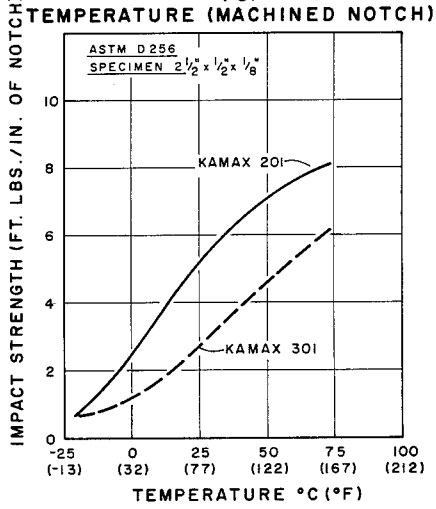


FIGURE 7

DISSIPATION FACTOR VS. TEMPERATURE 100 HZ

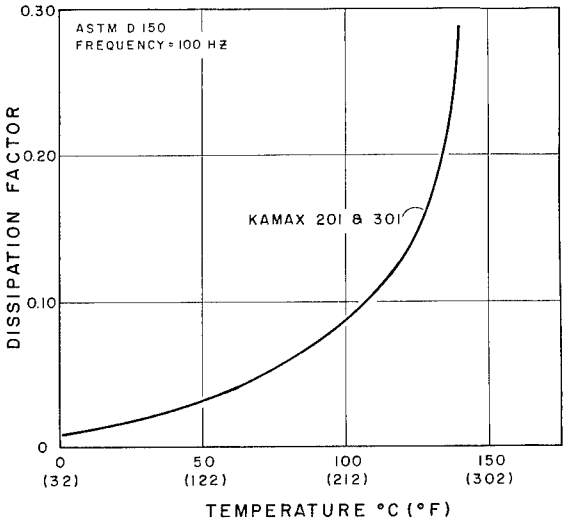


FIGURE 8

VOLUME RESISTIVITY VS. TEMPERATURE

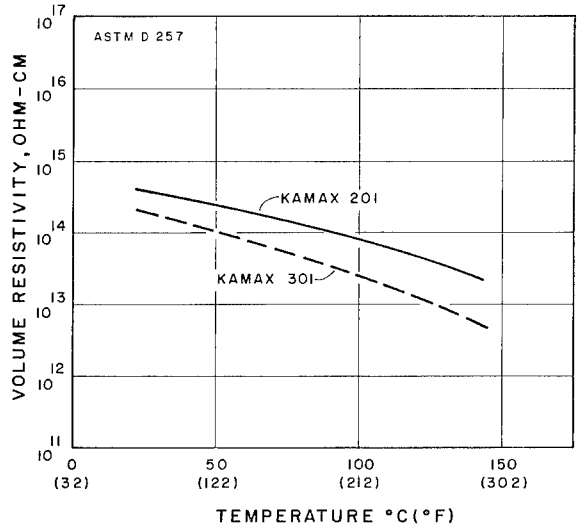


FIGURE 9

ALTERNATING FLEXURAL FATIGUE STRESS

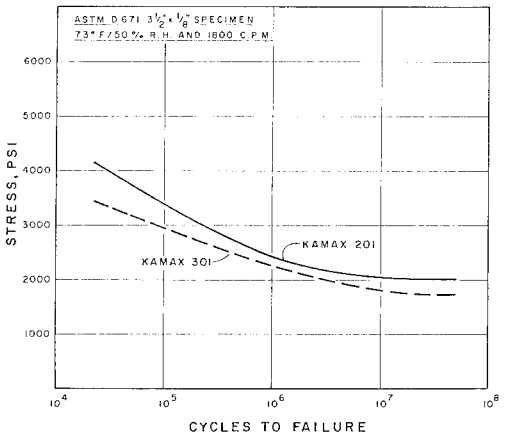


FIGURE 10

APPARENT FLEXURAL MODULUS OF ELASTICITY CREEP 73°F/50% R.H. 1500 PSI

(ASTM D 2990)

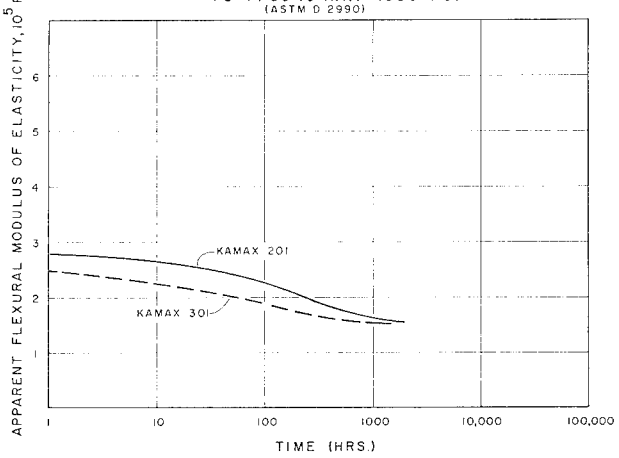


FIGURE 11

SPIRAL FLOW VS MELT TEMPERATURE

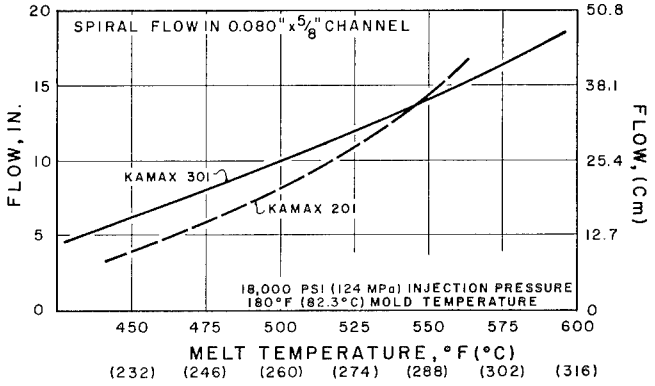


FIGURE 12

TENSILE STRENGTH VS MELT TEMPERATURE

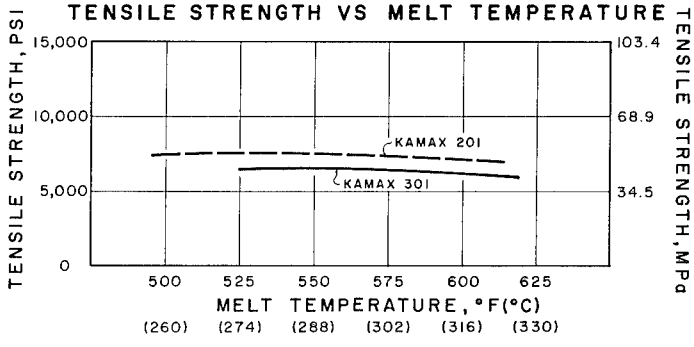


FIGURE 13

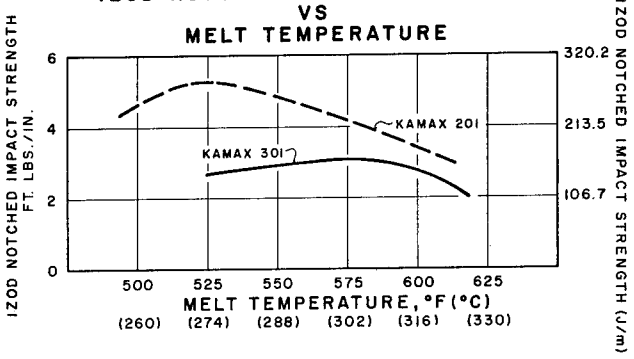


FIGURE 14

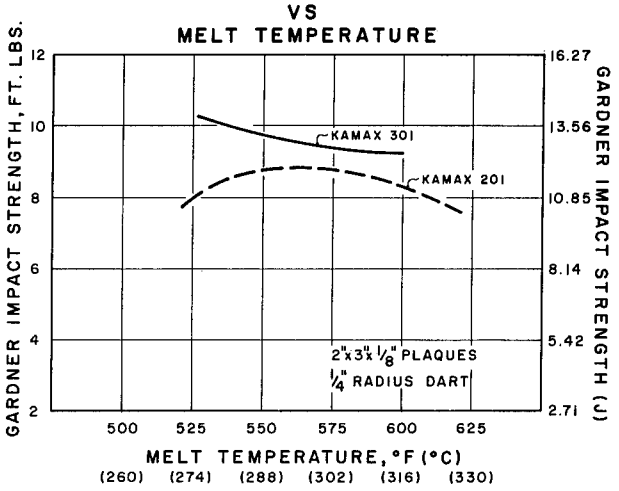


FIGURE 15

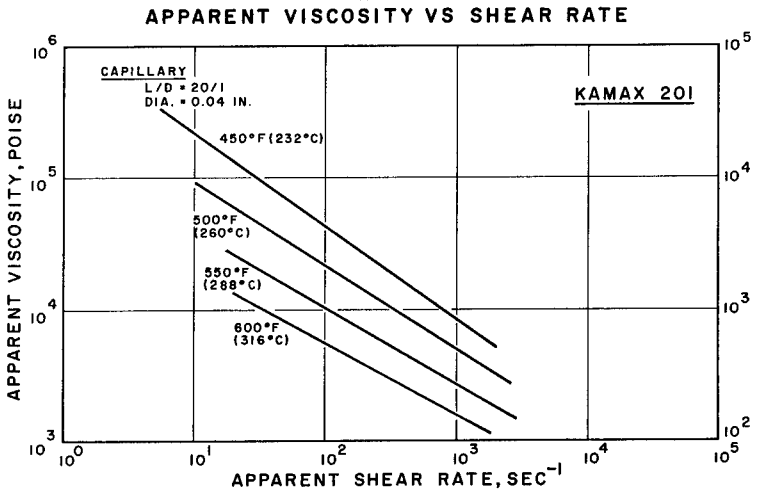
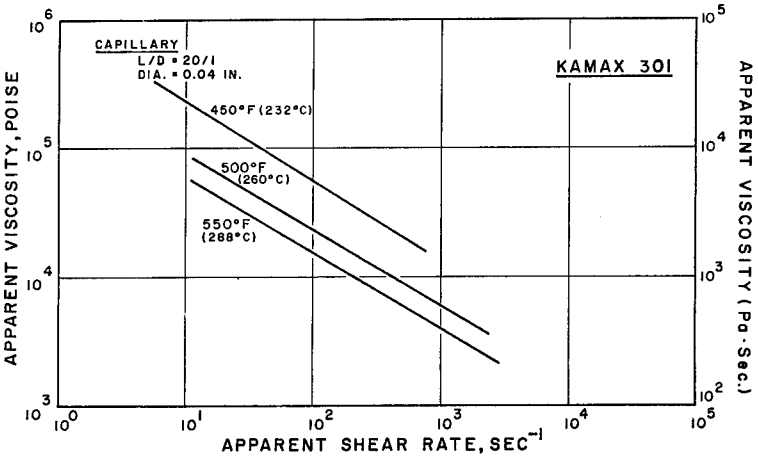


FIGURE 16



3678 H.C. Romuth #78-5

KEVLAR® ARAMID FIBER IN NON-ASBESTOS BRAKE LININGS

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INTRODUCTION

Asbestos has characteristics that make it well suited for friction applications including: thermal stability, adequate wear resistance, and strength. However, because occupational exposure to asbestos dust has been shown to cause lung cancer, asbestosis, and mesothelioma, industry is actively developing replacements. This paper will review work showing the potential of Kevlar© aramid fiber to eliminate the need for asbestos in friction products.

Finding a replacement for asbestos in friction materials is not simple, since no other single material has the same combination of friction performance, thermal stability, wear resistance, strength and cost. A logical approach is to use a low cost inorganic filler with higher cost reinforcing fibers added for strength and crack resistance. This approach would in principle make it possible to continue to use the production methods that have been developed for asbestos based friction materials.

A number of reinforcing fibers with varying advantages and limitations are listed in Table 1. As can be seen, there is no pattern of limitations and advantages. However, fibers of Kevlar© are unique in that they do not have characteristics that would result in performance negatives in a finished friction product. Fibers of Kevlar© should contribute strength and wear resistance to friction products without causing fade. Therefore Kevlar© fiber is a promising candidate for reinforcement of friction materials. Kevlar© is readily available from a commercial production facility which is being expanded to 45 million lbs/year capacity.

Kevlar© aramid fiber is made of an infusible aromatic polyamide polymer. On a weight basis it is five times stronger than steel. Composites reinforced with Kevlar© fiber have good resistance to external abrasion. Kevlar© also has much better high temperature properties than common organic fibers.

Kevlar© Product Forms for Friction Materials

In friction materials it is possible to use many forms of Kevlar© including:

- Cut fiber which can be processed in a mixer. Any length can be made and crimp can be added to improve dispersion.
- Continuous filament which gives the highest strength conversion.

In this paper, the main emphasis will be on the performance of cut fiber forms of Kevlar© in disc brake mixes. For experimental simplicity only a few elementary mixes were studied. Consequently, the discussion will be mostly about dry mixing technology, with only a brief mention of procedures for wet mixing of Kevlar© fiber. Results pertinent to manufacture, i.e., mixing, molding, and machining will be discussed followed by friction performance characteristics.

Experimental

Mixing experiments were run on a Patterson-Kelley LB-8 blender. The solids were premixed, then the Kevlar© fiber was added and mixing was resumed for 30 sec. to 10 min. Small scale mixing experiments for friction assessment only, were carried out in a Waring Blender.

Dry mixes were molded at 1000-10000 psi for 5-15 min. at 350°F. The pressure and time was selected to give optimum results depending on the resin content and thickness of the sample. Flex strength was measured on rectangular bars at 10/1 span/depth.

The SAE J-661A brake lining quality control test procedure (Chase test) was run by Greening Testing Laboratory in Detroit, MI, following the SAE recommended practice. A constant output wear test was run on the same dynamometer for 30 min. at 650 RPM, with 60 lbs. friction force at 420°F.

Car tests which evaluated, wear, fade, recovery and engagement characteristics, were by the MVSS 105-75 procedure.

RESULTS AND DISCUSSION

Brake Lining Production

The first step in manufacturing a friction material is mixing the ingredients. Cut forms of Kevlar© require special attention in mixing because the fibers are tough and do not break up but tend to clump together on prolonged mixing.

Although the form of Kevlar© in a friction mix does not have a major effect on wear and friction performance, long fiber forms strengthen more effectively than short fiber forms.

To show the effect of the form of Kevlar© we studied a brake mix consisting of 50% wollastonite, 20% barium sulfate, 15% dry phenolic resin and 15% cashew friction particles strengthened with different forms of Kevlar© at the 5% level. Mixing was on the Patterson-Kelley twin shell blender with intensifier bar similar to some equipment used in the trade for dry mixing disc brake compound. Mixes with various forms of Kevlar© fiber were mixed 5 minutes, molded and tested for strength. The results are given in Table 2 and support our understanding of a competition between clumping and dispersion when fibers of Kevlar© are mixed. The clumping is caused by sticking of the ragged ends formed when Kevlar© was cut. Based on the test results and subjective evaluation of the mixing experiments, we conclude that:

- Crimped, cut fiber disperses better than uncrimped.
- With uncrimped cut fiber, 1/2" length material disperses better than 1/4" in this blender type. This indicates that clumping is caused more by end contact than by intertwining of the fibers.
- Cut fiber with a diameter of 15μm disperses better than cut fiber with a 20% smaller diameter. This is probably due to lower fiber "concentration". Higher stiffness may also help prevent tangling.

- Well dispersed, longer fiber strengthens best because of the higher length to thickness ratio.

- Mixing must be stopped when optimum dispersion is reached. After this point subsequent mixing only causes clumping.

- In the molded part the addition of Kevlar® fiber increases the flex strength and reduces crack propagation. Figure 1 illustrates an example where flex strength was increased 80% and work to break was boosted seven fold.

Good dispersion of the Kevlar® fiber is more important for molding performance and machinability than for strength. Even with some clumping of the mix, flex strengths close to 10 kpsi are easily reached. However, samples where the Kevlar® is in clumps are difficult to distribute evenly in a mold. After molding, such samples have weak edges and tend to shred when machined. We have found that submicron particles of the constituents in dry brake mix aid dispersion and hinder formation of clumps and balls by the Kevlar® fibers. For example in a dry disc brake mix containing 50% dolomite powder of which 75% was smaller than 100 mesh, dispersion was poor, with clumping and poor molding performance. On the other hand a stable well dispersed mix was obtained when a fine ground dolomite powder which would all pass through a 200 mesh screen was substituted. In other experiments dispersion has been improved by adding hydrated lime with submicron sized particles substantially finer than 300 mesh to friction mixes. Presumably these particles block the ragged ends of the Kevlar® fibers, so that the fibers do not snag and clump. This effect can be seen by comparing the dispersion performance of Mix A and C with Mix B in Table 3.

Wet-resin mixes for drum brakes, made typically in Littleford mixers require a different technique. A 10-20 second mixing of fiber and one or more powders will open crimped Kevlar® readily. Since further mixing, especially after resin is added, tends to clump the fiber, dry ingredients should be premixed and diluted resin added uniformly to shorten wet-out time. Kevlar® fiber adds strength to "uncured" extruded strip for drum linings and cold compacts for disc pads, since it does not break down in mixing or bounce back from molding. Since the fibers are not porous (as asbestos is), attention is required to relieve gas pressure from curing and drying.

Friction Performance Characteristics

The incorporation of fibers of Kevlar® has no major effect on the inherent friction characteristics of a mix. This is shown for an experimental asbestos-free brake mix in Figure 2. An asbestos-based premium commercial disc brake material with similar friction characteristics is also included for reference. Mixes incorporating Kevlar® can have high friction combined with good wear resistance. Mix A, reinforced with Kevlar® (Table 3) has a significantly better wear rate of 3×10^{-3} in^3/hp-hr compared to 9×10^{-3} in^3/hp-hr for the asbestos based control. In car tests, Mix A tended to give rough stops, showing that lab tests alone do not adequately predict friction performance. Mix B, with a slightly lower friction coefficient, did not have this problem, and gave smooth braking performance, however molding performance was poor because of uneven fiber dispersion. This problem was solved in Mix C which had excellent dispersion. This mix gave the expected high level of performance in molding, machining and vehicle braking with smooth stops.

Although strengthening, as shown earlier, is dependent on the form of Kevlar® employed, wear tests of friction samples with different forms of Kevlar® indicate that wear is not very dependent on the form of Kevlar® that is used.

Wear is somewhat dependent on fiber orientation. Samples where the fibers are oriented perpendicular to the rubbing surface show less wear than samples where the fibers are parallel to the rubbing surface. Orientational wear effects were not observed for glass and asbestos in our tests, but wear was greater than for all orientations of Kevlar® fiber. Orientational effects on wear have previously been reported for Kevlar® and other fibers (1).

This work shows that fibers of Kevlar® aramid can boost the performance of non-asbestos friction materials bringing strength, wear, and friction to levels at least as high as those found in current asbestos materials. Our work is continuing to better define the best forms of Kevlar® for this application.

ACKNOWLEDGMENT

We gratefully acknowledge the assistance of T. J. Billings of 3M Company, who gave much of the encouragement and assistance needed to get us started in this end-use area.

BIBLIOGRAPHY

(1) Sung, Nak-Ho and Suh, Nam P. "Effect of Fiber Orientation on Friction and Wear of Fiber Reinforced Composites" Wear 53 (1979) 129-141.

TABLE 1

REINFORCING FIBERS FOR FRICTION MATERIALS

	Advantages	Potential Problems
Kevlar*	High strength and modulus Thermal stability Non-aggressive wear characteristics	Needs special attention in mixing
Steel	High strength and modulus Thermal stability	High density Corrosion Low cold friction
Glass	High strength and modulus	Melts at very high temperatures causing fade Loses fiber form in high shear mixing Molding spring back Low wear resistance Aggressive wear characteristics
Thermoplastic Synthetic Fibers	High strength	Melt, causing fade
Cellulosic Fibers	Infusible	Low strength and modulus Low char temperature
Carbon Fibers	High strength, very high modulus Infusible Thermal stability	Loses fiber form in mixing
Asbestos	High strength and modulus Thermal stability Infusible Good wear Also acts as filler	Linked to health problems

* Registered trademark of the Du Pont Company

TABLE 2

FLEX STRENGTH OF MOLDED TEST BRAKE MIX*

Mix	Kpsi Strength
No Kevlar+ added - Control	4.8
Kevlar® 1/2" Chopped Fiber 12µm diameter	8.1
Kevlar® 1/4" Crimped Chopped Fiber 12µm Diameter	7.6
Kevlar® 1/4" Chopped Fiber 15µm Diameter	7.3
Kevlar® 1/4" Crimped Chopped Fiber 15µm Diameter	7.3

* Compositition of Mix

50% Wollastonite
20% Barium Sulfate
15% Cashew Friction Part NC104-40**
15% Dry Phenolic Resin NC125**
(Kevlar® added at 5% Level)

** "Cardolite Cashew Phenolic Resin"
3M Co., St. Paul, MN

+ Registered trademark of the Du Pont Company

TABLE 3

TESTS OF DAY FRICTION MIXES

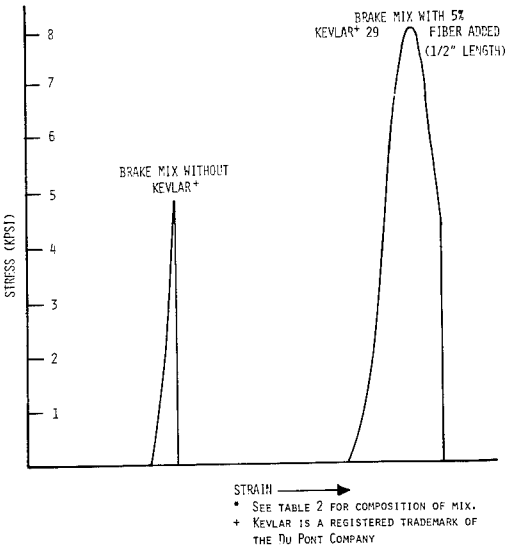
	Composition	Dispersion	Dispersion Stability	Brake Disc Molding	Brake Disc Machining	J661A Test: Friction Performance	J661A Test: Wear	J661A Test: Fade	On Car Performance
Mix A	26% Wollastonite 26% Dolomitic Hydrated Lime with Sub-micron particles 100% < 300 mesh 16% $BaSO_4$ 11% Cashew Friction Particles NC 104-40* 10% NC126 Resin* 5% 1/4" Crimped and Chopped Kevlar+ Fiber 12um diameter	good	good	good	good	excellent	excellent	good/ excellent	some roughness
Mix B	50% Dolomite 75% < 100 mesh 15% $BaSO_4$ 15% Cashew Friction Particles NC 104-40* 15% NC 126 Resin* 5% 1/4" Crimped and Chopped Kevlar+ Fiber 12um diameter	poor	poor	poor	poor	good, friction coefficient a little low	excellent	excellent	excellent braking problems related to molding
Mix C	50% Dolomite 170% < 200 mesh 15% $BaSO_4$ 15% Cashew Friction Particles NC104-40* 15% NC-126 Resin* 5% 1/4" Crimped and Chopped Kevlar* Fiber 12um diameter	good	good	good	good	excellent	excellent	excellent	excellent
Asbestos based premium quality linings normally contain:	45%-60% Asbestos 15% $BaSO_4$ 20% Organics 5% Other Materials	excellent	excellent	excellent	excellent	excellent	good	good-excellent	excellent

* "Cardolite Cashew Phenolic Resin" 3M Company, St. Paul, MN

+ Registered trademark of the Du Pont Company

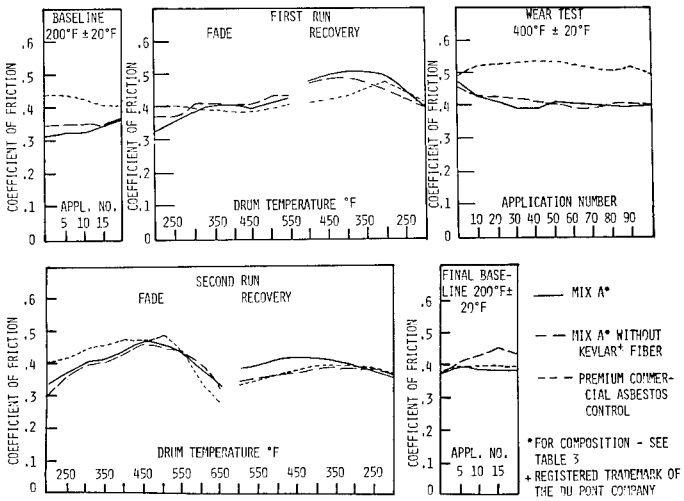
FIGURE 1

FLEX TEST OF MOLDED BRAKE MIX*
IN THREE POINT BENDING



* See table 2 for composition of mix.
+ Kevlar is a registered trademark of the Du Pont Company

FIGURE 2 J661A TEST PLOTS (CHASE TEST)



DEVELOPMENT OF ADVANCED PRESS CONTROLS FOR COMPRESSION MOLDING FRP

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INTRODUCTION

Presently there is great emphasis on reducing the weight of automobiles. The glass fiber reinforced thermosets (and specifically the Sheet Molding Compounds) have the potential to achieve many of the necessary weight reductions. To maximize the utility of these materials, parts made from them must:

A. Require minimum surface finishing.
B. Not require special painting procedures.
C. Be moldable at an economical rate.
D. Have consistent and high physical properties.
E. Use a minimum of material.

Solutions to some of these requirements have been found in the Molded Coating technique [1], Heat Transfer Analysis [2], and mechanical charge handling. However, to utilize these developments, the closing speed, pressing force and parallelism of the press must be controlled accurately. Similarly, the molding of thin parts (i.e., 1.0 to 2.0 mm) with little or no orientation of the reinforcing fibers, requires precise closing speeds and mold parallelism.

Compression molding is chosen instead of injection molding because it has a greater capability for molding the material to meet the functional requirements. For example, with compression molding, continuous filaments of the reinforcing fibers can be included, glass fiber reinforcement loadings up to 65% can be achieved, the short flow and large charge patterns eliminate weld lines, damage to the reinforcing fibers is minimized or eliminated, and the molded coating process can be utilized.

Conventional commercial press controls are inadequate. So, at General Motors Manufacturing Development, press controls have been created. One such control provides programmable force and velocity control in a single system (PFVCS). This paper describes that control system. This paper also shows the present state of development and implementation.

PERFORMANCE REQUIREMENTS

For the large panel type parts under study, the precision control is only required during the final 12 to 25 mm (0.5 to 1.0 inch) of mold closing. From that 25 mm point on through the pressing cycle until the opening of the mold passes back through that point, the mold halves must be held parallel to each other. It has been arbitrarily established that parallelism across the molded part will be held within 0.25 mm (0.01 inch) between the 25 mm (1.0 inch) position and a point 1.5 mm (0.06 inch) from final part thickness. Between the 1.5 mm point and final part thickness, parallelism should be maintained within 0.05 mm (0.002 inch). These parallelism controls are built into the system.

The velocity of most conventional hydraulic presses is constant during the pressing stage. Sometimes the ram speed decreases as the resistance of the material being spread builds. Regardless, the relatively constant closing speed of the mold causes the material in the cavity to flow at constantly increasing speeds. The final filling of corners and rib tips can be a high velocity "squirting" even though the press appears to move very slowly.

To counter these effects, the PFVCS is made so the press closing velocity can be programmed. The system could be made to have an infinitely changing velocity. However, it is believed that about ten specific velocities are probably adequate for any single mold. The actual values of these velocities and the ram positions at which each is to take affect is variable, and so has been made programmable through the machine control panel. The available velocities range from 9.9 to 0.1 mm/s (24 to 0.24 in./min.), and are held to the greater of $\pm$ 5% or $\pm$ 0.05 mm/s.

Once the mold has filled with material, the press stalls on it and motion stops. Pressure must then be maintained to maximize heat flow from the mold to the material being molded and to drive secondary flow during cure. Conventional presses develop a constant force that results from a relief valve setting. It can be argued that such a constant force is not ideal. For example, when the mold first fills and the SMC is at its lowest viscosity, a high cavity pressure will tend to force it through the shear edge and around ejector pins. However, after a few tens of seconds when cure is taking place, continued application of high cavity pressure will force secondary movement in the material compensating for the polymerization shrinkage.

When molded coating [1] is applied, a high pressure is required to spread the coating material and impregnate the substrate. Then, pressure must be reduced to negate effects from the compressibility of the substrate.
Again ten points were chosen as a reasonable number of force levels. These ten force levels can be programmed into the control system for each mold. The time at which each programmed force is to be applied is entered at the same time. The control system then interpolates linearly between points.

When molded coating material is to be applied, the force program is interrupted, the press decompressed, and the mold opened a small but specific programmed distance. Then the mold must be closed and the force program continued.

FIRST APPLICATIONS

The first application of these control concepts was a system for a tie bar press [3]. Hydraulic actuators were placed in the four corners of the press bed to react against the ram as shown in Figure 1. Control of the press was achieved through a micro-processor which read LVDT's (also at the press corners) and controlled through servo valves the outflow of hydraulic fluid from the hydraulic units. The program was input through the control panel as shown in Figure 2. That system proved the feasibility of the concept.

A second system was made and installed in the 18 MN (2000 ton) column type press in the GM Manufacturing Development plastics lab (as shown in Figure 3). Because it is a laboratory installation, a mini-computer is used instead of a microprocessor. That allows a great deal of flexibility for changing program sequence; and also provides a printout of actual performance. Program inputs and the performance printout is made through a teletype terminal. An example of the inputted velocity program is shown in Figure 4, and the output of press performance is shown in Figure 5. Figure 6 shows a plot of the data in both Figures 4 and 5 superimposed to illustrate how well the press followed the program. Velocity programs have been run in which the velocity of the SMC moving across the cavity surface is maintained constant. These programs have ranged through an order of magnitude difference in the flow front velocity even though the velocity remained constant during any one press closing cycle.

Several molds have been run in the 18 MN (2000 ton) press. These include the molds for both an inner panel and an outer panel for a deck lid (i.e., the outer panel mold is shown in

Figure 3). The outer panel was made 1.75 mm (0.070 inch) thick and the inner panel was made 2.00 mm (0.080 inch) thick. The parallelism control feature kept the part thickness within 0.25 mm (0.010 inch) on both parts. Similar part thickness control was achieved on the mold for the outer panel for the current full size GM station wagons. The value of the velocity control was demonstrated when the inner panel for the station wagon tailgate was run in the press. That part is criss-crossed with deep and narrow ribs. The press closing was programmed to slow dramatically at a point 1.0 mm (0.040 inch) above final part thickness. That very slow closing speed pressed the SMC down into the ribs without separating the resin from the glass fibers. Since the press closing speed was programmed to be considerably faster for all positions above the 1.0 mm (0.040 inch) point, total closing time was still relatively short.

INTERIM PARALLELISM CONTROL

Before the installation on the 18 MN (2000 ton) press was debugged and proven, it became necessary to implement the Molded Coating process [1], another development, into production. The Molded Coating process depends upon the parallelism and precision mold opening features of the PFVCS. Since the PFVCS was not ready (and even if it was, Manufacturing Development could not supply copies in quantity) and since no commercial source could supply it, an interim system was required. That system became known as the "Open-Loop" system since it did not have position or pressure transducers feeding actual conditions back into the control.

The "Open-Loop" system still operated with hydraulic cylinders in the corners of the press reacting against the downward motion of the ram. Instead of controlling the outflow of these cylinders with servo valves, the outflows feed into four slave cylinders. There is one slave cylinder for each corner of the press, although these are not mounted at the press corners. These slave cylinders are mounted in tandem on a single rod so they each have the same displacement.

As the hydraulic fluid from the cylinders in the press corners flows into the one side of the slave cylinders, an equal amount of fluid must flow out the other. The outflow from the four slave cylinders is connected in parallel and flows through a relief valve. The setting of the relief valve determines the total resistance to the press ram. But that total resistance can be divided quite unequally between the four corners. The system is illustrated in Figure 7.
The "Open-Loop" control cannot achieve perfect parallelism of the press. As parallelism improves, the pressure differences diminish and that decreases the corrective force. The system does achieve a reasonable degree of parallelism control. And, it has the necessary hydraulic circuitry to re-set it at the bottom and top of each stroke to avoid accumulation of error. Also, by having a single drive cylinder with a fixed stroke to move the slave cylinders, the precise opening required for coating was achieved.

The open-loop control is limited, however, by the compressibility of the hydraulic fluid and by leakages around seals. Its inherent accuracy falls short of what is needed for optimizing the compression molding of large thin panels.

CURRENT STATUS

The open-loop system is considered a short term stop-gap measure. So, commercialization of the closed loop and programmable control system is being pursued. A counterforce system like that on the 18 MN (2000 ton) press is proposed for retrofitting to existing molding presses. Several press manufacturers and control specialty companies are cooperating in that endeavor. In addition, new press design concepts are being encouraged which will incorporate the necessary control into the basic press design.

Sophisticated control systems, like the one described in this paper, are quite costly to retrofit onto existing presses. Each press will be in a different (and usually unknown) state of repair. Much of the retrofitting will actually consist of rebuilding. Also, there are a lot of different press constructions that must be accommodated. So, each situation requires a large engineering effort to adapt the control to the particular press. The application of the control philosophy to new presses in which these controls are an integral part of the press concept seems to be the best approach in the long run.

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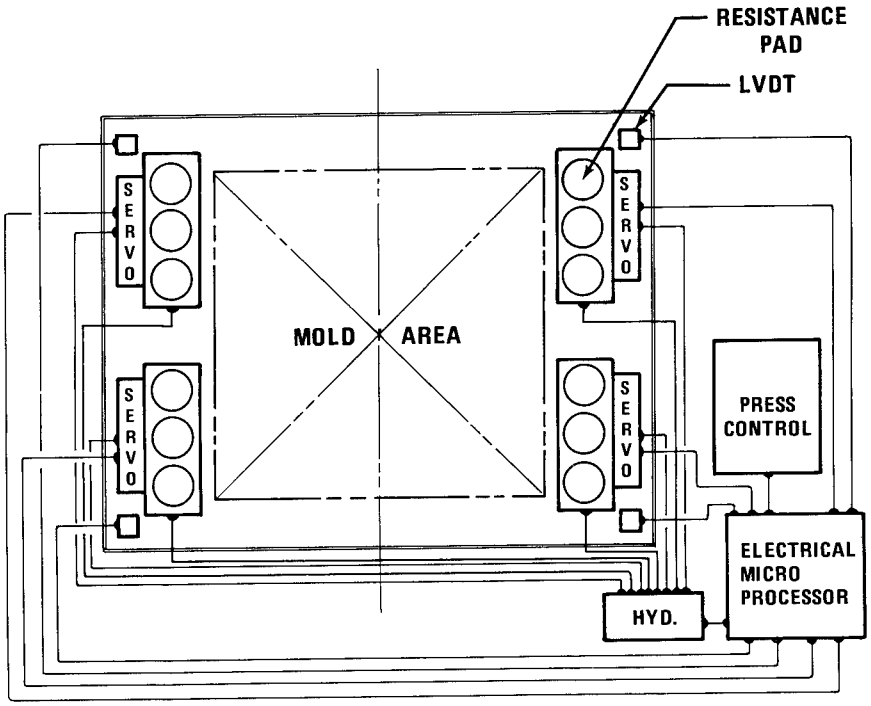


Figure 1 The concept for the PFVCS is to have hydraulic cylinders at the corners of the press bed. Position of the ram is measured with LVDT's and that information is used by a micro-processor to command servo valves on the oil outflow of the cylinders.

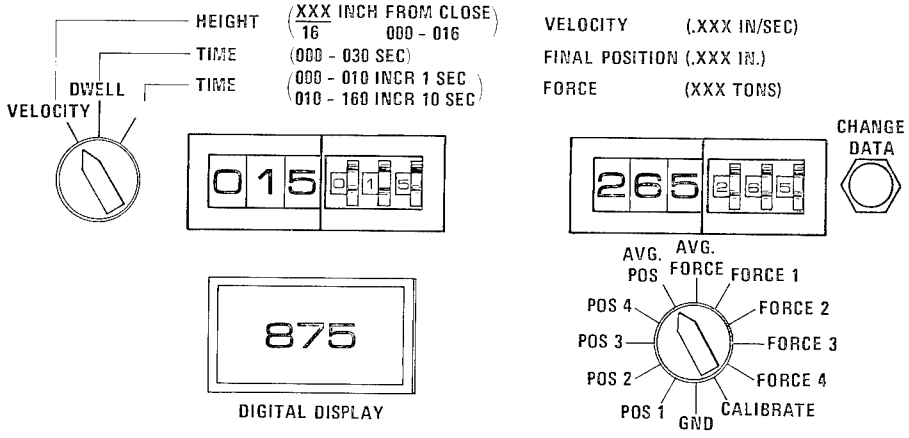
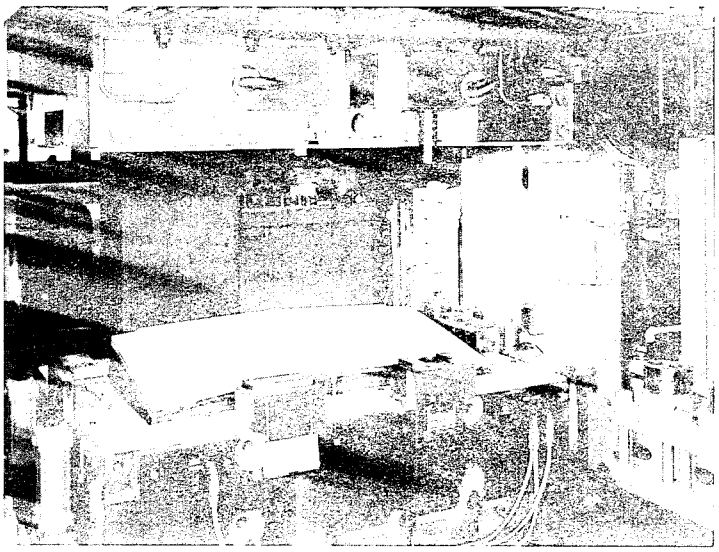


Figure 2 The desired velocity and force programs can be entered into the micro-processor through thumb wheel and selector switches in the control panel.



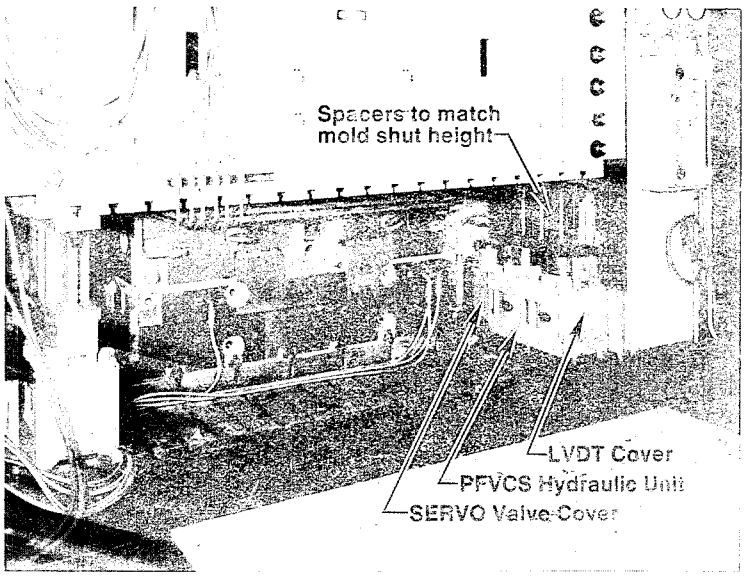


Figure 3 An 18 MN (2000 ton) has been equipped with the PFVCS. That press is shown open (top) and closed (bottom). Each PFVCS hydraulic unit includes the counterforce cylinders, LVDT, pressure transducer, servo valve, accumulator and filter.

```
POS.MM) "-X.XXX/SEC.
 25.0       7.5
  7.5       4.0
  4.5       2.0
  3.0       1.0
  1.0       0.5

X(RTN)X.XXX=   0.0
```

Figure 4 The velocity (shown) and force programs are entered through a teletype on the laboratory press.

```
      FOLLOWING DATA RECORDED  AT LAST PRESS STOP.
SECTIONS IF AVERAGE, A POSITION, SUM, A PRESSURES.

 25.4   25.4   25.7   25.2   25.5   267   64   37   53   61
 25.4   25.3   25.4   25.0   25.4   265   63   37   54   60
 21.4   21.4   21.7   21.2   21.5   260   57   30   34   53
 17.5   17.5   17.3   17.2   17.4   262   50   33   45   57
 13.4   13.5   14.0   13.3   13.7   273   44   33   39   57
  9.0    9.7   10.1    9.6   10.0   322   33   37   37   55
  6.9    6.5    7.2    6.7    7.1   210   33   37   32   56
  5.4    5.2    5.6    5.3    5.4   237   47   37   46   56
  4.2    4.2    4.2    4.1    4.2   314   77   32   68   76
  3.1    3.1    3.1    3.1    3.2   336   52   92   56   91
  2.6    2.6    2.6    2.6    2.6   474  125  100  117  110
  2.1    2.1    2.2    2.1    2.1   473  123  101  100   93
  1.4    1.4    1.5    1.5    1.4   359   82   96   85   97
  1.1    1.1    1.1    1.0    1.1   272   67   89   63   71
  0.8    0.7    0.8    0.8    0.8   260   55   83   51   69
  0.6    0.6    0.6    0.5    0.6   227   41   87   41   55
  0.4    0.4    0.5    0.3    0.4   214   34   87   35   56
  0.2    0.3    0.4    0.1    0.2   207   32   86   32   56

***** END OF VELOCITY CONTROL *****
```

Figure 5 Actual press performance is printed out through the teletype. Each line of print-out represents a one-half second time interval during the previous press closing cycle. The left hand column shows average ram position in millimeters. The next four columns show the positions of the individual corners. The sixth column is total tons of force resisting the downward motion of the ram, and the last four columns show how that force is distributed among the four corners.

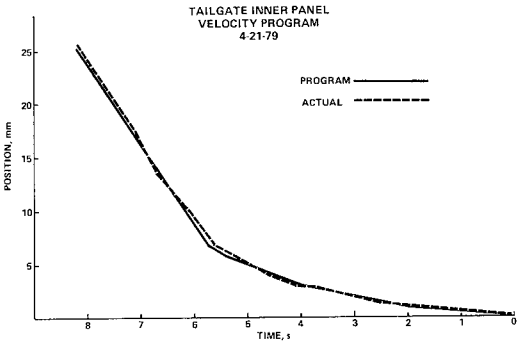


Figure 6 The desired velocity program shown in Figure 4 is compared graphically to the average actual performance (left column in Figure 5) to evaluate effectiveness of the control.

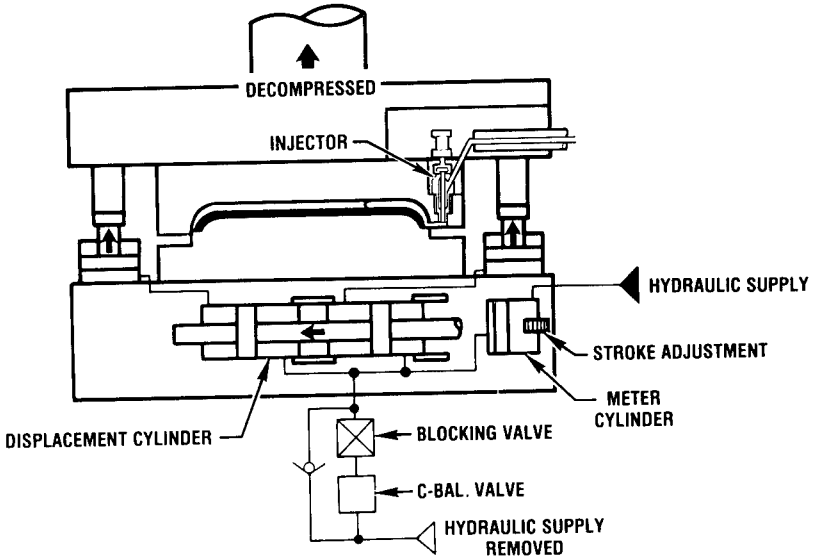


Figure 7 The "open-loop" parallelism control uses a tandem piston flow divider to insure equal displacement of the cylinders at the four corners of the press.

POSITION AND PARALLELISM CONTROL OF COMPRESSION MOLDING PRESSES

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INTRODUCTION

The first compression molding presses were, as you might expect, rather simple and at times quite crude. These were mostly presses that were originally designed for general shop use or other manufacturing processes.

The first presses specifically designed for FRP compression molding were carry-over designs from the rubber molding industry. These were straight side-plate presses which were actually quite rugged but inaccurate and fairly small. The side plate design had its limitations and was not readily adaptable to larger press sizes.

As part sizes became larger and accessibility from all sides of the press was needed, the open tierod construction (Figure #1) was the design most commonly used. Open rod presses served the FRP compression molding industry for many years and still are the most economical design for many small parts requiring less accuracy. However, as part accuracy became more important the relatively loose barrel guides and high tie rod side deflections could not meet the more rigid requirements. Many different adjustable guide designs were tried with the tierod presses but none were really very successful and the deflection problems of the tierods were always there.

To fulfill the next evolutionary step in compression molding, the era of the open housing press emerged and remains today (Figure #2). The stiff box section design of the housings greatly reduced side deflections and the adjustable guide systems that developed,closed guide running tolerances to a minimum.

Phenolic wear strips, combined with tapered guides which make close tolerance adjustments much easier, allow near zero guide clearances to be achieved. Single acting rams, those without piston rings, greatly reduce oil leakage and keep power consumption and maintainance to a minimum.

Automatic loading and unloading for compression molding presses is developing rapidly. Cycle time reduction, accurate and consistent workpiece positioning, and worker safety being some of the benefits realized.

Now we have arrived at what is a very important innovation to the modern compression molding press. This key is a simple, low-cost, position and parallelism control system for controlling the moving platen and mold during the molding and stripping operations.

The system accomplishes three main functions.

First, the capability to maintain parallelism between molds during molding and stripping. This will achieve uniform material distribution throughout the mold, promote a more controlled heat loss pattern from the mold surfaces, help create a more uniform glass fiber orientation, and lengthen mold shear edge life through simultaneous and flush edge contact. This will result in a consistent final thickness, a stronger part, and reduce the finishing cost to achieve Class A finishes.

The second main function of this system is the capability of initial mold stripping to an accurate and consistent open position for usage with an in-mold-coating injector system.

The third main function is final mold stripping.

DESCRIPTION OF SYSTEM (Figure #3)

The workhorses of the system are (4) simple single-acting cylinders. One is mounted at each corner of the press bottom platen and nested between the press uprights to allow complete access through the press from front to back. This is to facilitate maximum die size usage and full access area for either manual or automatic loading. These leveling cylinders have a one inch workable stroke and one eighth inch of extra stroke which is used to operate the protective overstroke device. Their standard capacity is 20% of full press tonnage. However, units of various capacities can be used to meet specific requirements.

A typical 2000 ton compression molding press would require a 400 ton parallelism system. These cylinders individually are rated at approximately double their stripping force when used during the parallelism control portion of the cycle. Therefore, each 100 ton cylinder could conceivably work at 200 tons to balance unequal moments created in the molds. Overpressure protection is provided should an unforeseeable accident happen and full tonnage be applied to only one leveling cylinder.

The heart of the system is a multi-ram control unit forming a simple yet unique hydraulic system without complicated electronic or hydraulic circuitry. Each leveling cylinder mounted in the press controls one of four slave cylinders at the control unit. Additionally, all (4) slave cylinders are mounted to act in unison and are controlled simultaneously by one larger control cylinder equal to slightly more than the combined forces of the (4) slave cylinders. The control cylinder exhausts through a preset relief valve.

A small tubing line connects each leveling cylinder with its respective slave cylinder. The oil volume in this closed circuit is kept to an absolute minimum because the accuracy of the entire parallelism control system is largely a direct function of the compressability of the volume of hydraulic oil in each closed circuit. Therefore, the smaller the volume of oil to be compressed, the smaller the out-of-parallelism error.

The conventional press side cylinders cannot be used to control an accurate position or maintain parallelism. The compressibility of these large volumes of oil creates an unacceptable accuracy.

Prior to press closing, all parallelism system cylinders are precharged to 3500 PSI. This allows the system to react immediately. The oil must be compressed to a point where great enough forces can develop in the leveling cylinders to straighten the moving platen. Without precharging, the delay required to compress the system oil would allow the upper mold to move into more of an out-of-parallel condition than it may have already. This is because material may already have started to distribute throughout the mold when the leveling cylinders are contacted.

Leveling forces will vary with the out-of-parallel condition of the press, the accuracy of mold line-up, and off center loads created by many conditions, some of which are non-symmetrical loading of workpiece, uneven material flow, non-symmetrical molds, etc.

In a hypothetical case, if the moving platen were parallel and no off-center loads were experienced, the press would push the (4) leveling cylinders downward equally and simultaneously at the predetermined pressing speed. The oil displaced from each leveling cylinder would, in turn, push its respective slave cylinder downward. All (4) slave cylinders would develop equal oil pressures and push the larger control cylinder downward, exhausting oil through the relief valve.

Practically, this usually will not happen. The moment-force diagram, (Figure #4) shows what happens realistically. Force P is the resultant press force and is the same regardless of the number of pressing rams used, M is the force on the mold, L_1 and L_2 are the respective forces of the leveling cylinders. Moment arm A_1 is the distance from the centroid of the mold off-center force to the center of the press. Moment arms A_2 are equal and are the distances from the center of the press to the leveling cylinders.

In this diagram the forces M and L_1 try to rotate the moving platen in a clockwise direction. Force L_2 acts in a counterclockwise direction. When off-center loads create a moment, the moving platen will try to rotate, in this case in a clockwise direction. As the moving platen lowers on the right hand side, the oil in the right hand leveling cylinders is compressed to a greater extent than the oil in the left hand leveling cylinders. Therefore, Force L_2 becomes greater than Force L_1.

Bear in mind that there is an equal volume of trapped oil between each leveling cylinder and its respective slave cylinder and that all the slave cylinders will move in unison against the larger control cylinder.

The platen will move out-of-parallel only the distance of the differential compresibility of the oil in the leveling cylinders. Oil is a very stiff medium, the bulk modulous being approximately 200,000, therefore the deflections are quite small. The system accuracy, as shown in Figure #5, depends on the size of the parallelism unit used in the press. Four (4) 8-1/2" leveling cylinders used on a 2000 Ton Press producing a 500 ton off-center load 12" from the center of the press, would maintain press platen parallelism within approximately .0009" per ft.

The ram areas of the leveling cylinders are 14.3 times the ram areas of the slave cylinders. (Figure #3) Therefore, to control the same volume of oil the control unit strokes 14.3 times the stroke of the leveling cylinders. This longer stroke, compared to the one inch stroke of the leveling cylinders, allows much more accurate stroke adjustment settings to be made.

The small-tonnage long-stroke combination forms a relatively compact unit which mounts neatly on one of the corner housings of the press.

An adjustable limiting device allows selection of the in-mold-coating opening distance from .010" to .200". This mechanism automatically locks-in at the end of the initial press down stroke and measures the opening distance from that position. With this feature, part thickness variations from cycle to cycle will not effect the opening distance for the in-mold-coating operation.

TYPICAL CYCLE

After the workpiece is loaded, the molding cycle is actuated and the press hold-up device is disengaged. The moving platen approaches at fast advance, then at a predetermined position slows to the intermediate speed. At this speed, low pressure intermediate tonnage can be programmed to initially distribute the material before the press slows to the final pressing speed.

Prior to this, the entire parallelism system was automatically purged of any air which may have developed in the oil. Additionally this removes the hot oil build-up that will occur in a trapped system.

As the press approaches the final close position, approximately 1/2" to 7/8" from the end of stroke, the press moving platen contacts the (4) leveling cylinders. (Figure #6) For clarity, only the (2) leveling cylinders and their respective slave cylinders are shown.

The press continues downward with the leveling system functioning continuously. When the press tonnage builds to a predetermined point, the parallism unit begins controlled decompression and the full preselected tonnage is applied to the molds. Therefore, the leveling tonnage does not detract from the main ram tonnage. Pressure is now held for part of the cure cycle.

Before opening for in-mold-coating, the parallelism system is purged of air again and the system is precharged with low pressure. With this readjustment feature, each leveling cylinder will contain a slightly different volume of oil. This is due to the small out-of-parallel condition that may have been created on initial close. This assures that the upper mold will strip and reclose in the same slight out-of-parallel position, if any was reached in the initial down position. Final reclose then is parallel to the top surface of the partially cured workpiece. This will allow a uniform distribution of the coating material, within the limits of the leveling device.

After initial stripping and injection of in-mold-coating, the press recloses,maintaining parallelism,while working against the leveling device and the workpiece. Again the leveling system begins controlled decompression and the full preselected tonnage is applied for the remainder of the cure cycle. At any time during the cure cycle, the press tonnage can be reduced and held for a portion or the remainder of the cure cycle. There has been some success using this method to reduce workpiece surface irregularities without in-mold-coating.

During final cure, the leveling system again purges itself of air and precharges at low pressure. After final cure, the press decompresses and the leveling system strips the molds parallel to any slight out-of-parallel condition that may exist. An important feature is that the high tonnage stripping is confined to these (4) short stroke cylinders, thus eliminating this function from the costly long stroke main cylinders of the press. Two small single acting cylinders return the press to the preselected up position where the hold-up locks are engaged and the part unloaded.

The position and parallelism control system is also manufactured as a completely separate unit which can be retrofitted to existing presses. This includes open tierod presses which will be revitalized by this system and become much more accurate and versatile for compression molding.

The unit can also be built in modules. If only a parallelism control is required, the in-mold-coating control hardware would not be part of the package. If only additional stripping force is required, the entire control unit hardware would not be used with the (4) press mounted cylinders.

It is recognized that this system may not be as accurate as a sophisticated electronic servo-controlled computer monitored package. But the intent is to furnish an uncomplicated, low cost system, sufficiently accurate for producing quality parts in a production environment.

ACKNOWLEDGEMENT

The concept of this Position & Parallelism Control Unit (Patent Pending) was developed by Myron Korytko, Group Chief Engineer of the Hydraulic Press Engineering Group at Erie Press Systems.

OPEN ROD PRESS

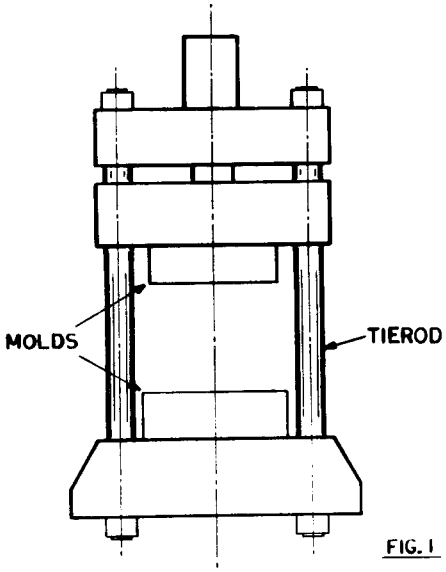


FIG. 1

OPEN HOUSING PRESS

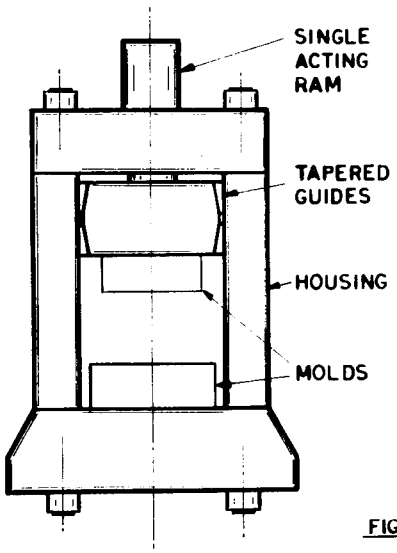


FIG. 2

POSITION & PARALLELISM CONTROL

PAT. PEND.

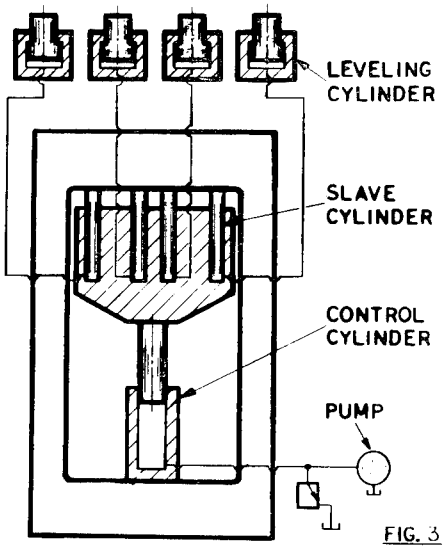


FIG. 3

SYSTEM ACCURACY

500 TONS LOADING 12 IN. OFF-CENTER
136 IN. L.-R. BETWEEN LEVELING CYLINDERS

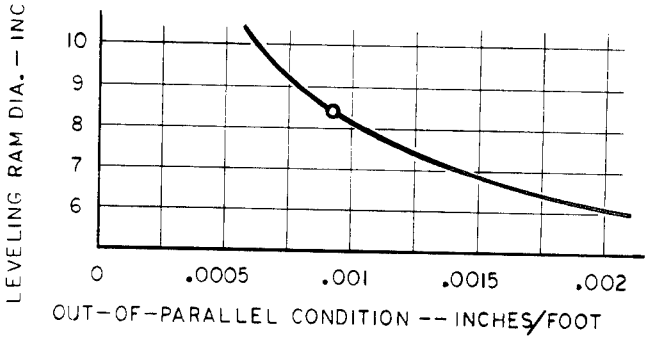
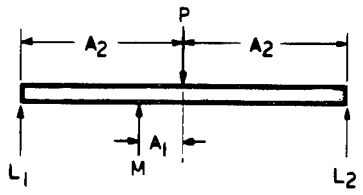


FIG. 5

MOMENT-FORCE DIAGRAM



$$L_2 = \frac{\left(\frac{MA_1}{A_2}\right) + P - M}{2}$$

$$L_1 = P - M - L_2$$

FIG. 4

SYSTEM AT PARTIAL STROKE

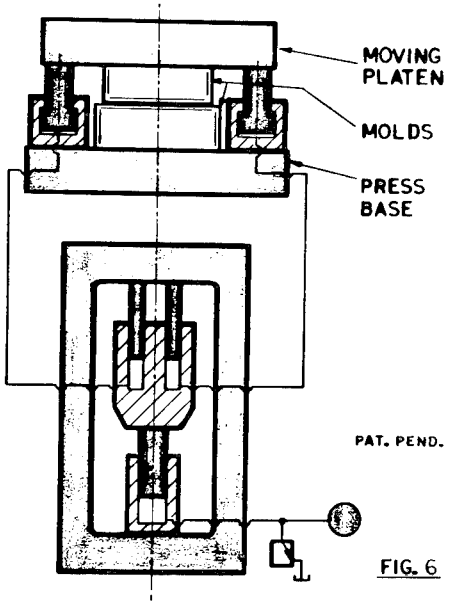


FIG. 6

RATIO CONTROL OF AUTOMOTIVE SMC WITH COLORIMETRICS

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Jack D. Relyea – Chevrolet-G.M.C.

Coatings and Resin Division
P.P.G. Industries, Inc.

Chevrolet-Flint Manufacturing Plant
General Motors Corporation

OVERVIEW

Chevrolet-Flint Manufacturing is relatively new in the SMC industry. The sheet forming operation and molding press line went into production in August of 1977. Chevrolet compounds and forms a 60" wide, 16 oz./sq. ft., 27.5% glass reinforced sheet. PPG Industries supplies the Selectron RS 50315 (Polyester low profile resin) and Selectron RS 59003 (Pigmented MgO Thickening Dispersion). Grille opening header panels for the Malibu Classic and the Monte Carlo lines, and a G-Van engine cover, were initially produced on the molding line. Since then, the lines have been expanded to include the Caprice header panel for 1979 and the Impala header panel for 1980.

One of Chevrolet's initial goals was to supply the press line with maturated material having a viscosity variance of ± 5 million centipoise. The current limits are established at 20 - 30MM centipoise measured at 72 hours. The resin system was designed to reach an ultimate viscosity plateau in approximately 48 hours. The 72-hour values of 20 - 30MM implies, therefore, ultimate viscosity.

Chevrolet and PPG recognized that these were extremely tight limits within which to work. The purpose was to avoid having to continuously adjust molding parameters at the press because of viscosity variations of the material. The objective of this paper is to describe a simple, but what we feel unique, technique now being used to help us maintain these limits.

In the first few months of the operation, we were experiencing occasional periods of "non-control" when we could not maintain the above mentioned parameters. It appeared that these variations were probably a result of one, or a combination, of the following conditions:

1.) Inability to accurately predict reactivity and/or final viscosity plateaus from Quality Control data of incoming materials.
2.) Contamination of raw materials in the bulk storage system (moisture, etc.).
3.) Loss of ratio control when combining the "A" paste (filled polyester resin) and the "B" paste (filled MgO thickening dispersion).
4.) Periodic variations in mechanically weighing the raw materials being supplied to the automatic mixers.

In reviewing the above possible causes, Items No. 1 and No. 3 were isolated as requiring further attention. Significant progress in both areas has resulted in the ability of Chevrolet and PPG to maintain maturated viscosity values within the original goal. This paper will deal only with Item No. 3, ratio control.

The design of the overall system (bulk storage of raw materials, automatic mixing and delivery), although excellent for the overall operation, presented unique problems which necessitated a more sophisticated monitoring process for ratio control. Primary concern was to detect changes in pumping efficiencies due to pump wear.

Visual observation of color differences of the paste at the doctor box was adequate for gross variations in the ratio but were not considered adequate to maintain the desired control. At PPG's suggestion, the evaluation of colorimetric instrumentation was undertaken in anticipation of the following benefits:

1.) Elimination of operator variability in judging color.
2.) Ability to quantify and document a specific color.
3.) Closer accuracy.

To elaborate briefly on the need for closer accuracy in ratio control, viscosity data and a color graph (Figure No. 1) on two typical shipments of "B" resin are shown:

BACKGROUND

We do not intend to deal with the theory of colorimetrics or its history of development. That information is available in reference publications such as R. S. Hunter's "The Measurement of Appearance." For our purposes, let's simply state that the instrumentation chosen has a light source of known energy at each wavelength of the visible spectrum. This source illuminates the sample to be measured. Colorance in the sample modifies the light and reflects it through filters to photodetectors which produce electric signals proportional to the light incident on them. By adjusting the filters, the instrument simulates a standard observer viewing the sample in daylight.

There are several distinct, but mathematically related, color coordinate systems currently in use to classify color. All systems require three numerical values to completely describe a specific color. The following systems are most commonly used:

1. XYZ (CIE)
2. L, a, b (Hunter-Square Root)
3. L, a, b (Glosser, et.al. - Cube Root)
4. L*, a*, b* (CIE)

The selection of the color system to use for a specific application can be very important. From the aforementioned coordinate systems, equations can be developed for the evaluation of color differences. Both the L,a,b and the L*,a*,b* coordinates are used unaltered in the common colored difference equations. Since the L,a,b coordinates can be read directly as the output of some of newer Hunter Labs instruments, that color coordinate system was chosen for convenience. In addition, some of the literature indicated that the L,a,b color system expanded the darker regions of the color space and provided better discrimination of the most saturated colors. We will thus comment only on the L,a,b system.

Figure No. 2 illustrates a color space utilizing the L,a,b axis. As noted on the space, the L axis discriminates between white and black; a perfect black would be 0 and a perfect white would 100. We determined early in the program that utilizing only L values produced sufficient information and accuracy for our purposes. So, within the L,a,b system, only the L value is documented.

SAMPLE PREPARATION TECHNIQUE

The procedure currently in use is a result of experimentation primarily intended to isolate the variables affecting accuracy and reproducibility. We do not wish to imply that we have isolated every variable, nor have we precisely quantified the effect of all those variables defined to date. For our purposes, the degree of control, at present, is more than adequate. The actual test procedure, including operation of equipment, is very simple and quick. It is possible to sample the doctor box and take the reading in less than three minutes. However, for extremely fine control purposes, we normally wait 10 minutes between sampling and reading. The instrument, a Hunter D 25-3 Colorimeter, is maintained in the SMC Laboratory in an adjacent room.

Preparation of samples requires the following supplies:

1.) 2 (4" x 5") photographically flat glass plates
2.) .00025" thick, spectrographic grade mylar film (primarily used to avoid cleaning the glass plates after each test)
3.) Two, .030" thick sections of shim stock
4.) Stop watch

The following series of slides will briefly illustrate the method of sample preparation. The sample is prepared by (1) placing a layer of mylar on one of the glass plates, (2) placing one of the shims at either end of the mylar, (3) pouring the sample onto the center of the mylar (at the controlled time), (4) placing a second layer of mylar over the sample, then (5) compacting the sample flat with the second glass plate. The shim stocks and glass plates serve to guarantee uniform thickness and flatness of each smple as well as preserving the sample from distortion during positioning. Since the technique is dependent on reflected light, the type of glass, cleaniness of the glass, type of transparent film, and elimination of air bubbles and wrinkles in the film are extremely important.

In addition to the technique variables, the process variables noted below were also closely examined:

1.) Variation in L values and/or tint strength between shipments of the "B" Resin
2.) Variation in L values of "B" Resin on a daily basis
3.) Variation of the paste color from batch to batch ("A" paste and "B" paste) caused by variation in percent of filler
4.) Variation of the past color caused by changing filler supplier
5.) Decreasing L value (darkening) of the combined pastes with time. (As the paste thickens, an observed darkening concurrently takes place, requiring close attention to time when preparing and reading samples.)
6.) Comparison of production-mixed samples with laboratory-mixed standards in relation to the phenomenon observed in No. 5 above. (The degree of accuracy can be verified by comparing viscosity growth rate of the laboratory standards with the production retain samples.)

RESULTS

The first step in the color analysis is to develop a color graph with which to work. By plotting L values as a function of ratio, linear relationships can be seen. A linear regression of these points will give the best approximation of the plots and establish a mathematical relationship; that is, the line slope (m) can be calculated. It is our hypothesis that there exists an optimum line slope which best represents this ratio to L value function. The position of the line on the graph may change (up or down), but the slope will remain constant. One note here should be that, within the limits of this study, all of the functions generated appeared and computed linear. No effort was made to identify the nature of the function outside of the 13:1 to 16:1 operating parameters.

In this investigation, a total of 14 color graphs were generated over the course of several months. The purpose was to verify the procedure's reliability across several lots of RS 59003. Figure No. 3 shows the graphic results of representative color graphs. As already noted, these graphs resulted from plotting L values as a function of A:B ratio. Ratios of 13:1 to 16:1, which bracket the Chevrolet operating limits, were used. Table II lists these values. Through the linear regression, slope values were assigned to each group.

In reviewing the slopes, one can detect some degree of parallelism between the lines. This supports our original hypothesis that the lines will be parallel, only the graph positions change. Reasons for this position change stem from slight variations in the approximate 9% carbon black loading and/or differential tint strength between lots of pigment itself. In addition, a supplemental investigation revealed that the calcium carbonate filler also exhibits slight differential "pigmenting" power between lots.

The task, at this point, was to develop the most optimum slope function which best represented the ratio-to-L value relationship exhibited throughout this study. Again, utilizing the linear regression, the resulting slope (m) was 0.797, which we will use throughout the remainder of this paper as our baseline function (Figure No. 4).

The question of reproducability of L values was raised; in addition, the effect of any L variation on ratio control was questioned. By reviewing the long term Chevrolet production data, it shows that 85.4% of the time the L value varied, during the course of the daily checks, no more than 0.50 at a fixed pump setting (see Table III). A variance of no more than 0.35 could be expected 51.2% of the time. By transposing the L value ranges onto the baseline function, the expected error factor for 0.50 and 0.35 would be ± 0.31 and ± 0.22 of a ratio (see Figure No. 5). A supplemental note here is that it has been our experience that, with efficient pumps and a refined testing technique, we have observed periods of L value variances of as little as 0.20 throughout the course of several production runs. This, of course, could increase the ratio monitoring reliability by decreasing the error factor down to ± 0.13 ratio unit.

The true purpose of this study was to determine whether we could control the SMC ratio, and thus the three day maturated viscosity, with colorimetric analysis. The review of thickening data, as already noted, shows that a full ratio spread in the operating range (e.g., 14.0 ± 0.5:1) will still place Chevrolet within the desired molding viscosity window. By translating this full ratio back onto our optimized function (Figure No. 6), we can see that the L value variation tolerance is 0.80. Referring again to Table III, one can see that we can achieve variations of 0.80 and below 95.1% of the time. Thus one could conclude that colorimetric analysis can, in fact, both monitor the specific ratio and also maintain the SMC compound within molding parameters.

UTILIZATION OF COLORIMETRICS

Should other compounders adapt this technique for similar applications? It will depend on three factors:

1.) Do you desire to control your ultimate viscosity ranges within tighter limits than currently possible?
2.) Is the cause of variation the result of non-control of ratios?
3.) Is the technique adaptable for your individual situation or resin system?

Controlling the ratio in our system is not the final answer; it is only one variable which must be monitored and adjusted as the circumstances require. The resin system was designed for 100 pphr of "A" resin to 9.4 pphr of "B" resin. A variation in the amount of magnesium oxide in the "B" resin will change the level of reactivity and thus change the above mentioned relationship. In response, PPG has developed a magnesium oxide titration technique for the "B" resin. As a result, Chevrolet's ability to periodically make the analysis, and transform the data to a specific ration of "A" paste to "B" paste, is the key to the degree of control achieved to date.

Once we had an accurate procedure for measuring the ratio at the doctor box, analysis of that data was unbelievably revealing. Three specific examples of the importance of the data follow (see Figure No. 7):

1.) A gradual, but significant, drifting of the color from day to day, which required continual readjustment of the ratio to maintain a specific color. This did not occur when pumps were new. As the pumps wore and pumping efficiencies changed, the drifting phenomenon began, eventually requiring pump replacement. Without colorimetrics, we were puzzled by gradually increasing or decreasing 72-hour viscosity variations.
2.) When worn pumps were replaced, a dramatic shift in color was immediately observed, resulting from the change in pumping efficiency. Lab personnel are now able to adjust and match our previously established L value within 20 minutes of a pump change.
3.) In shifting production from one shipment of "B" resin to another (once per month), if an adjustment is required because of a significant change in predicted viscosity growth, the adjustment can be made immediately.

ACKNOWLEDGMENTS

In closing, we would like to indicate that the co-authorship of this paper by Chevrolet-Flint Manufacturing and PPG Industries—Coatings and Resin Division should not be viewed as a mutual endorsement of PPG's resin system or Chevrolet's process. It should, however, be viewed as the type of cooperation required in solving problems which affect both customer and supplier.

We would like to acknowledge the assistance of Mr. Paul Ranville and Miss Vicki Gilbert, chemists at Chevrolet-Flint Manufacturing, and Mr. William D'Alessandro and others of PPG's Molding Technical Center and PPG's Color Laboratory. The work and data supplied by these people made this presentation possible.

Neither PPG Industries nor General Motors Corporation warrants the use of any information on materials or processes contained in this paper. Nor does PPG or GM warrant freedom from patent infringement in the use of any such information.

BIOGRAPHY

RICHARD B. JONES

Mr. Jones received his B.S. degree from Allegheny College. He joined the Coatings and Resin Division of PPG Industries, Inc. in 1977 and is currently a Technical Representative for the Automotive Molding Resins group. His responsibilities include both market and technical development for thermoset polyester molding.

JACK D. RELYEA

Mr. Relyea received a B.S. degree in Metallurgical Engineering from Michigan Technological University in 1964. He has been employed at Chevrolet-Flint Mfg. since graduation and is currently serving as General Supervisor of the Chemical and Metallurgical Laboratories at that facility. Current responsibilities include the Sheet Molding Compounding quality control laboratory.

Table I

Laboratory Ratio (A/B)	24 Hour Viscosity #1	24 Hour Viscosity #2	72 Hour Viscosity #1	72 Hour Viscosity #2
13/1	29.6 - 75°*	43.0 - 80°	45.8 - 72°	60.8 - 78°
14/1	20.8 - 75°	31.7 - 80° (14.5)	28.2 - 72°	48.4 - 77°
15/1	12.8 - 76°	24.0 - 80°	19.8 - 72° (15.5)	31.2 - 77°
16/1	8 - 77°	17.1 - 80°	15.4 - 72°	22.7 - 77°

*NOTE: Viscosity data is in million centipoise and temperature in degrees Fahrenheit. Brookfield HBT viscometer, TF Spindle at 1 RPM.

In reviewing this and other supportive data, several points should be noted:

1.) We are confident that 72-hour data is representative of final growth in the system.
2.) Utilization of 24-hour data by itself does not provide sufficient information to predict final viscosities. The rate of thickening, as well as the ultimate viscosity, can vary.
3.) To maintain final viscosity value of 20 - 30MM, we feel it is necessary to maintain a ratio control of ± .5 units.
4.) In the example, a ratio adjustment from 14.5/1 for Shipment No. 1 to 15.1 for Shipment No. 2 is required.
5.) The "Color Graph" (Figure No. 1) reveals the straight line relationship for each of the example shipments when the L value of the color is plotted for the laboratory-mixed ratios. Shipment No. 1 (14.5/1 Ratio) was set at an L value of 26.25. Shipment No. 2, adjusted to a 15.5/1 ratio to maintain the 25MM ± 5MM viscostiy, should have an L value reading of approximately 27.65.
6.) The ability to predict final 72-hour viscosities at the time of compounding is essential.

TABLE II

Series No.	Ratio 13:1	Ratio 14:1	Ratio 15:1	Ratio 16:1	Slope (m)
1	25.47	26.30	26.98	27.73	0.777
2	25.38	26.20	26.97	27.65	0.773
3	25.48	26.35	27.12	27.97	0.816
4	25.24	26.13	26.87	27.61	0.787
5	25.10	25.88	26.56	27.27	0.730
6	24.96	25.78	26.71	27.34	0.783
7	24.36	25.19	25.84	26.68	0.779
8	25.68	26.45	27.21	28.01	0.775
9	24.64	25.45	26.14	27.01	0.780
10	25.14	25.81	26.66	27.43	0.772
11	25.14	26.00	26.59	27.52	0.811
12	25.61	26.39	27.15	27.85	0.748
13	24.73	25.49	26.25	27.01	0.760
14	25.88	26.67	27.46	28.24	0.787
Composite Baseline Function	25.19	25.98	26.78	27.58	0.797

TABLE III

"L" Value Variance	% Frequency
Less than 0.25	34.2
Less than 0.30	43.9
Less than 0.35	51.2
Less than 0.40	66.0
Less than 0.45	73.2
Less than 0.50	85.4
Less than 0.80	95.1

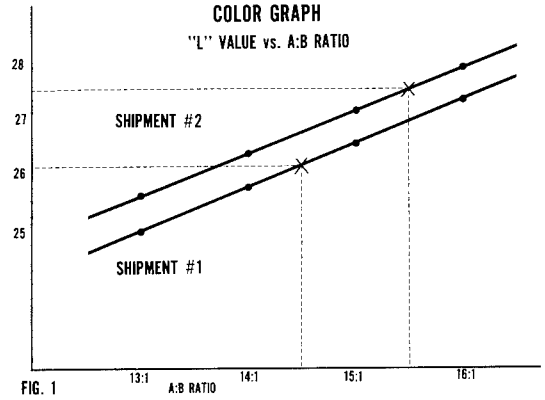

FIG. 1

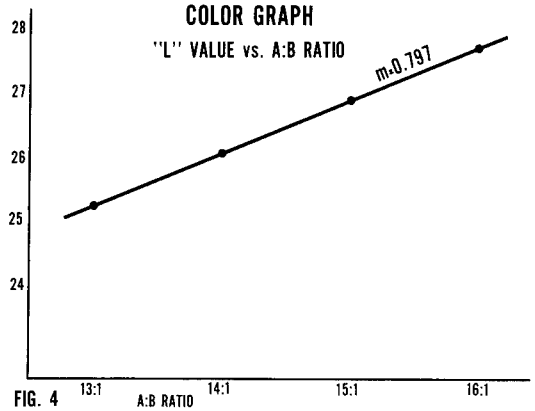

FIG. 4

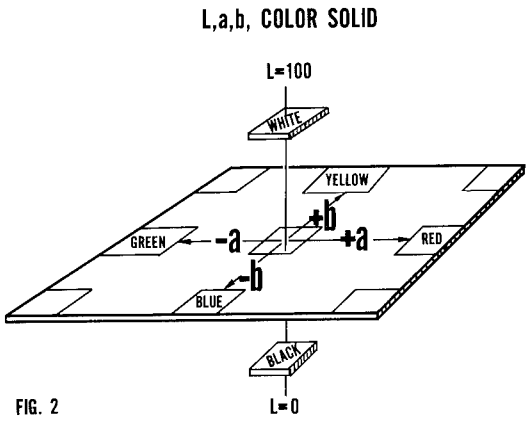

FIG. 2

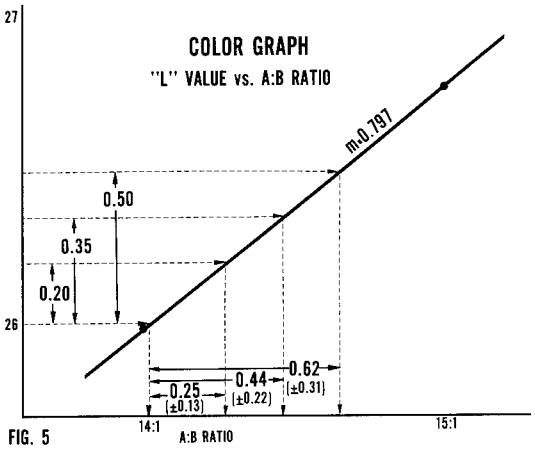

FIG. 5

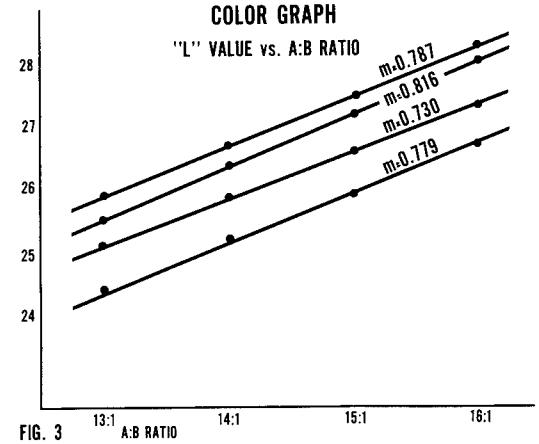

FIG. 3

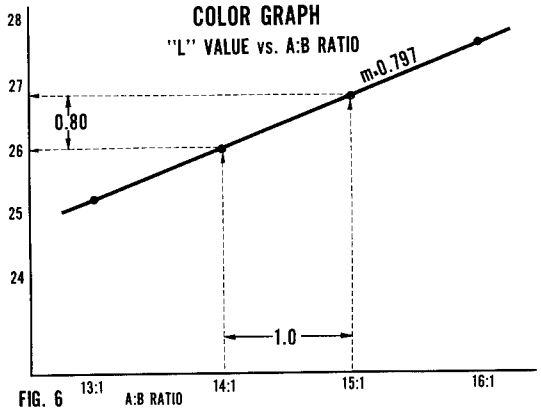

FIG. 6

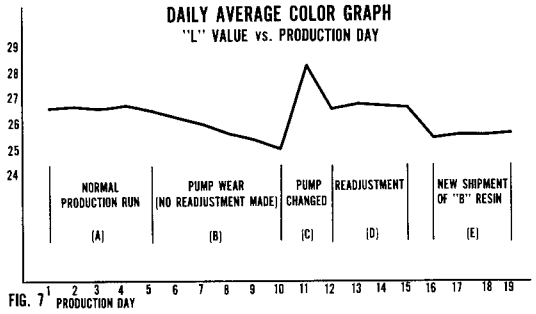

FIG. 7

NEW IN-MOLD COATING COMPOSITIONS FOR AUTOMOTIVE USE

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INTRODUCTION

Federal regulations to improve present gas mileage to 27.5 miles per gallon, for the average U.S. car by 1985, were the main driving forces for the automobile companies to select low profile sheet molding compounds (SMC) as replacement for steel in exterior class A type surfaces. SMC offers many advantages over steel and other plastics because of its weight, cost, design versatility, and strength to weight ratios.

The advent of in-mold coatings is further expected to aid in the break-through of the low profile SMC systems for exterior automotive applications.

Advantages of in-mold coatings over conventional primers have been discussed previously (1) at the 1977 SPI Conference; and the mechanics of molded coatings were presented in detail by Robert Ongena (2) at the 1978 SPI Conference.

Conventional in-mold coatings are typically two-component systems containing a urethane prepolymer which has to be mixed with a pigmented saturated polyester/polyol blend in exact ratios. Curing is achieved by heat and pressure, and the urethane reactions and vinyl polymerization occur simultaneously. Typical curing cycles are 1-2 minutes at 150°C at 400-1000 PSI. Drawbacks of the two-component systems are high equipment cost, elimination of all moisture, short pot life, adherance to exact mixing ratios and potential clogging of lines carrying the viscous prepolymer.

REQUIREMENTS OF IN-MOLD COATINGS

Successful in-mold coatings have to overcome the mold release properties of the cured SMC part (which may contain up to 5% zinc stearate), and have to be formulated with sufficient lubricant to release from the mold without sticking. The primed SMC part has to withstand standard curing cycles of conventional topcoat enamels and lacquers and provide adhesion for them. Adhesion, therefore, is one of the prime properties of in-mold coatings.

Furthermore, molded coatings should show minimal shrinkage upon curing in order to help fill sink marks and overcome other defects of the SMC part.

ICI has developed a series of one-component, in-mold coatings, which eliminate the need for extensive metering equipment. The one-component systems:

- Simplify equipment needs and eliminate the need for complicated and precise mixing which dramatically reduce cost.
- Have excellent pot life and have cure rates in the 30 to 60 second range.
- Have excellent adhesion properties and can be formulated to provide a variety of film hardness.

DEVELOPMENT OF ONE-COMPONENT IN-MOLD COATINGS

In the early stages of our development program, we looked at many available styrene solutions of polyesters based on various glycols, isophthalic, terephthalic, and fumaric acid or maleic anhydride and found them to be unsatisfactory because of lack of adhesion and brittleness.

Addition of more flexible comonomers to the styrene polyester blends such as 1.6-hexanediol diacrylate or 2-ethyl hexyl acrylate resulted in improved flexibility, but did not help solve the adhesion problem. Conventional silane adhesion promoters also proved to be unsuccessful in this regard.

Conventional two-component in-mold coatings have good adhesion mainly due to the fact that free NCO groups can react with residual functional groups of the cured SMC part. If free isocyanate groups remain after the one minute curing cycle, they will react with the atmospheric moisture and can cause embrittlement of the primer.

CHEMISTRY OF RESINS FOR ONE-COMPONENT IN-MOLD COATINGS

ICI development work concentrated on patented vinyl maleate urethanes (VMU) to achieve coatings from hard to flexible and rubbery.

A typical structure of a VMU resin is shown in Figure 1. As you can see, these resins are typically derived from one mole of maleic anhydride and 2 moles of a bisphenol A polyether; this diol is then reacted with 2 mols of a polyisocyanate as, for example, TDI and the resulting prepolymer is then end-capped with 2 moles of a hydroxy alkyl acrylate. The resulting resins thus have 3 reactive double bonds -- 2 terminal vinyl groups and 1 maleic double bond in the center of the molecule. They are highly reactive with monomers such as styrene,as well as with a variety of acrylate type monomers.

Resins where X ranges from 1 to 8 moles have been evaluated. Those based on 2 to 6 moles of propylene oxide per mole of bisphenol A were found to give coatings with the best overall properties. Higher PO resins tend to be very flexible and too thermoplastic. Further modifications of the basic resin structure by choice of diol, isocyanate, alkylene oxide or hydroxy ester, based on acrylic or methacrylic acid, are possible but have not been studied in detail. Coating properties can also be changed if part of the styrene is replaced by other monomers, or by the amount of total monomer present.

COATING SUBSTRATES

Most of our coating work has been done with low profile SMC systems containing a thermoplastic acrylic polymer as the low shrink additive. The SMC typically contains 30% glass, 30% resin and 40% calcium carbonate as filler. Other commercially available SMC systems including several of ICI's filled ITP SMC formulations were briefly investigated as substrates for in-mold coatings.

RESIN VARIATIONS

The first of a series of one-component in-mold coatings based on vinyl maleate urethanes, identified as XPL-5039, is made from maleic anhydride and 2 moles of propoxylated bisphenol A (BPA) containing between 2-8 moles of propylene oxide per mole of BPA. The other building blocks are TDI and 2-hydroxy ethyl acrylate. The sole monomer is styrene.

A second system, XPL-5039a, will be discussed where part of the styrene is replaced by trimethylolpropane triacrylate. A third very rigid coating, XPL-5039b, is based on BPA reacted with only 2 moles of propylene oxide. The last material evaluated, XPL-5039c, has terminal methacrylate instead of acrylate groups.

The coatings contain pigments and fillers to simulate the grey color of steel. Standard initiators, inhibitors and dispersion techniques were used to prepare the coatings.

Typical cure conditions were 2 minutes at 150°C and 600 PSI for the SMC part to ensure satisfactory cure in the thick parts of bosses and ribs of the SMC part. The coatings were used under the same conditions of pressure and temperature for a time of 60 seconds or less. A representative tabulation of the formulations described is shown in Table 1.

COATING EQUIPMENT AND COATING PROPERTIES

All initial development work was done using a conventional flat compression mold. After the curing cycle for the SMC part, the mold was opened and the catalyzed coating applied manually. Figure 2 shows a more complex part, a telephone box, uncoated. Upon manual application of the coating to the top of the cured SMC part, the coating shows excellent flow and coverage as shown in Figure 3.

The telephone box is a much more complex part to mold in comparison to a flat panel or a slightly curved panel due to the 90 degree flow angles at the sides and the sharp edges of the protruding nipple areas.

Figure 4 is a close-up of the nipple areas. Please note the excellent coverage around the sharp edges of the nipples.

Figure 5 demonstrates the excellent adhesion as measured by the cross-hatch test of a coating based on one of the ICI formulations described.

Figure 6 shows XPL-5039 partially topcoated with a two-component acrylic red lacquer. Figure 7 shows a close-up of the good adhesion of both finishes to the SMC part.

A green acrylic lacquer was used to partially topcoat the telephone box of the next slide (Figure 8). A close-up (Figure 9) shows the excellent adhesion of the total coating system, using XPL-5039a as the in-mold coating.

Table 2 summarizes the cross-hatch adhesion tests initially, after exposure to water and humidity and after topcoating. The standard XPL-5039 has excellent adhesion all the way through. XPL-5039c having methacrylate end groups also performs well. XPL-5039a containing trimethylolpropane triacrylate lost some adhesion after the water exposure.

XPL-5039b is the resin with the highest cross-link density and also has the poorest adhesion. Work is continuing on this product in order to improve adhesion while maintaining the excellent hot strength.

The next slide (Figure 10) shows 3 panels of XPL-5039 after the Gravelometer test performed at -18°C. The test was done according to SAE J400. The Gravelometer results for all the experimental coatings are summarized on Table 4. Surprisingly even XPL-5039b based on BPA, reacted with only 2 moles of propylene oxide, performed well in this test.

Coatings exposed at our Delaware test fence show no loss of adhesion or color change after 6 months with only minimal reduction of gloss.

Generally, coatings have shown excellent can stability at RT and 50°C. Catalyzed samples were molded after 8 weeks aging at room temperature without loss of activity or loss in properties.

Although our in-mold coatings are based on urethane chemistry, the final compositions are free of unreacted isocyanates and are safe to handle.

SUMMARY

We have developed and patented one-component in-mold coating systems, which eliminate the need for elaborate metering equipment and the drawbacks associated with two-component systems containing free isocyanate groups, and the coatings are now under extensive market development.

Because of the patent coverage and the many variations possible, ICI can cooperatively work with potential customers to tailor special systems where necessary.

DR. JOSEPH FELTZIN

Dr. Joseph Feltzin is Development Manager of Polymer New Product Development for ICI Americas Inc. Dr. Feltzin holds B.A. and M.A. degrees from Brooklyn College and received his Ph.D. in organic chemistry from Polytechnic Institute of Brooklyn. He joined the company in 1965 as Development Supervisor for New Polymer Products, and was promoted to his present position the following year. Dr. Feltzin is a member of the American Chemical Society, the Chemical Society of London, the New York Academy of Sciences, and Sigma Xi. He holds twenty patents and has several pending in the polymers field.

MR. ERICH KUEHN

Erich Kuehn is a Senior Research Chemist in the New Product Development Department of ICI Americas Inc. His responsibilities presently include development in the areas of in-mold coatings and ITP resin systems. He also has done work in new resin synthesis and fire retardant unsaturated resin systems. He holds twenty eight U.S. patents in the polymer field. He holds a M.S. degree in polymer and paint chemistry from the Fachhochschule Niederrhein, Krefeld, Germany and he is a member of the ACS.

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(2) "The Mechanics of Molded Coatings for Compression Molded Reinforced Plastic Parts" by Robert Ongena. 33rd Annual Technical Conference, 1978. Reinforced Plastics/Composites Institute. The Society of the Plastics Industry, Inc.

TABLE 1

XPL-5039 FORMULATION

VMU Acrylate Solution	47.12
Rubber Additive	7.00
Pigment Wetting Agent	0.20
Inhibitor Solution	0.38
Release Agent	0.75
Pigment/Filler	21.00
Styrene	23.55
	100.00
Initiator	2.00
	102.00

TABLE 2

ASTM D3359-74
CROSS-HATCH ADHESION

	XPL-5039	XPL-5039a	XPL-5039b	XPL-5039c
Initial	5	5	0	5
After TM 55-3 (96 hrs.,100% RH, 100°F)	5	5	1	5
After TM 55-12 (2 hrs., 100°F)	5	2	2	5
After Red Enamel	5	5	2	5
After Green Lacquer	5	5	2	5

1 - Poorest
5 - Best

TABLE 3

STABILITY OF XPL-5039

	VISCOSITY, CPS, RT
Initial	2078
1 Month	1934
4 Months	1950
9 Months	2268

TABLE 4

GRAVELOMETER, SAE J400 AT -18°C

XPL #		RATING
5039, Specimen	1	9 Good+
	2	8 Good
	3	9 Good+
5039a, Specimen	1	9 Good+
	2	7 Good-
	3	8 Good
5039b, Specimen	1	5 Fair
	2	8 Good
	3	7 Good-
5039c, Specimen	1	9 Good+
	2	6 Fair+
	3	9 Good+

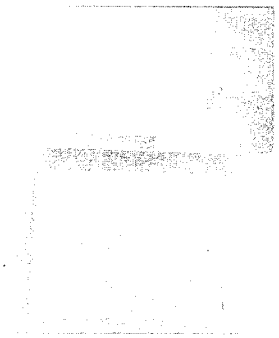


Figure 2: T-Box, Uncoated

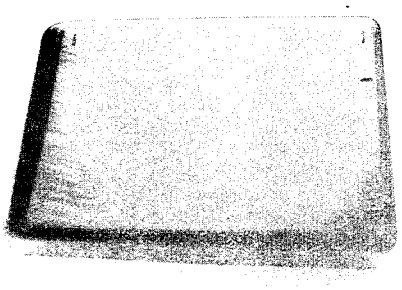


Figure 3: T-Box, Coated With XPL-5039c

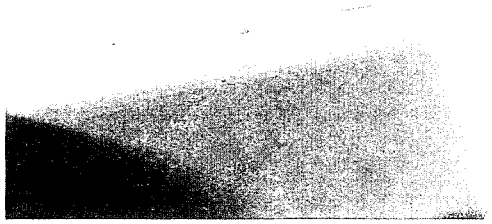
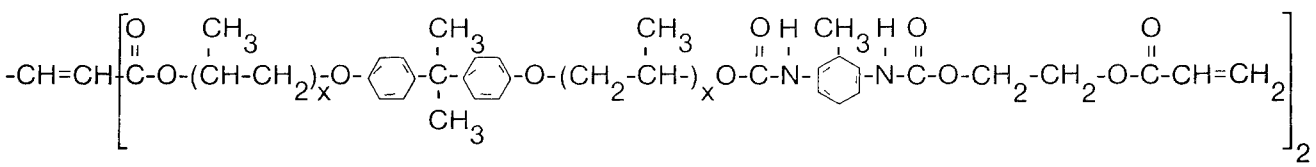


Figure 4: T-Box, Coated With XPL-5039, Nipple Area, Close Up



X = 2 - 8

FIG. 1

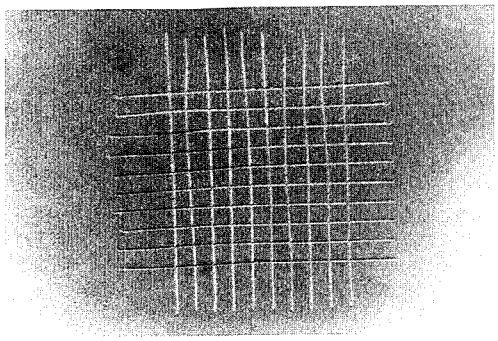


Figure 5: T-Box Coated With XPL-5039, ASTM D3359-74, Close Up

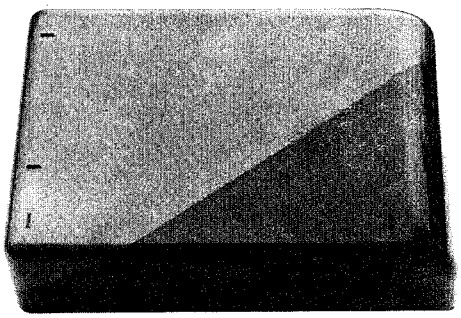


Figure 8: T-Box Coated With XPL-5039a Plus Green Acrylic Lacquer

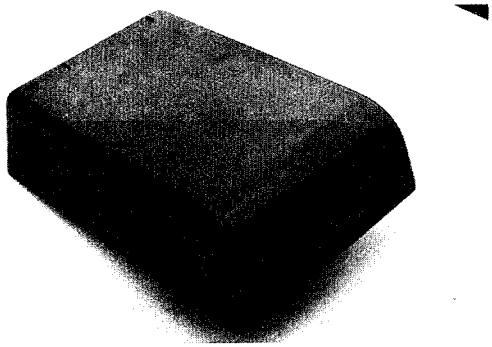


Figure 6: T-Box, Coated With XPL-5039 Plus Red 2-Component Red Enamel

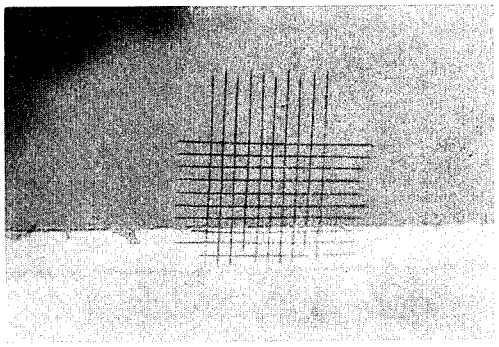


Figure 9: T-Box Coated With XPL-5039a Plus Green Acrylic Lacquer, ASTM D 3359-74 Close Up

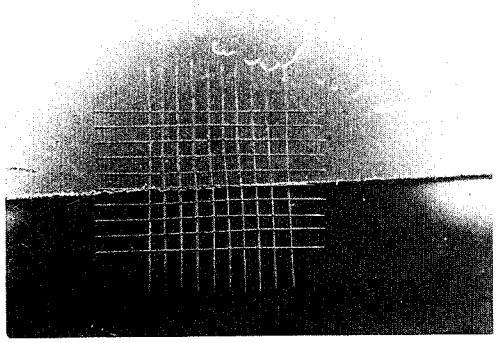


Figure 7: T-Box Coated With XPL-5039, Plus Red 2-Component Red Enamel, ASTM D3359-74 Close Up

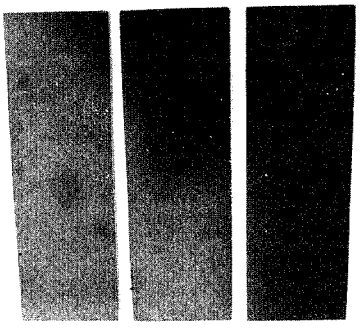


Figure 10: Panels coated with XPL-5039 after Gravelometer Test SAE J-400 at -18°C.

METALLOPLASTICS—A CONCEPT FOR CONDUCTIVITY

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INTRODUCTION

If the auto industry is to be able to take advantage of the light weight and unique physical properties of plastics in designing the cars of the 1980's, it must find ways of giving the plastics some of the qualitites of metals that have made the high production rates feasible. Furthermore, if the auto of the 80's is to include the many electronic controls required for high efficiency and improved safety, those same plastics must incorporate the ability to shield against stray electromagnetic radiation that will be increasingly pervasive with time. Finally, if all of this is to be feasible, it must be accomplished at low cost or the role of plastics won't meet those rosy projections we have been seeing. Metalloplastics offer one route to these goals.

Metalloplastics are the product of a new concept in plastic formulation that appears to offer plastics many of the desirable characteristics that the auto designer has long looked toward metal to supply. Metalloplastics give greatly increased electrical conductivity so that they may be electrostatically painted. The plastic never builds up a static charge, and the plastic will form an EMI shield around electronic controls or ignition noise sources so as to protect sensitive electronic circuits.

Perhaps even more important, Metalloplastics have a greatly improved thermal conductivity (of the order of that of glass or ceramics) so that the entire production cycle may be modified to take advantage of the fact that heat can be introduced and withdrawn an order of magnitude faster than ever before. Besides shortening the production cycle, this may make it possible to eliminate sink marks at bosses and incorporate a wider range of thickness within the same part since heat transfer is no longer the limiting phenomenon.

Metalloplastics are formed by adding low concentrations of fine metallic fibers to plastics - a concept which can theoretically be applied to all plastics and all types of plastic processing. We have worked with pure aluminum fibers and aluminum coated glass fibers about 1 mil in diameter. Our work to date has been limited to a fairly narrow range of applications because of some practical plastic processing problems. These problems can be overcome in time if the auto industry is as enthusiastic about the potential as we are. I will show you the work we have done and how we see it being extended.

The key to our optimism is that these startling effects are being produced in plastics with concentrations as low as 5 to 10 percent by weight of a low cost, metalized fiber. In the course of my talk I will show you rationale which says that even these concentrations may be reduced by factors of two to five. These low concentrations greatly simplify the incorporation of the fiber and result in the minimum modification of the plastics normal physical properties. The addition of colors, foaming agents or other plastic modifiers is not limited by the fibers, so the full range of plastic capabilities are maintained.

Because the fibers are now in production in quantities of several million pounds per year (MBAssociates has the Free World's largest integrated facility for producing radar chaff located in Lillington, North Carolina. With small variations in the producing technique, MBA produces chopped and continuous roving types of metalized fibers under the trademark Metafil.), there is no need for the construction of additional expensive production facilities or the uncertainties of waiting for a production line to get into operation before the concept can be applied. The key components of aluminum and glass are readily available in extremely large quantities, so promise a stable long-term supply of fibers.

THE THEORY OF METALLOPLASTICS - IMPORTANCE OF FIBER SHAPE

The basic concept that led to the creation of Metalloplastics is that extremely small concentrations of additives can make plastics conductive if they are in the form of conductive fibers with length to diameter (L/D) ratios of 100 or more.

In the past, conductivity had always been obtained by the addition of chunky fragments of copper or silver - or if only thermal conductivity was sought, even sand particles. The results were always the same - it required a weight percentage of 60 - 80 percent and a volume percent loading of 40 to 50 percent for significant effects.

The striking difference between the use of chunky fragments and fibrous materials in their effect on conductivity can be seen from the diagram in Figure 1. If one loads a plastic with 5 percent by volume chunky fragments (shown as spheres for convenience), a random distribution of the spheres leads to variable gaps between the spheres, but for 6 mil spheres there will be, on the average, a 6 mil gap to the nearest sphere. Thus, heat or electrons flowing through such a matrix cross alternate paths of about equal lengths in the two media.

If one takes the same 5 percent of material and disperses it as 1 mil diameter fibers which are 100 mils long, the picture is quite different. Even if the fibers were all arranged parallel to one another and at an even spacing, they would be only 3 mils apart. When they are allowed to take random orientations, it becomes inevitable that they will touch one or more of their nearest neighbors, as shown in Figure 1. This provides an almost continuous path through the composite along the highly conductive fibers.

Thus, simple intuition tells us that fibers will be much more effective in lowering the electrical resistivity of plastic and increasing the thermal conductivity than are chunky fragments.

ELECTRICAL CONDUCTIVITY

Our intuition also tells us that the effects of low concentrations of fibers on these two properties will be quite different. Whereas thermal conductivity will be increased by such low concentrations of the fibers that one fiber does not touch its neighbors, the electrical resistivity won't be significantly modified until an almost continuous path is available through the conductive fibers.

This was very clearly demonstrated with chunky fragments in 1966 by J. Garland[1]. His experimental data of electrical resistivity of Bakelite as a function of the volume percent of silver particles added is shown in Figure 2. It shows that the resistivity changes very little until the silver particle loading approaches a critical concentration - then it drops catastrophically and the composite becomes a good conductor.

Since Garland suspected the critical concentration was that associated with forming continuous chains of particles in the matrix, he devised an ingenious technique of measuring the average number of contacts each silver particle had with those around it. This data is indicated on the curve. From chain forming theory, one knows that the larger the average number of contacts, the longer the chains. Finally, when the average number of contacts approaches two (2), the entire particle population is interconnected in one long chain.

As Garland's data shows, the critical concentration does occur in that narrow concentration region between the formation of significant chain lengths (m = 1.26) and one continuous chain (m = 2.0).

When one uses fibers instead of chunky particles, the shape of the curve remains the same but chain building starts at much lower concentrations. We have been able to confirm experimentally that the critical concentration falls as a function of L/D, as in Figure 3, so that at L/D of 1000, the critical concentration is 2 percent or less.

The breadth of the curve indicates the estimated experimental uncertainty, since the L/D's are estimated average from a distribution of fiber lengths. The Battelle data indicates somewhat lower critical concentrations than our work. This may mean that the Battelle distributions were more uniform than ours.

Thus, the theory and experiment confirm that to get good conductivity (low resistivity) at very low concentrations of fibers, one should use the maximum L/D feasible for the manufacturing process.

The other puzzling aspect regarding making plastics electrically conductive with fibers is how the fibers make metal to metal contact in the plastic matrix. One would initially suppose that there would always be a plastic film between the fibers serving as an insulating layer. As a matter of fact, this is probably true when the plastic wets the fiber well and there are only low forces between fibers. Even above the critical concentration, it has been observed that the resistance drops markedly if the measurement voltage is greater than ten volts, implying a breakdown voltage is being observed. To lower this interface effect, some users have added small amounts of carbon powder. MBAssociates has developed a process (Cross-Link™), which avoids the use of any additives and still produces a very marked reduction in resistivity as shown in Figure 4 over that observed with simple mixing. This Figure shows the effect of increased concentrations in lowering the resistivity for two fiber lengths and the low concentrations required if the Cross-Link process is used. Note that resistivities as low as 0.01 ohm cm can be obtained which will be important for EMI shielding applications.

THERMAL CONDUCTIVITY

The thermal conductivity of a composite of high conductivity fibers in plastics can be accurately estimated by the equation of Nielson[2] as verified by D. Briggs of Battelle[3] with experimental measurements on a wide range of fiber materials in plastics.

The rather simple equations used for the estimation of thermal conductivity are as follows:

$$\frac{\text{Conductivity of composite}}{\text{Conductivity of polymer}} = \frac{1 + A \cdot B \cdot \phi_2}{1 - B \cdot \chi \cdot \phi_2}$$

Where A = ke - 1
ke = generalized Einstein coef.

Typical Values of A

L/D	1	2	4	6	10	15	36	80
A	1.5	1.58	2.08	2.80	4.93	8.38	30	100

$$B = \frac{(K_2/K_1) - 1}{(K_2/K_1) + A}$$

Where K_2 is thermal conductivity of fiber
K_1 is thermal conductivity of polymer
$\chi = 1 + 1.775\ \phi_2$ for fibers
ϕ_2 = volume fraction of fiber

If one inserts the appropriate parameters for Metafil® fibers into these equations, the curves shown in Figure 5 are obtained. Unlike the electrical case there is no critical concentrations at which dramatic changes in properties occur; rather, the curves are all gradually changing functions of concentration. The fiber length does play a significant role up to lengths of 0.1 inch (L/D = 100); beyond that the change is less dramatic.

The curves show that very great increases in thermal conductivity can be achieved with low concentrations (less than 10% by volume), particularly for the longer fibers. The upper curve for long parallel fibers indicates that a two order of magnitude improvement in thermal conductivity is possible in the direction parallel to the direction of the fibers, which can be very important for composites which use unidirectional layups or fabrics.

It is to be noted that the thermal conductivity graph shows a unique region in the low concentrations and short fiber lengths marked "Electrical Insulation Region." This region, in which one has no significant electrical conductivity and yet significant improvements in thermal conductivity, is to be expected since the electrical resistivity is not reduced by low concentrations of fibers with short fiber lengths. The region is not known to be as sharply bounded or exactly bounded as indicated in the chart since adequate experimental work has not been done. However, these boundaries are approximately correct and serve as a guide to anyone wishing to develop plastics which are improved in thermal conductivity but can be used for electrical insulation.

EXPERIMENTAL DATA - ELECTRICAL

BMC

Much of our early work reported in 1977 was done with bulk molding compound (BMC) because the manufacturing techniques of compounding and molding are very gentle on the fibers and make it easy to maintain good L/D ratios. By submitting our fibers to three different plastic manufacturers we are able to satisfy ourselves that for compounding and molding reproducible production results could be obtained.

We evaluated the samples by measuring the electromagnetic shielding capability of samples containing ten percent by weight of Metafil fibers that were originally 3/8 inch long. After applying the "Cross-Link"™ process to optimize the electrical conductivity, we were able to demonstrate EMI shielding levels for 1/10 inch thick panels as shown in Figure 6. This indicated excellent shielding levels (>35 dB) up to 100 MHz and satisfactory shielding levels (>20 db) for most electronics to 1000 MHz.

SMC

Since sheet molding compound (SMC) can use one inch or longer fibers without significant damage to them in manufacturing, it should provide even better shielding. For this application, we had to develop continuous metal coated glass roving that had many of the handling characteristics of the heavily bound, standard E glass roving strands and yet would let the strand separate into individual fibers when it was incorporated into the SMC sheet.

As anticipated, the longer fiber length made possible a reduction in the required concentration of fibers to about six percent by weight (about three percent by volume) and showed improved shielding levels in the 100-1000 MHz range. Figure 7 shows typical results with 6 percent and 12 percent Metafil loadings.

THERMOPLASTICS

Normal injection molding and extrusion manufacturing techniques for thermoplastics incorporate a high shear screw that breaks ups the fibers to lengths in the 5 to 15 mil long region. At such lengths it requires 35 to 40 percent by weight of conductive fibers to give significant conductivity. Development work in progress has indicated that the critical level for conductivity can be reduced to 25 percent if steps are taken which increase the fiber lengths to 50 to 75 mils. More work is needed in this area to reduce the process to a standard manufacturing technique.

Excellent results have been obtained in thermoplastics by using a lightweight mat of the conductive fibers manufactured by International Paper. When such a mat is incorporated in the surface or laminate of a thermoplastic sheet, one obtains a plastic sheet that is an excellent EMI shield - with or without a surface conductivity depending on the location of the mat.

Allied Chemical has incorporated such mats into their STX type materials. Using two 1½ oz/yd^2 mats which contained 75 percent Metafil, gave a sheet with the shielding levels shown in Figure 8. With the use of the Cross-Link™ process, the shielding levels are well above the 35 dB required for even severe shielding applications. Work is continuing to see how much forming and stretching of the sheet can be done while maintaining satisfactory levels of shielding.

For applications where only static bleed is required, a single layer applied at the surface would give excellent results and still allow pigmenting of the film or sheet to most any desired color.

FABRICS

A joint program with Hexcel Corporation has produced a family of fabrics and prepregs trademarked Thorstrand™ which incorporate various levels of Metafil fibers in E glass and Kevlar (DuPont Trademark) fabrics. Fabric weights vary from 4 oz/yd^2 to 10 oz/yd^2. These can be incorporated in wet layups or molded shapes which need varying levels of conductivity. One fabric, TEF 7, designed for aerospace use has demonstrated its ability to withstand a 200,000 ampere lightning strike. Others such as TSF 180 are intended to give excellent EMI shielding (>35 dB) and static bleed capability to a surface. By varying the ratio of Metafil to E glass or Kevlar, one can obtain a wide range of conductivities and physical properties to match selected application requirements.

EXPERIMENTAL DATA - THERMAL

There is only limited thermal conductivity data available since this area has not attracted as much interest as the electrical conductivity. General agreement is indicated with the theoretical curves as long as fibers are random in orientations. With thin panels, the flow which produces fiber orientation reduces the thermal conductivity perpendicular to the surface and increases it in the plane of the plate.

One of the most interesting results of the increase in thermal conductivity was reported by Battelle (Conductive Composites for EMI Shielding - an emerging technology 1979) using their aluminum fibers (similar to Metafil A). They showed reduction in cycle times of 27 percent and lower peak exotherms in samples of glass reinforced polyester with 5 percent aluminum fibers. This could be of particular importance to any high production operation where reduction of cycle time converts to significant cost savings.

Another significant result has shown the great improvement in fire resistance that can be obtained. With a layer of TEF7 fabric incorporated in the surface of a high temperature epoxy laminate, a constant temperature 800°C steel probe left only a light discoloration where pressed against the surface for 15 minutes. Repeating this test against a phenolic panel left a deeply charred and blackened surface after only 15 seconds.

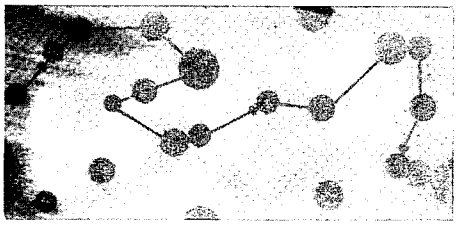
FUTURE IMPROVEMENTS

As startling as these improvements are in the effect on conductivity, it should be noted that there is still room for even more dramatic effects. The limitations to date have been in the length of fibers which can be introduced in standard production processes.

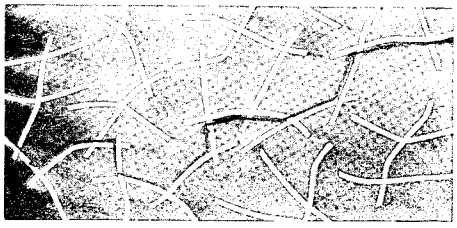
However, since the effects are related, not to length, but to length to diameter ratios, then one may greatly improve the effects by making the fiber diameters an order of magnitude smaller. The fibers in these studies were of the order of 1 mil in diameter but fibers are now routinely produced in the 0.2 mil diameter range.

If such fibers as these could be coated with metal, one would expect to get significant reduction in the concentration required for the same fiber length. The challenge would be to do this at the same low cost as can be done with the 1 mil fibers.

A second area for improvement is to take advantage of the improved thermal and electrical conductivity to modify production processes so they are both simpler and less damaging to the fiber. With high thermal conductivity plastics, one no longer has to use a high shear screw to introduce heat into the plastics by viscous working. Instead, the heat can be introduced by simple heating bands, resistance heating, inductive heating or many other techniques. As these new methods are developed, entire new areas of application will be available.



CHUNKY PARTICLES — LONG PATH THROUGH PLASTIC



FIBERS — SHORT GAPS IN PLASTIC

FIGURE 1 COMPARISON OF A TYPICAL FLOW PATH THROUGH COMPOSITES USING THE SAME VOLUME PERCENTAGE OF MATERIAL AS SPHERES AND FIBERS (L/D = 100)

SUMMARY

The addition of a few percent of metal and/or metallized glass fibers (L/D of the order of 100/1) to plastics leads to a family of materials which we have called "Metalloplastics". They show electrical resistivities as low as 0.01 ohm cm so combine excellent conductivity and EMI shielding capability with the light weight and moldability of plastics. The fibers increase the thermal conductivity of the plastics up to 100 fold so can have very significant effects on molding cycle times, uniform heating and cooling rates and heat transfer rates in the final product.

Low cost, high production techniques make several million pounds of such fibers each year for other applications providing a ready supply for the plastics market. Several forms of the fibers-(chopped roving, mats and fabrics) are presently undergoing testing by industry.

Biographical Sketch

Dr. Davenport obtained his Ph.D. in Physical Chemistry from MIT in 1948. He spent seven years at Hanford in nuclear reactor physics developing new concepts for reactor designs. This was followed by eight years at Stanford Research Institute as Assistant Director and Director of the Poulter Laboratories which specialized in the physics and chemistry of shock and detonation waves. He holds several patents in the application of shock waves to explosive welding.

As Director of the Ordnance Laboratory for Singer Company and TransTechnology, his group furnished a major portion of the small explosive devices for the Apollo program and brought pyrotechnic delays to a new level of precision.

Dr. Davenport's work with conductive fibers began after he joined MBAssociates in 1975. MBA built the free world's largest chaff plant for making aluminum and aluminum coated glass fibers to be used by the military as radar decoy material. Research aimed at developing low cost solar panels of the plastic and making plastic EMI shields for computers showed that the basic chaff material could fill an important commercial role.

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(2) Industrial Engineering Chem. Fundamentals., Volume 13, No. 1, 1974

(3) Polymer Engineering & Science, December 19, 1977, Volume 15, No. 12

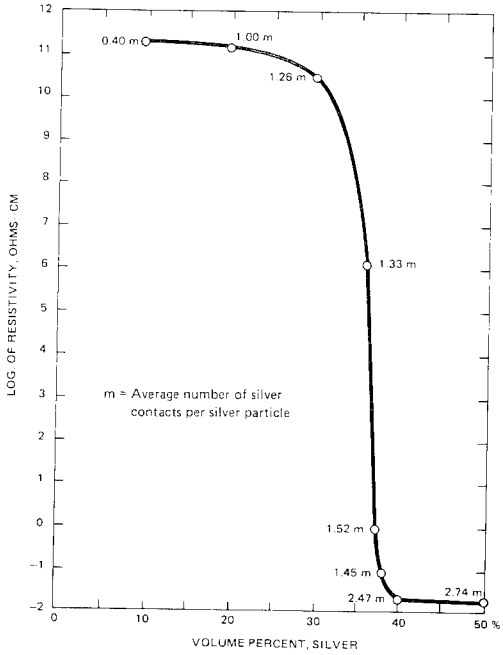

FIGURE 2 DECREASE IN RESISTIVITY AS A FUNCTION OF THE VOLUME PERCENT OF CHUNKY SILVER PARTICLES ADDED TO BAKELITE

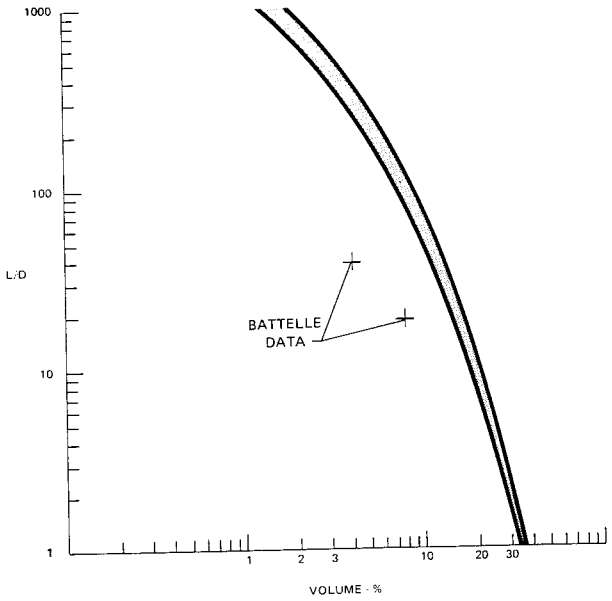

FIGURE 3 CRITICAL CONCENTRATION FOR ELECTRICAL CONDUCTIVITY AS A FUNCTION OF L/D OF THE FIBER

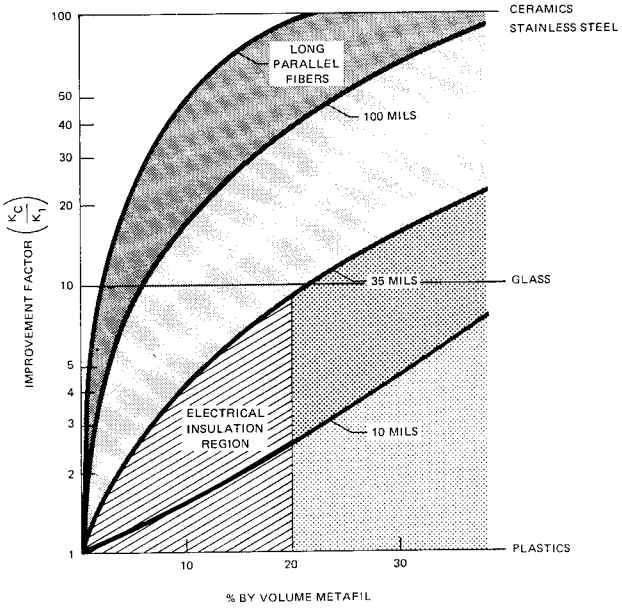

FIGURE 5 THERMAL CONDUCTIVITY IMPROVEMENT WHEN VARIOUS METAFIL LENGTHS ARE ADDED TO PLASTICS

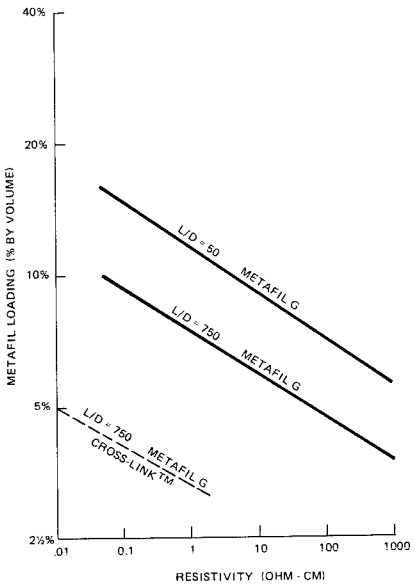

FIGURE 4 RESISTANCE OF METAFIL COMPOSITES NORMAL & CROSS-LINK FORMULATIONS

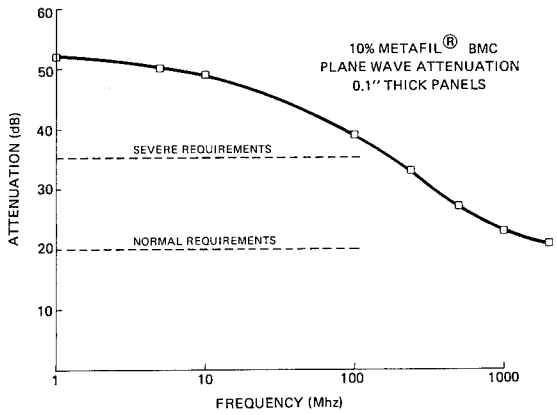

FIGURE 6 EMI SHIELDING LEVELS FOR BMC

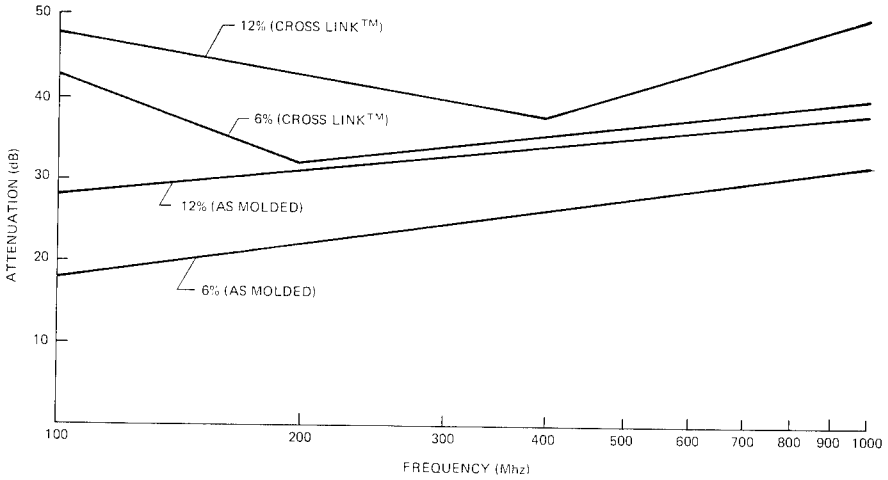

FIGURE 7
1/8" SMC MOLDED WITH 6% AND 12% METAFIL®

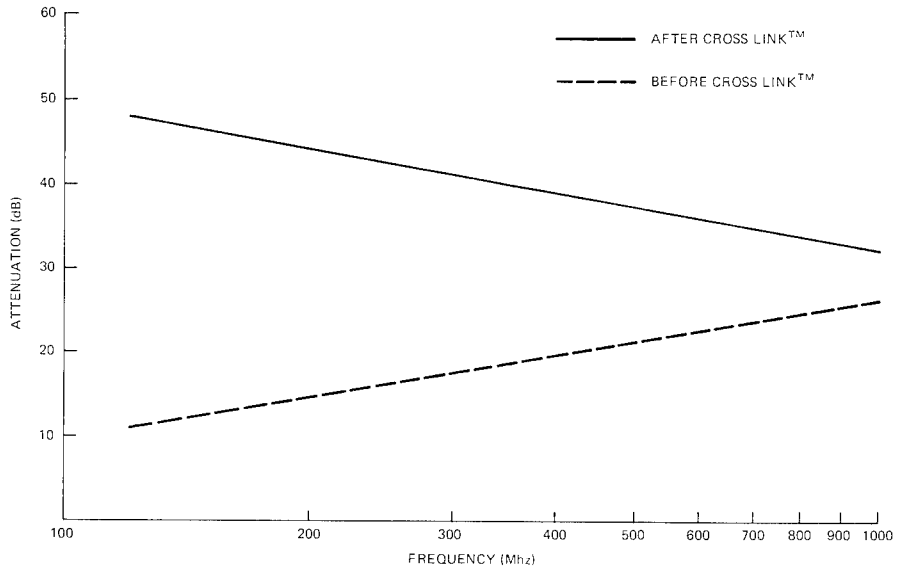

FIGURE 8
THERMOPLASTIC SHEET WITH 3 OZ/YD^2 OF METAFIL® MATERIAL

AUTOMATION OF SMC MOLDING PROCESS

Gerald Nelson

SMC Corporation, Livonia, Michigan

ABSTRACT

The intent of the presentation is to show in movie form the latest advances in automation in the SMC industry. The film, originally shot in January 1979 will be revised in an update to reflect the latest trends in the industry. The extent of the film revision will depend somewhat on scheduled changeovers within the molding facilities at press time. The film will include the highlights of the Ford Milan Facility as well as some advances in other areas.

A NEW RIM AUTOMOTIVE APPLICATION: MOLDINGS THAT DUPLICATE WOOD

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INTRODUCTION

RIM urethane materials have been accepted in automotive applications because of their very good performance characteristics, design freedom and reasonable cost.

The principal parts made of RIM, to date, in automotive applications have been front end and rear end fascia pieces. These parts include many elements such as front grille work, light openings, and license plate holders. In addition, designs are highly stylized with smooth sweeping curves and detailed features. The color and gloss of the fascia finish must match that of a car body. The parts are thin in cross section and emphasize flexibility and impact resistance both for fixed object damage and for pedestrian safety. Some of the typical programs utilizing RIM technology have been the 1975 General Motors Chevrolet Monza, Buick Skyhawk, and Oldsmobile Starfire front and rear fascia, the 1977 Pontiac Firebird front fascia, the 1978 Monte Carlo front and rear, the 1978 Camaro front and rear fascia, the 1978 LeMans/Grand Am front and rear fascia, the 1980 Ford Thunderbird-Cougar front and rear fascias, and the 1979 Chrysler Omni Horizon front and rear. (Figures 1,2)

In late 1975, Chrysler Corporation expressed an interest in duplicating wood grain in a urethane molding for their proposed LeBaron station wagon. Based on experimental work, Davidson Rubber indicated that such products would be feasible even though there had been no prior automotive production of that type. The challenge was to adapt several technologies to produce detailed RIM parts in the high volume required for automotive use. The parts were to be both decorative and functional. The combination of technologies required included the direct duplication of wood grain detail from wood models, the use of the RIM process to achieve high productivity, and the use of staining and painting techniques to obtain decorative effects in grain texture. The parts had the added advantages of damage resistance and very good weathering durability.

PRODUCT CONCEPT

Current technology has simulated wood but does not duplicate wood grain effects with respect to grain, dimension and texture. For example, extruded polyvinyl chloride rub strips, gravure printed with wood patterns, and metal strips, again printed with wood patterns, give a simulation but do not provide the three (3) dimensional effects achieved either by real wood or the LeBaron urethane. The three dimensional effects are evident on a micro scale as grain width and depth; and, on a macro scale as molded unit frames that have shape, contour and style. As compared to extruded strips of PVC fitted on the side of the vehicle the units look like real wood and are easy to apply.

Compared to fascia, the parts duplicating wood have a textured (not smooth) surface, use thicker cross sections (up to 500 mils vs. 120 mils), use an integrally colored substrate, and have extensive steel inserts molded in for attachment. The problems encountered in manufacturing are significantly different for the two types of parts.

PRODUCT DESIGN

The work as outlined for the station wagon included:

(9) body moldings for sides and tailgate
(2) front fenders
(4) doors
(2) rear fender quarters
(1) tailgate
(5) roof rails - to be provided as part of a luggage rack.

The above requirements indicated a minimum of ten (10) separate major molds to be built and matched for grain appearance. Planning requirements indicated that 1800 pieces/day would be needed. Manufacture of production parts was started in May 1977 and is continuing now.

DETAILS

The major elements to the overall program included modeling, mold development and manufacture, adaptation of RIM technology, and adaptation of paint technology. Each area required careful control as well as integration through to final product appearance and fit. The general processing sequence included molding an unpainted part, base color painting, grain color application, and finish clear coat application.

Master MOdeling

Wood models of carefully selected white ash were prepared by Chrysler. Various treatments to enhance the wood grain for molding detail were evaluated. These included burning, water soaking, solvent treatments, sanding, and brushing. The most acceptable treatment method proved to be brushing. Concurrent molding evaluations determined the grain depth that gave acceptable final appearance.

The wood models were made at full scale. This minimized fit problems in final assembly. Effects of molding shrinkage were avoided by the use of inserts. (Figure 6)

Mold Fabrication

Cavity

The production molds built were nickel electroforms. Initial reproduction of the models was done with cast silicone rubber forms. The forms were carefully supported, then cast epoxy working masters were prepared from the rubber forms.

The epoxy masters were inspected for accuracy in detail and measured for grain depth and dimensions. The masters were then given a chemical treatment to produce good surface conductivity. The master epoxy mandrels were mounted and prepared for electrochemical deposition to form the nickel-copper-nickel mold shell. Deposition of the metals to form the shell was carefully paced to provide a unit of good thickness, for strength, and of high surface quality.

After removal from the plating bath, the shell mold was cleaned and trimmed. Heating and cooling tubes were fitted to the back of the mold. The unit was

then carefully mounted in a prepared metal mold base and secured with epoxy resin.

Operating hinges, guide pins, fittings, and other auxiliaries were attached to the base. Fasteners were added to provide insert retention during molding operations. Runner systems required for RIM molding were machined into the base and base plates, and attachments were provided for RIM heat connections. The runner systems were conventional and included an aftermixer.

Cover

The cover was fabricated from a cast aluminum block. Duplicating techniques were used to match cover and cavity contours. The cover was mated to the cavity and positioned with the guide pins.

When fully assembled, the weights of each of the nine molds ranged from 2000 - 3000 lbs.

Processing Equipment

Reaction injection molding requires metering systems for polyol and isocyanate streams including storage and feed tanks, high pressure pumps, and high pressure mix heads. Clamps or presses are required as mold carriers. The equipment is commercially available and has been described in the literature. (Reference 3,4,5)

A typical flow sheet is shown as Figure 7.

During the non-firing mode, the two components, isocyanate and polyol, are circulated under low pressure through the injection mix head back to the appropriate feed tank. The flow rate, temperatures and pressures are carefully controlled. During the firing mode, the pressure in the system is built up to 2000 psig; recirculation is cut off by a diverter valve; and, shots of the two components are delivered to the mold through the mix head. The ratio and size of the shot, material temperatures, flow and pressures are carefully controlled. The mix head is of a self-cleaning design. In general, this RIM equipment is accurate and reliable. Typical RIM operating parameters are shown in Table I.

Urethane Materials

Reactive urethane formulations have been extensively reported in the literature. (Reference 1,2,6,7) The proprietary formulations used in these operations are based on MDI isocyanates and conventional polyols (diols and triols) with addition of various catalysts and pigments. Formulation viscosities are in the range of 500 - 100 centipoise.

Typical physical properties of the molded urethane are shown in Table II. The density of the urethane was planned at 0.6 specific gravity to minimize part weight.
In LeBaron application, the urethane is pigmented to obtain a base color match. This insures good base paint coat color match and eliminates substrate show-through if the finished part is scuffed or gouged.

Insert Materials

The steel inserts being used in the program are a combination of roll forms and die cut pieces welded to form a finished assembly. Steel thickness is 40 mils. For each complete set of 14 inserts, 64 individual pieces welded to shape, are required. The inserts are designed for attachment to studs on the car body. (Figure 8)
The finished inserts are zinc phosphate treated and painted with a metal primer to give corrosion protection and to insure good urethane foam adhesion. The insert primer thickness is 1.2 mils. Typical urethane peel adhesions are 18 - 20 lbs./in.

Paint Parameters

Paint processing specifications are shown in Table III: Paint application is done with conventional air, airless, and electrostatic equipment.

SUMMARY

In general, we have found that RIM technology is very adaptable and can provide interesting, decorative parts at low cost.

High volume automotive RIM production parts with duplicated wood grain texture are being produced for Chrysler for the current LeBaron station wagon using this technology. (Figure 9) The project has been unique because it resulted in:

1 - Parts duplicating wood texture made in light weight electroform molds in high production volume by the RIM process.

2 - The first complex RIM parts made with integrally molded inserts, and with an integrally pigmented urethane formulation.

3 - The first automotive RIM parts made at a low density (0.6 specific gravity vs. 0.9 - 1.1 for fascia).

4 - Complex RIM parts made with a short molding cycle (3 - 4 minutes) in relatively thick cross section (up to 0.5 in.).

5 - A unique combination of molding, staining, and painting to give decorative effects that duplicate wood and have superior damage resistance and weathering properties.

ACKNOWLEDGMENTS

The author would like to recognize that the work covered by this paper was done by a large team from Chrysler Corporation and Davidson Rubber Company, and in addition, with the close cooperation of suppliers.

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Table I

Typical RIM Operating Parameters

Head Size	11 mm (Krauss Maffei)
Pumps	rotary piston
Press Tonnage	50
Index (Iso/Polyol)	100 - 105
Delivery Rates	90 - 170 lbs./min.
Feed Temperatures	70 - 100°F
Mold Temperatures	120 - 150°F
Cycle Times	3 - 4 minutes

Table II

Typical RIM Urethane Properties

	Typical
Tangential Modulus of Elasticity (psi)	3900
Tensile Strength (psi)	990
Elongation (%)	315
Specific Gravity	0.6
Heat Sag (250°F)(in.)	0.75
Tear (Die C)(pi)	175
Hardness (Shore A)	65

Table III

Paint Parameters

Base Color Thickness	1 mil
Grain Coat	1 - 3 mils
Clear Top Coat	0.4 - 0.6 mils

Paint requirements are shown in Table IV. Our tests show that the Chrysler side rail parts pass all these requirements.

Table IV

Paint Requirements

Fadeometer (250 Hours)
Weatherometer (1000 Hours)
Humidity Resistance (250 Hours)
Salt Spray (250 Hours)
Intercoat Adhesion
Cycle Crack Resistance
Water & Soap Resistance
Acid Resistance
Solvent Resistance
- Gasoline
- Antifreeze
- Xylol
- VM & P Naphtha
- Isopropyl Alcohol

Impact Resistance 80 in./lb.
Grease & Oil Resistance
Weather Resistance
- (Florida 24 Months)
- (Detroit 12 Months)

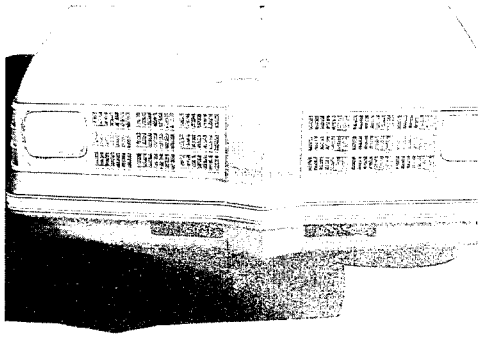


FIG. 1 - PONTIAC GRAND AM

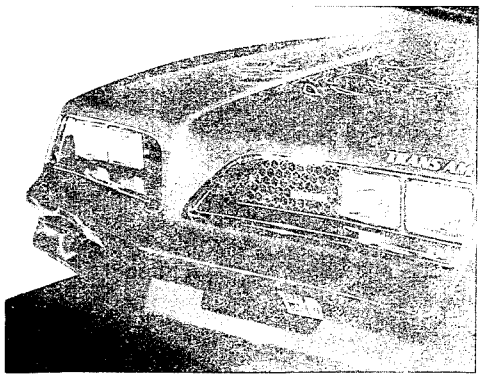


FIG. 2 - PONTIAC TRANS AM

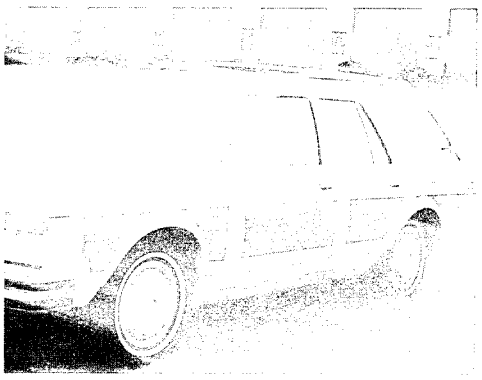


FIG. 3 - CHRYSLER LeBARON

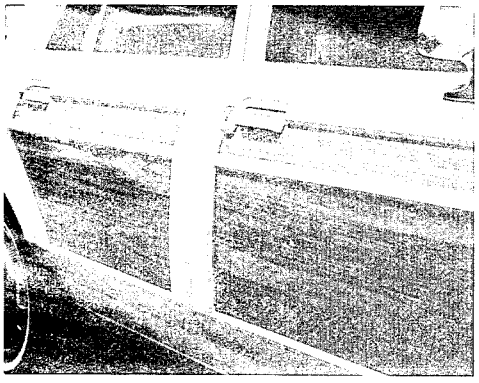


FIG. 4 - CHRYSLER LeBARON

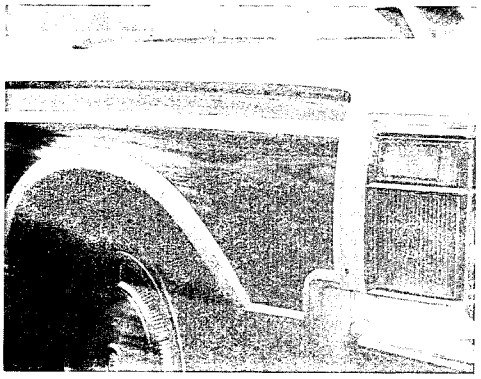


FIG. 5 - CHRYSLER LeBARON

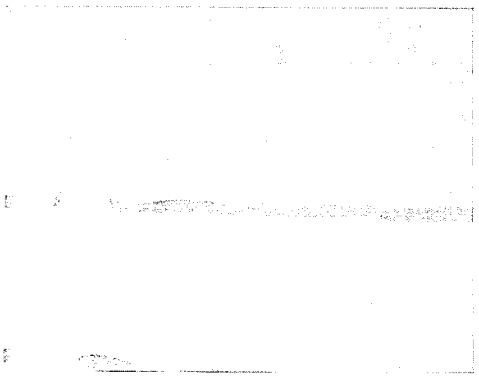
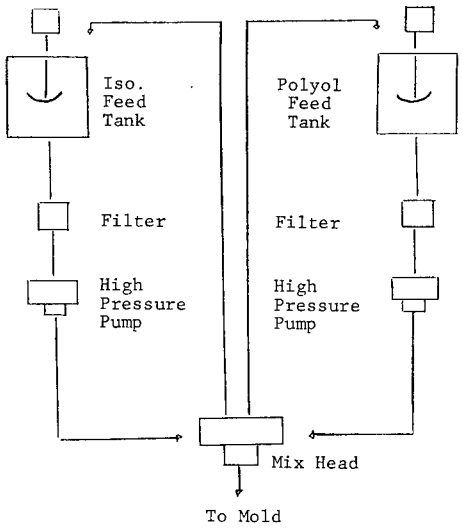


FIG. 6 - WOOD MODEL

Figure 7 - RIM Flow Sheet



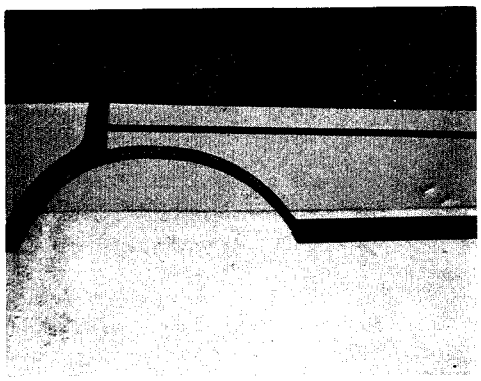


FIG. 8 - STEEL INSERT

FIG. 9 - CHRYSLER LeBARON

AN UPDATE OF THERMOSET MATERIALS FOR THE AUTOMOTIVE ENGINEER

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PART I

The first part of this discussion on thermoset materials will dwell briefly on the status of this field today. The second part will concentrate on two new developments in the thermoset area. One, a new piece of equipment and then a new material.

Thermosetting materials are by no means new to the plastic industry. Some compounds, such as, phenolics were first developed in 1909. Thermoset materials are rigid, infusable solids. They are formed in a steel mold by chemical change or cross-linking under heat and pressure. This, in effect, is a complete change in the chemical structure of the basic raw materials. Materials included in the thermoset classification are: urea, melamine, phenolics, diallyl phthalate, polyester, epoxy and silicone.

MATERIALS -

Three of the major phenolic material suppliers are presently marketing compounds which have a very low coefficient of expansion. These materials have already been placed in service as a replacement for the steel used in disc brake pistons by one automotive manufacturer. Still another material manufacturer has announced a new material which it claims can be used in competition with engineered thermoplastics.

There are well over 200 types of molding compounds available to the design engineer. It must be stressed, how important is the communication link between the design engineer and the material manufacturer so as he can keep abreast of the latest developments.

EQUIPMENT -

Thermoset materials can be processed by compression, transfer and injection. Many developments in the injection area such as cold manifold molding, process control, and upgrading of machine controls, for greater cycle speed, make the injection process very attractive from the economy standpoint. The compression and transfer process have been enhanced by the availability of screw plasticizers. The use of these machines eliminate preforming and make for a much better plastification of the material. This results in faster cycles with a much better product.

PART II

In recent years with the advent of more stringent EPA regulations and the increased cost of thermoset materials and their processing costs, it became increasingly obvious that the recycling of thermoset scrap would have to be investigated. Although there were many crushers, pulverizers and grinders available, none were combined and utilized in one economical and efficient system. That is; until late 1975 when the HULL Corporation of Hatboro, PA introduced a scrap recycler in the form of a complete system for use by the molder.

A brief description of the machines operation is as follows:

1) The scrap or flash is fed into a pulverizer which reduces the scrap to granules approximately 1/4" square.

2) This is then fed automatically into a second pulverizer, or high speed atomizer, which reduces these granules to the required granulation for mixing with the virgin material.

3) This material is then fed automatically to the mixing tank. The virgin material is also fed automatically to the mixing tank. Both are fed volumetrically at desired ratio or recycle - virgin material.

4) After blending in the tank the material is either drummed off for future use or fed directly on to the production line.

Although there is still much work to be done on this process, it has been found that 15% of recycled material seems to be the ideal ratio to work with. This can result in an approximate cost savings of .10 - .15/eb on material. With the increased cost of raw material, and rising energy costs, the availability of this system should be kept in mind by the design engineer.

There has been a very recent introduction, to the U.S. Market, of a new line of thermoset materials. They are manufactured by Resart, Gmbh of Mainz, West Germany and consist of melamine, melamine phenolic, melamine polyester, and polyester. The latter two products are new to our plastic industry. These materials display very good physical properties. In particular, they have excellent electrical properties and superior heat resistance. They come in many colors and are heat stable.

To best illustrate the versatility of these compounds, we will describe a systems approach to manufacture of a head lamp presently in production. The head lamp assembly can be broken down into 6 phases.

Phase I - The Lamp Housing - This is molded of Resart 802 which is a glass-fibre reinforced polyester material with very low heat distortion. This results in a lightweight, corrosion resistant, non-warping housing which is economical to make.

Phase II - The Parobollic Mirror - This is molded of Resart 802, the same material as the housing, or may be molded of Resartherm K. These are engineering thermosets with high heat resistance. These materials give a lightweight, corrosion resistant mirror with a superb finish. There is no grinding or polishing and the mirror is produced in one operation.

Phase III -The Parobolic Mirror is metalized.

Phase IV - Bulb Socket - This is molded of Resartherm GL. It is formulated especially for use in lamps. It has outstanding electrical properties, such as, are tracing and dielectric. It also has excellent heat resistance.

Phase V - Diffuser Disc or Lens - This is molded of Resarit K12 acrylic molding compound which is UV absorbant, crystal clear and has outstanding impact resistance compared to glass.

Phase VI - SF Coating - The lens is then coated with Resarix SF. This is a clear laquer which imparts abrasion resistance, chemical resistance, unwanted reflections are cut out and sparkle is much increased.

Thus the circuit is complete. Now light shines from a completely new type of head lamp and is a perfect illustration of, how working with the material supplier can result in a complete system approach for the design engineer.

CRITICAL DESIGN PRINCIPLES FOR EXTERIOR BODY NYLON PARTS

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&
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Fibers Division
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INTRODUCTION

Molded plastic parts have been in use for many years as structural or semi-structural painted (exterior body paint) automotive body components. Recent developments have created high interest in use of large thin section thermoplastic parts (cowl vent grills, window frames, louvers) because of the unlimited styling potential and the weight reduction that is inherent with lighter weight materials. Many of these parts are decorative but design principles must be applied to mounting, and if rigidly mounted, must be considered as structural members.

EXPANSION OF MINERAL PLUS GLASS REINFORCED NYLON

Without going into detail, discussing material attributes, or defending material selection, the fact that reinforced nylon in several formulations is the most widely used thermoplastic material for painted automotive exterior body applications should be established as a bona fide fact. In fact, it is almost exclusively used.

One property of nylon that must be given prime importance in this type of application is that of moisture absorption. Associated with moisture absorption are several property changes but the key ones related to installation integrity of large thin parts are dimensional and modulus changes.

Precise characteristics of the material being used is required as there are significant differences in expansion as recorded in Figure 1 for the 65" long cowl vent grill pictured in Fig. 2. The dramatic difference emphasizes the importance of accurate data. Fig. 3 shows comparative data on Capron® 8266, Mineral Plus Glass reinforced Type 6 nylon for two automotive exterior parts exposed to a test environment of 100% R. H. and 100°F, and which has been used for calculations in this paper.

ASSEMBLY OF NYLON PARTS

The expansion of nylon being larger than its metal assembly fixture due to moisture absorption and temperature, thorough investigation of the effects of this differential expansion becomes very necessary.

FREE EXPANSION

In many instances of differential expansion in metal assemblies, clearance is provided between parts. This same method can be utilized, with elongated holes on the plastic part, which would permit free movement of a plastic part fitted to metal. Fig. 4 indicates two techniques of assembly.

Another assembly method utilizes metal clips fastened on the plastic part which would slide in slotted holes or receptacles in the main assembly.

CONSTRAINED EXPANSION

A seeming contradiction in terms, a plastic part rigidly assembled with no room for longitudinal displacement, nevertheless absorbs moisture and starts to expand longitudinally. This expansion manifests in one of two ways:

(1) Bulging of the part in between assembly points.

(2) Built-in compressive stress in the section of the part between assembly points.

Bulging: Bulging results due to the part finding a configuration to best accomodate its increased length. A part thus bowed is generally unacceptable especially in exterior body components such as automotive parts that have high visibility and aesthetics. In such cases it becomes important to realize that in a constrained section of the part the bulging deformation at midspan is in very high proportion compared to the actual expansion of the length of the part. This is illustrated in Table 1 and also in Fig. 5. An approximate formula is described in Fig. 6 to determine the bow height in relation to the expanded length of the section (1).

This formula is a good universal approximation for various end conditions such as those illustrated in Figures 7 & 8. Reference (1) gives complete theoretical validation of the accuracy of the above formula.

Built-in Stress: Proper design of the cross-section of a part between its assembly points can lend sufficient rigidity to ensure minimum bowing. This means that the expansion of the part is contained within the section as a compressive stress. The following pages present analysis and methods available in engineering design to achieve this end.

DESIGN PRINCIPLE & APPLICATION TO PREVENT BULGING

Designing for the minimum required cross-sectional rigidity is based upon the buckling theory of columns. The analogy compares a column with axial compressive end forces to an assembled plastic part constrained from expanding at its assembly points in which axial compressive forces are generated due to the part expanding and creating pressure at the constraints.

Bowing of the part will be minimum if the part will not buckle under the influence of such a compressive force. This can be achieved through adequate design of the cross sectional rigidity. Conversely, given a particular cross sectional shape, a safe assembly span can be recommended using this design procedure.

EXPANSION STRESS

Referring to Fig. 9, the actual stress that is built-up is calculated by considering a part of length ℓ and its free expansion $\Delta\ell$ which under a constraint is contained as a compressive strain given by,

$$\text{Constrained Compressive Strain} = \frac{\Delta\ell}{\ell}$$

and,

$$\text{Related Compressive Stress} = \frac{\Delta\ell}{\ell} \times \text{Modulus}$$

(at the given humidity and temperature)

This built-in stress is referred to as the expansion stress of the given material under the given environment.

Having determined the value of this expansion stress for the material we proceed to compare it with the limiting stress that can be built-in within the part beyond which this part will buckle.

CRITICAL BUCKLING STRESS

This stress is determined from Euler's formulas for buckling loads in columns. Depending on the method of constraint

the following formulas indicate the value of the Critical Load.

Built-in End Constraint:

$$P_{Cr} = \frac{4\pi^2 EI}{\ell^2}$$ (Ref. 2)

E = Modulus of material
I = Minimum inertia of section
ℓ = Length of part between constraints

Examples: Screw down assemblies, heat staked or riveted end conditions and restraint end conditions like hooks captured under the metal fixture. Refer Fig. 7.

Pivoted End Constraint:

$$P_{Cr} = \frac{\pi^2 EI}{\ell^2}$$ (Ref. 2)

Examples: Parts snapped in position, special cases such as those in Fig. 8.

One End Free, Other Built-in:

$$P_{Cr} = \frac{\pi^2 EI}{4\ell^2}$$ (Ref. 2)

Example: Overhang portion at ends of parts assembled to fixtures. Fig. 10.

In all the above cases, the value of the critical load divided by the area of the cross section gives the critical buckling stress. This stress is the theoretical upper limit which the built-in expansion stress can approach. If the built-in expansion stress exceeds this limit, bulging due to buckling is bound to occur.

Design Condition:

Expansion Stress < Critical Stress

DESIGN APPROACH

Based upon a particular meterial, and hence a given $(\frac{\Delta \ell}{\ell})$ material property, which represents the humidity expansion of the material and is the significant property affecting bulging deformation, correcting any potential bowing tendency in a part involves maximizing the critical stress limit for the part. This can be achieved only by maximizing the ratio $\frac{I}{A\ell^2}$, where A is the area off the cross-section.

This ratio can be written in terms of the slenderness ratio of the cross section, namely $\frac{\ell}{\kappa}$ (length of the column/radius of gyration of its cross-section) as follows:

$$\frac{I}{A\ell^2} = \frac{\kappa^2}{\ell^2} = \left(\frac{1}{\text{Slenderness Ratio}}\right)^2$$

Through design this slenderness ratio can be minimized by, increasing the cross sectional property κ by adding ribs, or by minimizing the span length ℓ between constraint points.

Span Length: Reduction of span length can involve more assembly screws, addition of restraint hooks (Fig. 7), or closely spaced stake points. In the event such methods are prohibitive, the cross sectional rigidity can be improved.

Stiffening Ribs: Addition of ribs based upon theoretical computation of the required radius of gyration has to be complemented with judgement on the designers part to minimize sink marks, avoid lateral buckling of the rib itself and also proper distribution of the ribs over the width of the part so that any edge without a rib in its proximity would not begin to bow independently of the total cross sectional rigidity. Reference (1) discusses this point in greater detail which is essential to the designer serious about applying this principle in practice.

Factor of Safety: In designing for the required rigidity of cross section, the slenderness ratio should be a margin removed from the theoretically indicated critical value. Reference (1) gives details on how we selected a practical usable value in our applications.

DESIGN CASE STUDIES

Spring Loaded End Constraints: Not infrequently the end constraints in a plastic part can only be described as intermediate between a rigid constraint or a freely pivoted condition. In the course of our analyzing exterior automotive window frame parts such as the one sketched in Fig. 11, the top span for instance is supported at the ends by a section of plastic which itself could twist. This section of plastic is depicted as a spring in torsion, and the top span of length ℓ is thus pivoted at its ends but under a spring torsion. In our analysis we developed the following formula for the Critical Buckling Load of such a top span.

$$P_{Cr} = \frac{\pi^2 EI}{\ell^2} \left(\frac{8a^2 + \frac{32}{3\pi} a + 1}{2a^2 + \frac{32}{3\pi} a + 1} \right) \quad (*)$$

where E, I, & ℓ have the same definitions as before

and $$a = \frac{K_o}{2EI} \times \frac{\ell}{\pi}$$

where K_o is the torsional spring constant (in.lbs./radian) of the section of plastic acting as a spring.

This value of P_{Cr} is divided by the area of cross section for the critical stress and is then compared with the expansion stress of the material to determine buckling potential.

The end sections that act as torsional springs can also bend laterally under the effect of the top span expansion force. Detailed analysis of such a section would involve frame analysis which has not been attempted yet. Fig. 12 shows a photograph of a test piece similar to such a window frame.

Metal-trim Reinforcement: On parts like window louvres, designs from styling quite often require metal ornamentation which lend additional rigidity to the plastic. We encountered a case where a channel shaped metal trim was snapped onto a plastic section as shown in Fig. 13.

The determination of Critical force that can be withstood by such a part is computed by just summing the EI product of the plastic and the metal and using the conventional expression. Thus for a built-in constraint,

$$P_{Cr} = \frac{4\pi^2 (E_p I_p + E_m I_m)}{\ell^2} \quad (*)$$

E_m = Modulus of metal trim
I_m = Cross sectional Inertia of metal trim
E_p = Modulus of plastic section
I_p = Cross Sectional Inertia of plastic section

Such an expression only yields an upper bound on the Critical force. Hence this is not a conservative estimate. A suitable factor should be used to lower the result to correctly represent the situation. One preliminary test indicated that this result would have to be reduced by a factor of 2 for a practical result.

Another important aspect of this method is that the smaller the cross section of the plastic, the greater the effect of the reinforcement. In comparing the expansion stress of the material to the critical stress of the part, the area of cross section of the plastic section is included in the denominator of P_{Cr}. The $E_m I_m$ product is generally a significant quantity and hence the smaller the plastic cross sectional area the larger the Critical stress that can resist buckling. In contrast the Critical stress of a part without a metal trim will only diminish for reduced cross sections since the numerator will not include the $E_m I_m$ product.

Steel Band Strengthening: In cases where ribbing is not possible a good idea is to stake a steel band of suitable rigidity to the plastic with sufficiently spaced stake points. The span between stake points can be computed using the design procedure described earlier.

Fig. 14 shows a photograph of a test piece staked to a flat steel band. Assuming built-in constraint at the stake points, the spacing should be less than 3.5". However the central span shows some evidence of bulging. It is safer to assume pivoted end conditions for determining span length for such a case which in effect will cut the present span in half.

Fig. 15 shows another similar situation where the flat steel itself curved over much like a bimetallic strip. A small flange on the steel band would prevent such a condition.

The stake pins themselves did not crush unduly due to the end force under expansion although calculations indicated a 20,000 psi crush pressure. For the material under test a mineral-glass Capron® nylon under the humidity conditions, such a pressure was acceptable.

* See Appendix Section

SOME RECENT CASE HISTORIES

We had an opportunity to assist in the design of some exterior automotive parts in which course we carefully studied these parts for buckling tendency. In most cases we recommended additional screw down points, or additional restraints like hooks. Where space permitted we took recourse to improving the section with the addition of ribs.

Fig. 2 shows a large 65"long cowl vent grille which required additional restraint points in between the assembly screws on the rear edge. The front edge has a deep enough ledge that acts as a rib, preventing buckling.

Fig. 16 shows a section of another exterior automotive part which was tested by us on a fixture for distortion, at 100%RH and 100°F. Prior to completion of the production mold this part was run without ribs on the underside of the section shown in the photograph, which resulted in bulging as expected.

CONCLUSION

The effect of environmental moisture and temperature on reinforced nylon automotive exterior body parts, particularly of thin section, in relation to assembly on metal fixtures has been discussed. The possible warpage that can occur due to the plastic expanding more than the metal has been analyzed and engineering design principles and and their application to correct such a phenomenon has been explained. Some case histories that illustrate the practical application of such a design procedure has been presented.

In summary, it is important to remember that thin section exterior body parts although mostly decorative have to be carefully engineered as structural parts that can withstand the effect of humidity and temperature which create stress within the part. How this can be done in a methodical engineering procedure is the gist of this paper.

ACKNOWLEDGEMENTS

The authors wish to express their sincere thanks to Leonard Simpson who did the sketches and photography together with the audio visual group at Allied Chemical Corporation.

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APPENDIX - A

Critical Buckling Force Determination For the Special Case Of Spring Loaded Ends

The theory for deriving the expression for Critical Buckling load for this case is based on the theory described in Reference (3), pp.161.

We chose an arbitrary deflection curve for the top span of length ℓ pictured in Fig. 11, which satisfies the given end conditions. This curve was chosen after careful curve fitting.

$$y = C\left\{\frac{a}{1+a}\left(1 - \cos\frac{2\pi}{\ell}x\right) + \frac{2}{1+a}\sin\frac{\pi x}{\ell}\right\} \quad (I)$$

in which C is a constant and has unit of length
ℓ is the length of the column
a is a dimensionless number related to the spring constant of the spring at the ends.

thus when $a \to \infty$ we have a curve resembling a deflected built-in beam.

and $a \to 0$ we have a curve resembling a deflected free-pivoted beam.

From the end constraint we know, the moment exerted on the beam due to the spring constant (K_o) is, $M_o = K_o y'|_{x=0}$

and the reaction moment within the beam at the end points,

$$M_o = EIy''|_{x=0}$$

Evaluating $y'|_{x=0}$ and $y''|_{x=0}$ from (I)

and equating the above two expressions for M_o;

$$\frac{2}{1+a} \times \frac{\pi}{\ell} = \frac{4a}{(1+a)} \cdot \frac{\pi^2}{\ell^2} \times \frac{EI}{K_o}$$

$$\text{thus} \quad a = \frac{K_o}{2EI} \times \frac{\ell}{\pi}$$

(Dimensionless)

additionally we observe that,

$a \to \infty$ when $K_o \to \infty$ (for a built-in case)

and $a \to 0$ when $K_o \to 0$ (for a free-pivoted case)

This proves the validity of the selected curve.

According to the theory described in Reference (3), pp. 162, we evaluate the strain energy and the potential energy for the curve described in egn. (I).

Equating these two expressions and solving for the end force P gives the condition for $P_{critical}$;

$$P_{critical} = \frac{\pi^2 EI}{\ell^2} \left\{ \frac{8a^2 + \frac{32a}{3\pi} + 1}{2a^2 + \frac{32a}{3\pi} + 1} \right\}$$

APPENDIX - B

Reinforcement Effect Of A Metal Trim Clasped Over a Plastic Beam Under Buckling Forces

For deriving the expression for Critical load on a column and also its deflection curve the governing differential equation is arrived at by relating the deflection characteristics of the beam at any point along the beam, namely curvature, to the resisting moment at the same point. Thus for any point on a bent beam,

$$\frac{1}{r} = -\frac{d^2y}{dx^2} = \frac{M}{EI} \qquad \text{(Ref. 2, pp.138)}$$

Metal Trim: When a metal trim is clasped onto the plastic beam without affecting the end constraints which means the metal trim itself is not constrained (Fig. 13), the external forces at the constraints applied on the beam remain the same as before but the internal moment at any point on the beam is now increased by the amount of contribution of the metal trim and the deflection curve of the beam takes a shape such that,

$$M_{plastic} + M_{metal} = \text{total internal moment}$$

but since radius of curvature is the same for both metal and plastic at any point on the beam,

$$\text{total internal moment} = \frac{E_{plastic} I_{plastic}}{r} + \frac{E_{metal}\ I_{metal}}{r} \qquad \text{(Ref. 2, pp.219)}$$

or,

$$-\frac{d^2y}{dx^2} = \frac{(M_{plastic} + M_{metal\ trim})}{(EI)_{plastic} + (EI)_{metal\ trim}}$$

This will be true if there were no shear slippage at the interface of the metal trim and the plastic. We took this to be more or less the case because the shear stress at the skin regions of a beam in bending is the lowest.

Using this above relation, the usual governing defferential equation for any given end constraint can be written and solved in the usual procedure as described in Reference (2).

The solution of this case will be the same expression as the normal case except that the EI product will now be the sum of the plastic contribution and the metal trim contribution.

Hence,

$$P_{Critical} = \frac{\pi^2}{\ell^2} \times (EI_{metal} + EI_{plastic}) \quad \text{...(pivoted ends)}$$

and,

$$P_{Critical} = \frac{4\pi^2}{\ell^2} \times (EI_{metal} + EI_{plastic}) \quad \text{...(built-in ends)}$$

Note:

This result is an upper bound for the critical load that can be withstood because we have assumed no shear slippage between the metal trim and plastic beam.

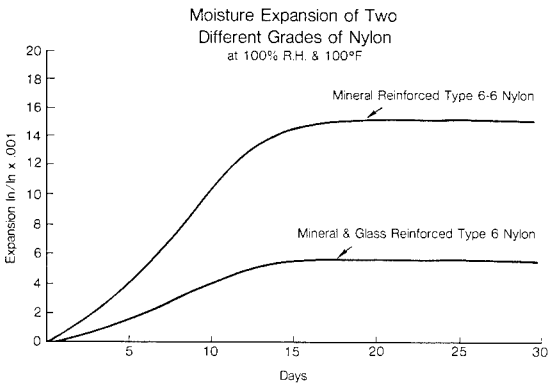


Figure 1

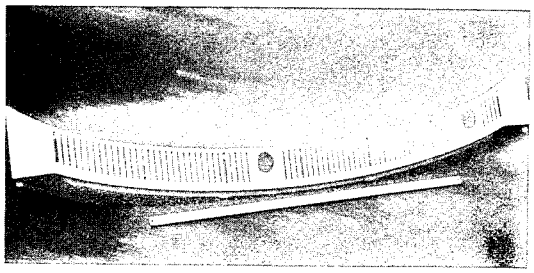


Figure 2

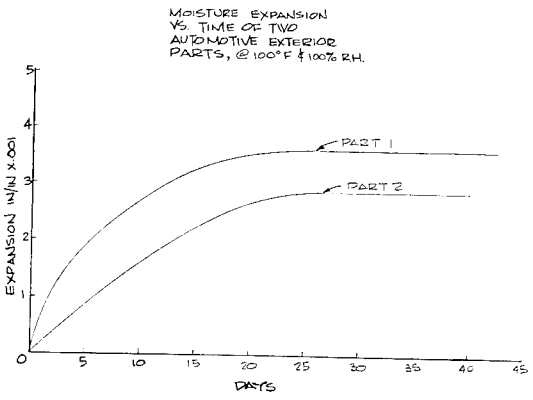


Figure 3

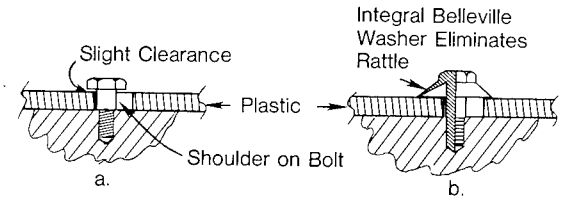


Figure 4

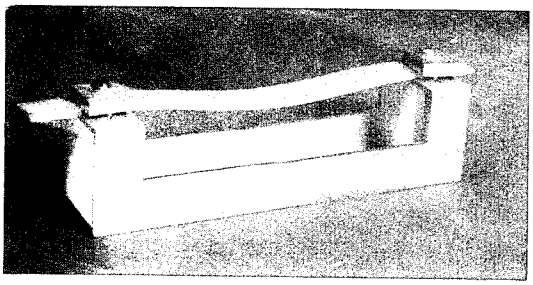
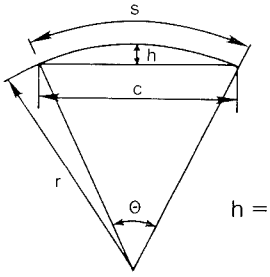


Figure 5

Table 1. Midspan Bulge Vs. Expansion of Bowed Part

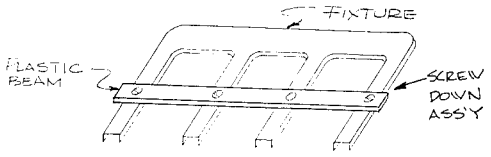
Span Between Constraints	Expanded Length of Beam	Bulge at Mid Span
10	10.000	0
10	10.001	.060"
10	10.002	.080"
10	10.003	.110"

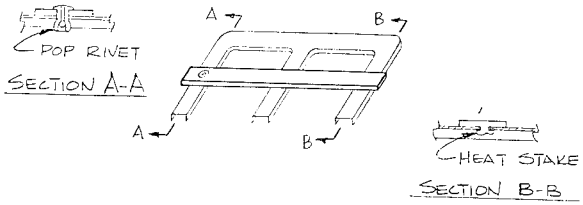


Initial length of beam = c
Expanding length of beam = s
Bow height = h
Subtended angle = Θ
Radius of curvature = r

$$h = \frac{s(1-\cos\sqrt{6(1-c/s)})}{2\sqrt{6(1-c/s)}}$$

Figure 6





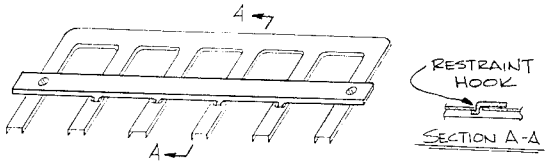
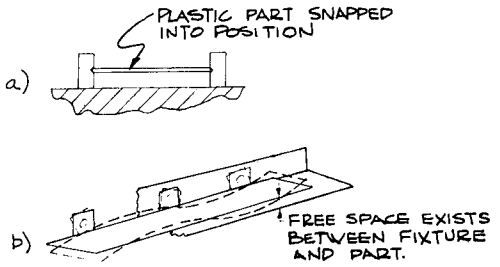
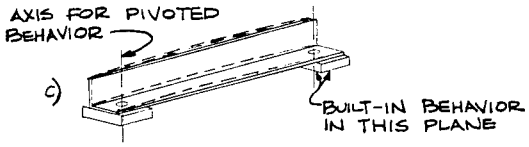


Figure 7





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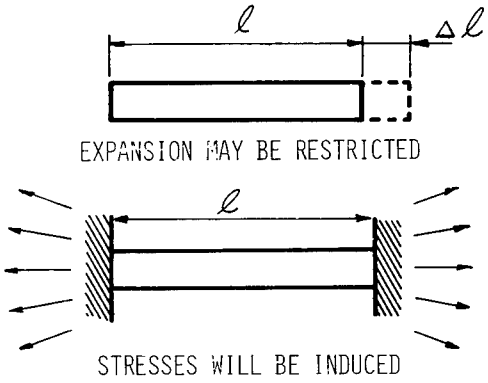

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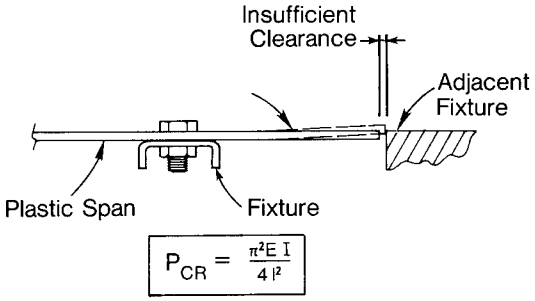

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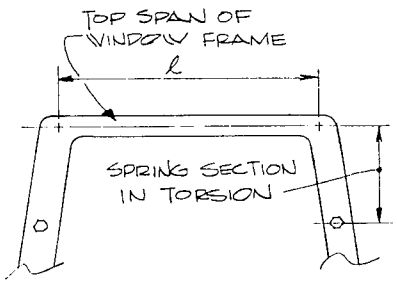

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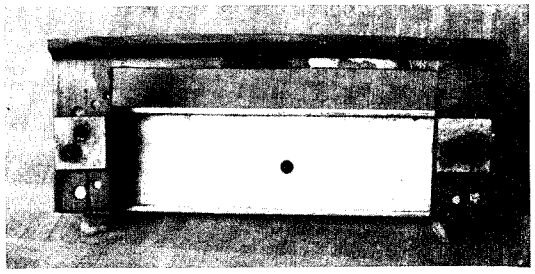

Figure 12

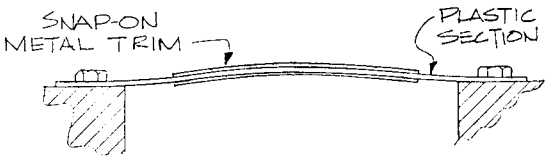

Figure 13

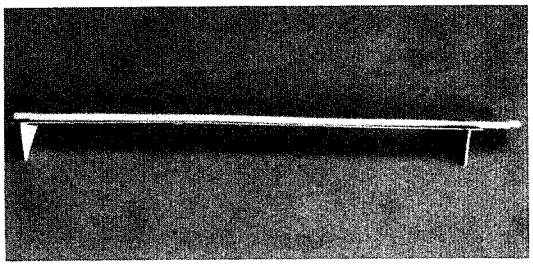

Figure 14

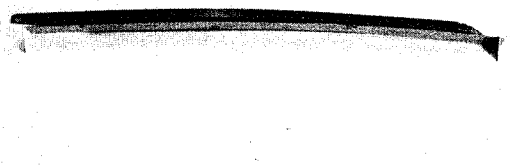

Figure 15

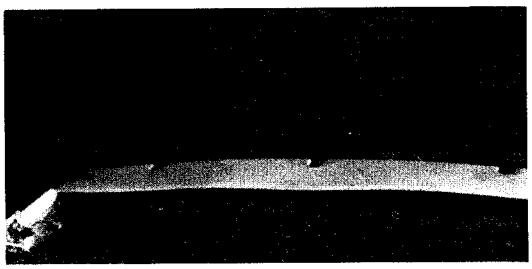

Figure 16

THE RECYCLING OF AUTOMOTIVE PLASTICS WASTE

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During the age of cheap energy, from 1895 to 1973, when an automobile had worn out, or become unfashionable, or got rusty, or needed an expensive repair, it was junked.

At first this meant leaving it to rust quietly away. Then, towards the end of the age of cheap energy, the fragmentizer was developed, which permitted the economic recovery of the ferrous metal content of the automobile, but little else.

We are now at the beginning of the OPEC age, which will cover the period from 1973 to about 2030, slightly shorter and much less comfortable than the age of cheap energy.

During the OPEC age petroleum and its derivatives will become progressively more expensive as the fortunate few who own the supplies restrict deliveries to those whose needs outrun their resources, until finally, in the nature of things, the wells run dry.

In order to delay for as long as possible the effects of this unfortunate, but foreseeable situation, we shall build more economical automobiles. These new, lighter cars will at first be fuelled by gasoline, then by diesel, then by gasohol and something like diesohol, and finally by alcohol.

Production of fermentation alcohol by sophisticated enzyme technology is probably the only way we can convert solar energy to liquid fuel for automobile purposes in time to meet the crunch.

By the time we are on to alcohol, which will be a very expensive fuel by American standards, we will have had to reduce the weight of the car to the point where ferrous metals will only be used where they are absolutely necessary.

All this will not happen overnight. But we already have a good indication of the rate at which the amount of metal in a car will decrease and the amount of plastics will increase.

The fragmentisers will adapt their equipment to the changing situation as soon as it becomes profitable to do so. Until now, there has been no incentive to recover the plastics fraction because no practical way of utilizing the mixed plastics was available.

The slide-tape presentation which follows shows the conversion of automotive plastics scrap into finished mouldings by the Klobbie process.

Now that three processes are commercially available which can mould useful articles from mixed and contaminated plastics scrap, we shall see efforts made to adapt the fragmentation plants to provide a useful plastics fraction.

Earlier attempts to solve the problem were unsuccessful because it was thought necessary to provide a means of segregating each individual plastics material. This can be done, of course, but at much too high a cost - a cost which no one will pay for contaminated materials.

The "light" fraction coming from the fragmentizer is a voluminous mess containing natural and synthetic textile fibres, paper fibres, light metals, glass, mud, rubber, plastic or rubber foams and thermoplastics.

It is necessary to separate out the foams, which is easily done because of their very low bulk density. It is also relatively easy to get rid of sand, glass and light metals by means of mineral jigs.

Rubber can be removed by using the greater resiliency of rubber to separate it from plastics.

The US Bureau of Mines' laboratories at Salt Lake City and College Park, Md., have most of the answers on the individual separation problems.

The mixture obtained from the separation of the shredded automobile will contain polypropylene, ABS, acrylic, high and low density polyethylenes, pvc, nylons, polycarbonate, and also such non-thermoplastic items as cellulose fibre, dmc, smc, phenolics, epoxies, etc. So long as the non-thermoplastic items do not exceed 20 - 25% they are unlikely to cause much trouble.

Moulded by one of the three mixed plastics recycling processes, this mixture will produce a tough, hard, resiliant material somewhat resembling a rot-proof, splinter-proof, warp-proof wood with a density of about 0.8. The material can be worked with normal woodworking machinery.

The products which can be made by the recycling processes from such a mixture differ from the normal plastics products used by the automotive industry in that they do not have a high quality finish, and the moulding processes do not lend themselves to fine tolerances, though the dimensional stability is excellent. The colour possibilities are limited to painted finishes. The opportunities in the construction of corrosion-proof lightweight truck body components must be enormous.

THE CHANGING ROLE OF ADHESIVES IN THE AUTOMOTIVE INDUSTRY

C.David Larson

National Adhesives, Bondmaster Automotive Products.

Abstract

The government mandated improvement in gasoline mileage is causing a total re-evalutation of the materials used in automobile construction. A brief discussion of why adhesives will become preferred, even mandatory with increased use of plastics is offered. The presentation will cover adhesive types and forms with emphasis on those preferred. Performance data will be offered for adhesive systems bonding both rigid and flexible plastics. New adhesives technology and application being considered in the automotive industry will require a re-evaluation of testing techniques. Surprising results were obtained using aircraft industry techniques to test structural bonds.

POLYURETHANE SEALANTS AS A REPLACEMENT FOR VINYL PLASTISOL SEALANTS

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ABSTRACT

Two component polyurethane sealants with superior adhesion and cohesive strength than vinyl plastisols have been designed for application on FRP and primed metal. Advantages offered are low temperature cure, no paint bleed through and higher performance. Proper dispensing requires knowledge of equipment and will vary with each application. A sealant with the same flow characteristics may be adjusted to different line conditions by correct catalyst levels without changing cured properties appreciably. The key to switching from vinyl plastisol to PUR sealants is the need to improve corrosion resistance and/or a result of decreased paint oven temperatures and wherever FRP is used.

EMABOND PROCESS – UNDERSTANDING THE TECHNIQUE

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INTRODUCTION

The EMABond Process is an electromagnetic bonding technique used commercially to produce structural, hermetic or high pressure seals on any thermoplastic material. During the ten years of its introduction to the plastics industry it has also found utility for bonding thermoset, aluminum, paper and wood products to themselves and to dissimilar materials. Understanding the theory of electromagnetic bonding, one can easily grasp the wide range of applications using such products as EMAMelt, EMASol and EMAPoxy in addition to the EMABond materials. An explanation of these products will be discussed in this paper.

THEORY

There are basically two types of radio frequency (RF) heating, namely, dielectric and induction. This Process is based on the principles of induction heating. The induction heating industry supplies systems to anneal and heat treat many forms of ferrous-type materials by subjecting them to an oscillating magnetic field generally in the 450 - 500 kilohertz range.

In the case of electromagnetic bonding for thermoplastic materials, a fine micron sized ferromagnetic powder in the form of iron or stainless steel powders is dispersed within a thermoplastic binder generally of the same polymer as that to be bonded. This thermoplastic electromagnetic material is then located at the abutting surface of the parts to be bonded and subjected to a high frequency magnetic field ranging from 3 - 10 megahertz. The power particles then produce heat losses in the form of hysteresis and eddy currents, thus melting the binder, and upon contact pressure, transfer the inductive heat via conduction to the abutting surfaces for fusion. The resultant weld becomes integral with the electromagnetic interlayer.

EMA-TYPE MATERIALS

EMABond- These materials are generally in the form of molded or extruded profiles which locate themselves at the bonding interface and develop fusion temperature to produce structural, hermetic or high pressure seals on any thermoplastic material. Because the binder is generally the same as the parent material to be bonded, the resultant bond retain the same characteristics.

EMAMelt- This is basically a hot melt composition at 100% solids containing a dispersion of the ferromagnetic particles. It is deposited with standard hot melt techniques, however, its utility is primarily when large surface areas are required to be bonded. Standard hot melt compositions are formulated with certain open time and tack free time in order to allow the fabricator sufficient time to assemble his products. Dispensing temperature and viscosity also becomes very critical to the application. With an EMAMelt composition, one can deposit at the lowest practical temperature and viscosity and, then, when the two substrates are together, subject the composition to the magnetic field and bring the EMAMelt to its most efficient temperature for optimum wetting and adhesion of the abutting surfaces. This assures no degradation of the basic hot melt and produces a fast and reliable means of controlled heat activation. Both abutting surfaces to be bonded are exposed to the same hot melt temperature. This affords fabricators with the ability to store a pre-coated surface and heat activate at a future time during the assembly operation. Open time and tack-free time are no longer a prime requirement for an application. Pot life is extended with no tendency for charring. Hot melt manufacturers are constantly being pressured to reduce costs even though raw materials used in hot melts are rising sharply. The EMAMelt approach is considerably more economical due to the fact that high priced additives for heat stability and open time and tackifiers are minimized.

EMASol- These products, as the name implies, are 100% solid vinyl plastisols liquid at room temperature and contain the ferromagnetic particles. Again, the standard techniques for curing vinyl plastisols into a wide range of durometers is to subject it to a convention oven heating or in some cases, by conduction on a hot plate. Since the vinyl plastisol is a non conductor, heat time and temperature are critical to a proper cure since temperature must be conducted from the outside surface of the mass to the inside. With an EMASol composition, a discrete heat source is located throughout the plastisol mass, therefore, once it is subjected to the magnetic field - there is an instant gel and cure of the entire mass instead of incremental heating throughout the mass. Curing time, depending upon the mass, is drastically cut down. Production rates are increased to an unbelievable one hundred fold. Plant space is drastically reduced by eliminating the high energy consuming, inefficient, low efficient, large convention ovens. Electrical power consumption is likewise drastically reduced. All in all, this concept of EMASol technology can revolutionize the present market place. One must weigh the advantages and disadvantages of the approach. The following chart outlines some of them:-

EMASOL

ADVANTAGES	DISADVANTAGES
1. Fast	1. Color effects due to magnetic filler.
2. Uniform through cure	2. High density.
3. Low power cost	
4. No part distortion due to oven exposure.	
5. No costly metal molds.	
6. Use of machinable thermoset or other non-conductive molds.	
7. Selective heating.	

EMAPoxy- These products are basically 2-package or 1-package epoxy compositions with ferromagnetic fillers. The primary use of these products is to provide a rapid development of exotherm temperature. They provide means of having an extended pot life, but when subjected to the magnetic field, they will develop instant temperature prior to gel. They eliminate use of clamps or fixtures to hold components together during the exotherm. Care must be taken not to degrade the epoxy by subjecting it too long in the magnetic field. Spot welds can be obtained with no

distortion in the overall part. It naturally is a very fast reacting composition but can be tailored for any application.

The above discussion outlined the four basic material types used in the EMABond Process. We will now review the following items in order to have a better working knowledge of using this technique:-

1. Components of Process.
2. Work Coil design.
3. Factors affecting heating rate.
4. Joint designs.
5. Typical applications.

COMPONENT OF PROCESS

There are four basic components of the Process, namely,
1. High frequency induction generator.
2. Work coil or inductors.
3. Fixturing.
4. EMA-type materials.

High Frequency Induction Generators- This is the power source which converts 60 hertz frequency to high frequency in the range of 3 to 10 megahertz. In some cases due to application, frequency of 27 to 45 megahertz may be used. The power output for a majority of applications ranges from 2-5 KW and in few cases up to 15 KW. The generator is supplied with a water-to-air heat exchanger for a self-contained water cooling of the tank circuit. As a standard unit, the generator is divided into three basic circuits, namely, the power supply, control circuit and the RF oscillator tank circuit. The latter is connected to an external work coil or inductor. It is the heart of the induction generator and care must be taken to balance the external work coil with the tank circuit in order to obtain maximum efficiency of heating. All equipment is FCC certified for any communications interference.

For special applications where mobility is required, the three circuits can be provided in modules wherein the external work coil is then connected directly to the terminals of the remote oscillator tank circuit consisting of a portable box with line cords going to the power supply and control circuits. This will provide portability for field installations.

Work Coils- The work coil primary purpose is to establish a uniform concentrated magnetic field through the EMA-type material in order for it to develop a uniform temperature. Since heating rates are relatively fast in the order of fractional seconds to a maximum of thirty seconds for one shot welding of large components, the uniformity of the magnetic field is extremely important and becomes dependent upon the different types of work coils.

Work coils are generally made from round or square copper tubing ranging in size from 1/8", 3/16", 1/4" and 3/8". Round coils can be flattened to make them oval in shape. Rectangular copper tubing is also available for special applications. In many cases, machined copper blocks can be made to conform more exactly to the part configuration where bending copper tubing is not practical or exact. In all cases, all work coils must be water cooled which is the purpose of the heat exchanger to provide controlled water temperature through the tank circuit.

Work coils are made to have direct contact to the part to be bonded if necessary. Since parts must be under contact pressure through the heat cycle, the work coil acts as the pressure medium plus establishes the magnetic field. Coupling distance of the work coil to the part is of paramount importance as can be seen in latter application.

There are four fundamental work coil designs of which modifications of each can be made. These are single-turn, multi-turn, hair-turn and pancake type. The single-turn coils can be circular, oval or rectangular and they produce a magnetic field within the inside surface - more concentrated on the coil surface and decreasing in intensity inward. There is very little if no magnetic field on the outside wall of the coil. For example, a one-inch I.D. circular coil is very intense within the boundary of the I.D. dimension, however, as the coil I.D. is made larger, say to six inches, there becomes almost an "eye of a storm" wherein there is minimal field within the vertical center line of the coil. If the bond line is located uniformily off the coil I.D., and if the part is designed to allow a reflector coil, a more concentrated magnetic field is thus established between the two coils with zero field on the reflector coil I.D. As a general rule, the depth of the field above and below the work coil is one-half the inside diameter. In order to throw the magnetic field further down or up, a sintered iron core material of proper frequency can be placed above or below the work coil surface. This allows the magnetic field to reach some generally inaccessible location for a greater depth of field. A multi-turn or barrel coil is simply more turns to encompass a greater area of heating. The same conditions apply for this type of coil as in the single-turn. If, for example, a two inch length of turns is desired, one can use a solid machined single-turn coil two inches thick. In any case, the amount of copper used in making the coil is related to maximum energy available from the generator power supply and its frequency. Trial and error test coils are usually the norm in many applications until the most efficient working coil is obtained. Experience dictates the most practical coil to use, keeping in mind the objective is to use the lowest KW rating generator for each application to minimize tooling costs. A hair-pin coil is basically a single-turn coil in a hair-pin type design. The magnetic field is very concentrated between the coil turns, or coupling distance as normally referred. This type of coil is used to heat perimeters up to 20 feet long along a flange by locating one turn under and the other turn above the flange. They are made to be split by having one turn fixed and the other movable and connected to a press action for direct contact pressure of the coil to the part surface. These coils are very practical and are also used to heat irregular contoured parts to weld along the part perimeter The coupling distance of the two turns are again very important and dictate the rate of heating. For example, depending upon the EMA-type and size the following typical heating times are required for a hair-pin coil coupling distance vs. bond length:-

Coupling Distance	Bond Length	EMA Size	Heat Time
.270"	3 ft.	.090" dia.	6 sec.
.200"	16 ft.	.085" dia.	40 sec.
.500"	6 ft.	.150" dia.	15 sec.

Using the same power source and a single-turn coil of about ½ inch diameter, a part can be bonded within 0.1 seconds. This illustrates the range of heating ability depending upon the part configuration, size of bond and EMA-type.

Pancake coil is wound in circular or rectangular fashion similar to the heating element on an electric stove. The magnetic field produced is relatively short above the flat surface. It is not practical to be machined, therefore, tubing turns should be very exact in order to produce uniform field above the turns. It can be used to bond continuous lengths of thin sheeting or filter cartridge end caps.

Until some expertise can be developed through experience, work coil design and building is a "black art" and extremely important to a successfully designed application. It requires more exactness in building as compared with the coils required in the metal heating induction industry.

The above four fundamental type work coils can be combined into multiple units in series or paralled for use in heating multiple stations with a single power supply. As stated, they can be made as split coils. Parts can automatically traverse through or on the coils for continuous type bonding. Spot welds can be made.

FACTORS AFFECTING HEATING RATE

The following factors are primary considerations for heating rate in the EMABond Process:-

1. Part size and geometry
2. Joint design
3. Size and type of electromagnetic material
4. Work coil design
5. Generator power output
6. Generator frequency output
7. Coupling distance of work coil to joint

Fixturing- As the name implies, work coils must be held in position for part handling and protection from operator contact. Even though the work coils are water cooled which means they never get hot to distort a part surface or can be touch after a heat cycle, production work coils must be protected from direct contact during a heat cycle, otherwise an RF burn will result. This is a high voltage, low current burn. There is no chance of electrocution. An operator does not go into shock, but will obtain a burn depending upon length of direct contact as to

its severity. It is therefore imperative that all production coils be insulated or made inaccessible to direct operator contact. Other than this there are no other hazards from a working coil or the Process.

Work coils are generally encased in a thermosetting material such as polyester/fiberglass or epoxy/fiberglass. These materials are machinable and can be formed as fixtures or nests for the work coil. No metal fixtures are used in direct contact with the work coil. Nylon or brass screens are used to assemble the non-conductive materials. Once the work coils are fixtured they can then be placed into a press or conveyorized system. Depending upon the coil type metal components can be used. For example, if a single-turn or multi-turn coil is used, metal components can be located one inch away from the coil O.D. and at least two times the coil diameter in the vertical plane.

To meet OSHA requirements when press action is employed, a dual push button is used which sequentially activates the pressure stroke, heat and hold cycles. This keeps the operator's hands away from being caught in the pressure cycle. In a continuous conveyor-type assembly, micro-switches can be used to actuate all cycles.

Joint Design- In designing a joint for the EMABond Process, one must remember that once the electromagnetic material is heat activated, it will start to soften and flow and depending upon its mass can be directed to flow into void areas or cavities as the case may be. This is another advantage of the Process in that the EMA-type material can flow and fill voids due to shrinkage or heat sinks in the molded part. In all joints, contact pressure must be provided to assure uniform transferral of inductive heat to the abutting surfaces. Depending upon the thermoplastic to be bonded, increasing contact pressure is required as one bonds the softer polyethylenes as compared to the engineering thermoplastics like polycarbonates and polysulfones with their higher melt temperatures.

These are basically three different joint designs for use which are dependent on whether the parts are injection molded, extruded, thermoformed, roto-cast or blow-molded plus, the desired location of the bond line within the part. These joints are referred to as flat/flat, flat/groove or tongue/groove. In all cases, joints should be designed in shear stress for maximum strength.

Flat/Flat- Whenever there are two flat surfaces to bond, the original cross-sectional area of the EMA-type material will spread out widthwise. For example if we are to bond two .060" thick sheets together and we start with a molded EMABond profile cross-section of .250" wide x .015" thick; the resultant bond could be as wide as .5 to .75" wide and it would be somewhat irregular in length. The final thickness of the composite could be .120" depending upon the amount of pressure used during the heat cycle.

This type of joint is generally used in bonding flat sheeting or film or molded thin wall flanges. It can provide leak-proof pressure seals as in bonding two thermoformed tray sections around the perimeter.

Flat/Groove- In this case we have a groove on one part and a flat surface to be bonded. An EMA profile is dropped into the groove having a thickness about .010/.015" greater than the groove depth. The width of the EMA profile is then determined by the general formula as follows:-

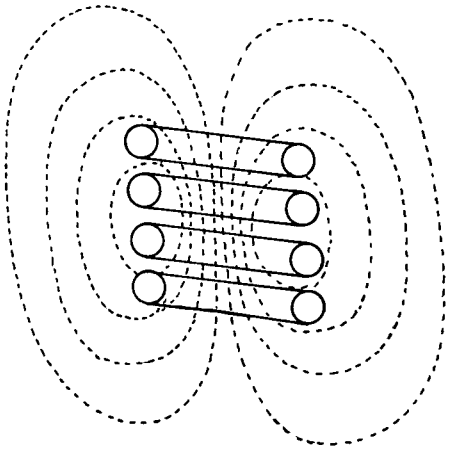
$$A_V = 1.05\ A_V$$

where A_E= cross-sectional area of EMA profile before heating.
A_V= cross-sectional area of void after heating.

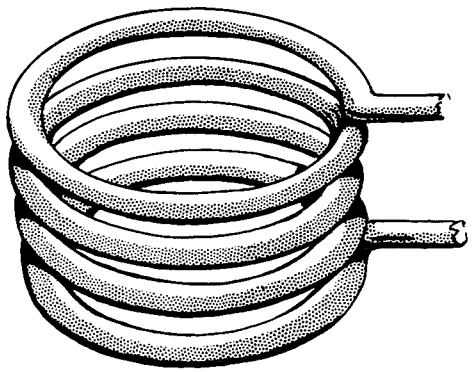
This general formula provides an internal pressure on the joint as it is being filled and is used whenever molded part assemblies require reliable pressure tight welds. The constant factor can range between 3-5%. Thus eliminating a 1:1 ratio in fill.

The analogy in most of EMABond type applications is similar to injection molding in filling a mold cavity. A certain amount of fill pressure is required in order to obtain a good molded part.

Tongue/Groove- This type of joint is preferred whenever possible for high pressure seals, especially when it is designed in shear. It will provide the ideal 100% reliable joint. The tongue is used to provide uniform registration of the preassembly while the flow goes up the opposite tongue wall in shear. Molding irregularities are easily filled. No flash on the parting line. The bond wall in shear can range from .015 to .040" thick.



MAGNETIC FIELD
in multi-turn coil



MULTI-TURN COIL

FIG. 1

SINGLE TURN COIL

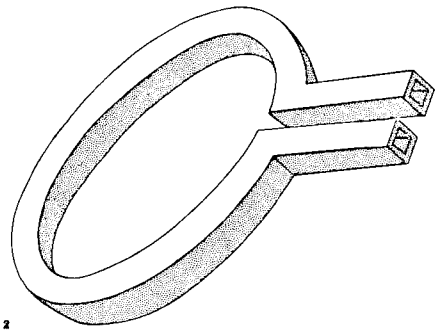


FIG. 2

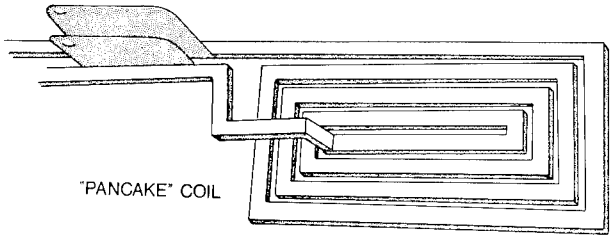


FIG. 3

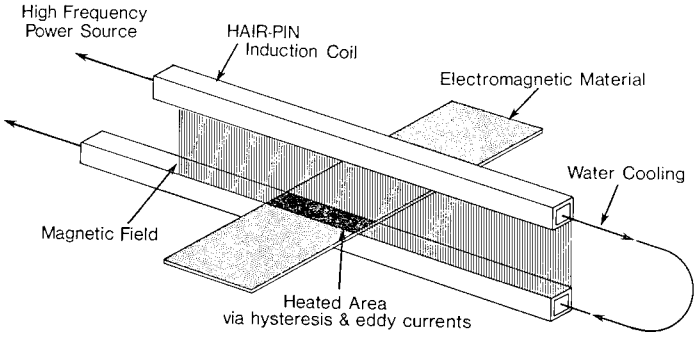
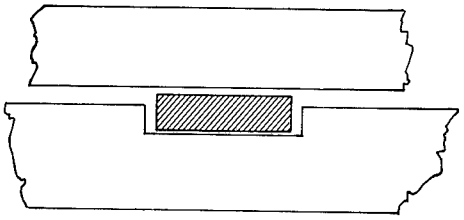
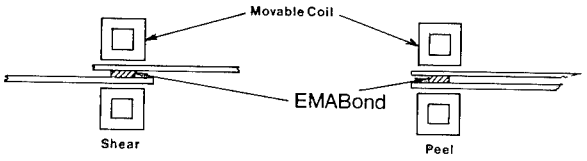


FIG. 4



FLAT TO GROOVE JOINT



FLAT TO FLAT JOINT

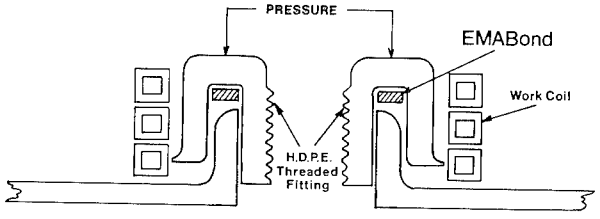


FIG. 5

TONGUE TO GROOVE JOINT

ULTRASONIC AND VIBRATION WELDING: TOOLS FOR GROWTH OF PLASTICS IN AUTOMOBILES

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INTRODUCTION

Plastics welding techniques and equipment are frequently overlooked in the automotive industry's race for weight and cost reduction, yet they have played a tremendous part in the success of major plastics applications. A knowledge of the capabilities and technological advances of two of the major methods, ultrasonic welding and vibration welding, can contribute to greater and more creative usage of plastics in transportation in the 80's.

ULTRASONIC WELDING

Since education of the theory of ultrasonic joining is not the purpose of this paper, only a brief description of the process will suffice. In this process, high frequency mechanical vibrations are utilized to melt the joining surfaces of thermoplastic parts and fuse them together with a strong molecular bond. Friction and the alternating high frequency stress produced by the vibrations heat the plastic at the interface causing it to melt.

There are five major components of an ultrasonic welding system: the power supply, converter, horn, fixture and stand. The power supply elevates the line voltage and converts its frequency from 60Hz to an ultrasonic frequency, generally 20kHz. Power supplies are available with power from 150 to 3000 watts. The converter, utilizing piezoelectric ceramics, converts the electrical energy to 20kHz mechanical energy in the form of axial mechanical vibrations.

The converter is connected to the horn, a resonant metal section tuned to vibrate at 20kHz. It is designed to transmit the mechanical vibrations of the converter to the parts being welded. Horns generally are fabricated from high-strength titanium or aluminum and are designed to conform to the part to be welded. When needed, the amplitude of the axial vibrations can be increased or decreased by a booster horn which is a secondary metal section between the horn and converter.

The pneumatic stand houses the converter, electronic programmers, pneumatic controls, and, in some models, an integrated power supply. The stand lowers and raises the horn/converter assembly onto the workpiece, providing proper alignment and applying a predetermined force.

The fixture, or nest, supports and aligns the part to be welded under the horn. It is generally fabricated from aluminum or steel and is sometimes lined with epoxy or cast polyurethane.

During the ultrasonic assembly cycle, the vibrating horn contacts the part under controlled clamp force through a timed cycle. Ultrasonic vibrations pass from the horn through the plastic material to the joint where heat is generated. The plastic melts, flows, and forms a permanent bond. After the vibrations stop, pressure is briefly maintained on the part to allow the plastic to solidify under pressure. Total weld cycle is usually less than 1.5 seconds.

This process has major advantages for the automotive industry. It is fast, clean, eliminates consumables, does not require a skilled operator and lends itself to automation. It produces excellent joint integrity and can be applied to the majority of thermoplastic materials in use in today's automobiles.

ADVANCES IN ULTRASONIC EQUIPMENT

Ultrasonic welding equipment has been used increasingly since 1963. The equipment from that era is relatively primative when compared with the sophisticated equipment of today. There have been many recent advances in equipment, perhaps the most important being higher powered units; 20kHz welders with power to 3000 watts are now available. This is more than double the maximum power available only three years ago.

Perhaps the greatest advantage of higher power is shorter weld time, since it directly affects the economics of an application. For a given amplitude, the energy required to weld is the product of the average power dissipated at the joint and the weld time. Therefore, increasing power significantly reduces weld time as shown in Figure 1. Because the heat loss from the weld zone into the surrounding area increases with time, the power-time relationship for equal welding is represented by the dotted line and shows that shorter weld time is more efficient(1).

Higher power enables a greater joint area to be welded. This translates into the capability to weld larger parts, because, with the same wall thickness, more linear inches of joint can be welded.

Plastics which require high energy levels can benefit from higher power. Typical of these are crystalline resins such as nylon, acetal, and thermoplastic polyester which require additional high energy to break down their crystalline structure before melting can occur. Others include high melt point amorphous plastics such as polycarbonate and polysulfone. The size of parts made of these materials has, in the past, been limited by the amount of heat energy which could be delivered by a welder.

A number of special features and auxiliary products have been introduced. One feature which has dramatically increased the reliability of ultrasonic welders and reduced downtime is a System Protection Monitor. More than just an overload circuit which protects critical components in the equipment, it compels a user to establish correct operating conditions and alerts him when an adverse operating condition occurs, such as the need to adjust tuning or a loose or failed horn, converter or booster.

A line voltage monitor indicates when the voltage to a welder is too high or too low. Either of these conditions could damage a welder, and they would certainly cause a variation in the output which would in turn cause sporadic welding results if not detected.

New auxiliary equipment includes a plug-in transistor tester for rapid, convenient troubleshooting, a welding systems analyzer to record welding parameters, and an energy control programmer/weld quality monitor which automatically compensates for variations in voltage, clamp pressure, small differences in part fit and other factors.

Advances have also been made in horn technology. With the advent of higher powered ultrasonics and the demand to assemble more complex parts, there has been a requirement for horns that weld better and handle a greater variety of part sizes and configurations.

Typical of the newest generation of horns are large size horns such as 4in. x 24in. (102mm x 610mm) and 9in. x 12in. (229mm x 305mm) which couldn't be driven by earlier, lower powered equipment(2). Others include composite full-wavelength and wear-resistant horns.

A composite horn is a full-wavelength device usually consisting of a main half-wavelength driver to which one or more half-wavelength horn extensions are attached. They are generally used in those applications where high energy concentration is necessary at localized points over a large area (i.e., multiple staking applications) or where part clearance presents a problem. The biggest advantage in using a composite horn is that higher amplitude can be built into the horn without causing excessive stress. This is important when considering horn life and weld repeatability. Composite horns can also provide greater part coverage, which in some cases can eliminate the need for an additional welder.

Although full-wave horns cannot be classified under "new technology," they have received little publicity and are relatively unknown. In the past, full-wavelength horns were primarily used when deep clearances (2-8in.) (51-203mm) in a horn were required. However, this fundamental design concept has been used to solve certain problems inherent in half-wavelength horns. For example, the most common failure in large diameter slotted horns is cracking across the stud (this is due to the horn being driven at too high an amplitude). A full-wavelength horn designed with a booster at its drive section can eliminate cracking across the stud. Amplitude is built directly into the horn, allowing it to be driven by a lower booster than previously required to produce the necessary amplitude to run the application. In effect, the stud has been moved from a high stress area to an area of lower stress.

The advantages derived from the use of full-wavelength horns are: 1. More uniform activity across the horn face. 2. Higher amplitude at the face. 3. Longer horn life (due to less stress). 4. Higher weld reliability.

Excessive horn wear, which leads to reduced horn life, usually occurs in the following situations: 1. Metal insertion applications where the horn contacts the metal insert. 2. Applications where the material being contacted by the horn is abrasive in nature (i.e., glass-filled thermoplastics). This is especially true when the horn comes in contact with molten plastic.

Depending on the situation, certain types of horns can be utilized to provide better service for such applications. For insertion, either hardened steel or carbide-faced horns should be used. In applications where the horn contacts an abrasive material, carbide-faced horns with EDM shapes or cavities have increased horn life by a factor of five in some cases. The use of hardened steel horns is not recommended for these applications because they are unlikely to withstand the high stresses developed when driven at the amplitude levels required by the application.

ULTRASONIC APPLICATION TECHNOLOGY

In the field of application technology, ultrasonic energy has been used to "remold" or form thermoplastic material, usually an extruded piece, into a desired shape. Detailed profiles or flanges can be formed on the end of a tube (may eliminate special fittings) for gas or vacuum lines or control cables. Tube ends can also be closed to obtain hermetic seals.

Ultrasonic welding equipment is easily adapted to automated systems. Used singly or in multiples to cover a large area, a wide variety of applications are possible. A fairly unique ultrasonic system using 32 welders to tack a flexible PVC door trim piece to a rigid ABS arm rest panel is shown in Figure 2. The edges of the PVC are automatically folded and wrapped over the ABS, and specially configured horns pierce through the material and melt into the ABS. The displaced melt solidifies, locking the PVC to the rigid panel. The unit eliminates the cost of staples and manpower.

In another example, inlays of cellulose butyrate are ultrasonically bonded to a steering wheel using one welder and a rotating fixture in a rotary scan welding system. The inlay is progressively bonded as the wheel passes under the continuously vibrating horn.

Ultrasonic energy is being used in conjunction with adhesives and solvents, materials which are usually eliminated by an ultrasonic operation. In this case, the ultrasonic energy is used to provide the heat necessary to reactivate the adhesive or accelerate curing when joining dissimilar materials including metal for functional as well as decorative parts. Ultrasonic energy is one of the most efficient heat sources available. It generates heat only at the desired location since energy is passed to that point in the form of 20kHz mechanical vibrations where it is then converted to heat. No temperature controls are required, and power is used only when activated.

These operations utilize the same equipment commonly used to weld automotive lamp assemblies, instrument panels and clusters, and emission control valves to name just a few of many.

Fabric and film applications for interiors are increasingly being processed with ultrasonic energy. Many synthetic fabrics are being "sewn," cut, or edge sealed in a number of industries. These operations are done in a plunge mode in which the horn comes down on the workpieces to perform an operation, or in a continuous mode in which the workpiece is fed between a continuously vibrating horn and a rotating anvil at speeds in excess of 150ft/min. (45 meters/min).

A typical ultrasonic welder with a continuous sealing attachment is shown in Figure 3. The application in this case is the bonding or "sewing" of nonwoven fabric to produce welting for hog rings used in the attachment of seat cushions to frames.

Two welts are produced at a time for an output of 300ft/min. (91 meters/min). Conventional industrial sewing machines operate at speeds of 75ft/min. (23 meters/min) and use a consumable, thread. The ultrasonic process eliminates the cost of thread storage, handling, and rethreading as well as the cost of the thread itself and needle breakage.

This same continuous operation can be used to simultaneously cut a fabric and seal the edge to prevent unraveling and eliminate either overedging or binding as seen in the samples in Figure 4. In the plunge mode, the same principle is applicable to producing openings with sealed edges in fabric for window cranks, seat belts and others.

From a problem-solving viewpoint, ultrasonic bonding could be used on cushions, headrests, and armrests to provide a continuous seal which would allow the auto industry to utilize a liquid foam process without having foam oozing through needle holes. To take advantage of this opportunity, it would be necessary to work with supported urethane fabrics rather than vinyl fabrics, because the latter are not as compatible with the ultrasonic process as the urethane. Fabric cost may make this impractical unless the advantages and savings of the overall process outweigh the fabric cost.

One of the most successful production applications utilizing ultrasonic sealing has been battery plate separators of polypropylene which make the lifetime battery possible. Most separators are currently being ultrasonically welded using either the plunge or continuous mode depending on the speed requirements of each individual manufacturer, replacing heat sealing. This method is faster, stronger, more consistent, and requires much less energy.

VIBRATION WELDING

A second, more recently developed assembly method is vibration welding. Production equipment became available in 1975. In vibration welding, the plastic is melted by heat generated by friction when one of the parts is pressed against the other and vibrated through a small stroke (relative displacement) of 0.030in. to 0.140in. (0.75mm to 3.5mm) in the plane of the joint for 2 to 4 seconds. When the vibratory motion stops, the parts are automatically aligned to the center of the stroke;

pressure is maintained until the plastic solidifies (usually less than 1 second) to bond the parts permanently with a strength approaching that of the parent material.

The equipment employs an electro-mechanical resonant suspension drive system(3). The drive element, or vibrator, consists of only one moving part, the resonating drive platen, which is suspended from the frame of the vibrator by springs. Reciprocating motion is achieved by magnetic force from two electromagnets acting on the drive platen member at a frequency of 120Hz or 240Hz.

Pressure is applied to the parts by a pneumatically operated clamping mechanism which engages the "tray" into which both parts to be joined have been loaded. As the tray is raised, the upper part is automatically fed into the drive fixture and a force of up to 2000 lbs.(8.9kN) is exerted between the two parts.

At the end of the cycle, the parts are automatically aligned and held under pressure until the plastic solidifies. The tray is then lowered, and the welded part (or multiple parts, since several can be welded at one time) is returned to the unload/load position.

The most recent advancement of the process is a 240Hz unit. This unit vibrates at half the stroke of the 120Hz welders and produces slightly less flash which is more easily controlled; however, it is more expensive than the 120Hz.

While this process is applicable to all thermoplastic materials including elastomers, in the automotive industry it has been used most frequently with nylon, polypropylene, polycarbonate, acrylic and ABS.

VIBRATION WELDING APPLICATION TECHNOLOGY

Vibration welding is, without a doubt, the most advantageous assembly method for welding nylon. It is difficult and, in some cases, impossible to weld by other techniques such as hot plate welding, ultrasonic welding and induction bonding because of its melt temperature, crystalline structure, hygroscopic nature and susceptability to oxidative degredation. Vibration welding has found its way into three major automotive applications (Figure 5). All three are under-the-hood applications and have demanding performance requirements in keeping with the properties of nylon, a high performance engineering thermoplastic.

Vapor emission control canisters of Zytel^{R} nylon 66 have been in use since 1975 and are still being produced on the original equipment. They resulted in a weight savings of 1.6 pounds (0.72kg) over former metal canisters. They are assembled in a fully automatic line with four vibration welders at an incredibly short 6 second total cycle resulting in an effective production cycle of 1.5 seconds per part. Over 15,000,000 are currently in use. A second generation of canisters just introduced also uses vibration welding. Nylon parts such as these do not require drying before welding.

The air diverter valve of Zytel^{R} 33% glass-reinforced nylon 66 requires a hermetic seal and high strength. The manifold outlet fitting is vibration welded to the body, two parts at a time. The switch from zinc to nylon resulted in a 60% weight reduction. The fitting weld must resist a 550 lb.(2.4kN) pushoff force, withstand the under-the-hood environment and be flash-free inside and out. The third application, a brake fluid reservoir of 13% glass-reinforced nylon, requires minimum burst pressure of 40 psi (276kPa) and must also be flash-free.

A number of polycarbonate automotive applications are vibration welded, but none are more demanding than the tungsten halogen headlamps of Lexan^{R} from G.E. shown in Figure 6. A strong hermetic seal and a flash-free interior are an absolute necessity. The lens is vibration welded to the parabola, and the bulb and socket are welded in place by ultrasonic welding. This headlamp is one-third the weight of its glass counterpart, is tougher, and has more precise optics. Other polycarbonate applications include auto lamp assemblies, headlamp doors and glove box doors.

Polypropylene, like nylon, another resin with very limited welding possibilities, is being easily vibration welded in such parts as vacuum reservoirs, windshield washer bottles, and station wagon interior storage doors. Cycle times for welds are 2 to 4 times faster than with hot plate welding.

Vibration welding is an infant by comparison with other assembly techniques, and one can expect to see additional advances in both equipment and applications. The same expectations are well founded for ultrasonic welding, also.

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2. Mainolfi, Sylvio, "What's New in Horns," Ultrasonic News, Branson Sonic Power Co., Sept. 1978, 4,5.
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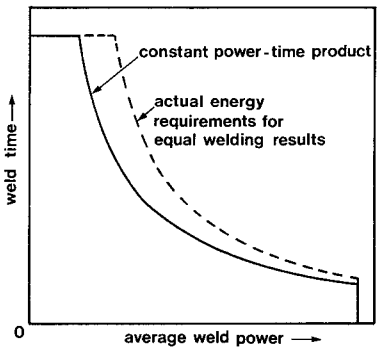

Figure 1. Power-time relationship in ultrasonic welding.

Figure 2. Multiple welder system for armrest-door panel of vinyl and ABS.

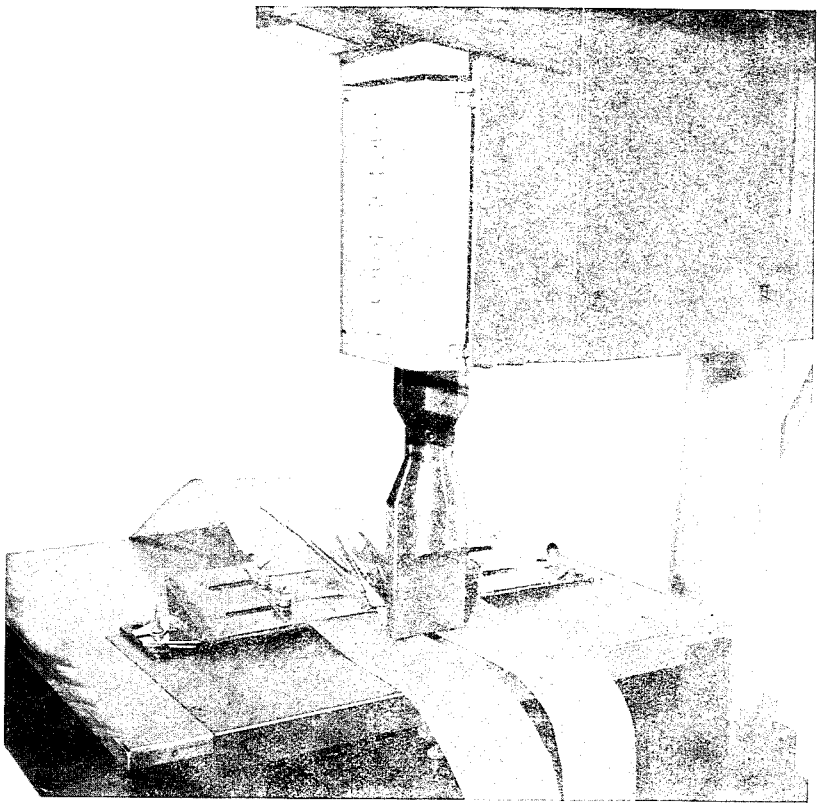

Figure 3. Typical ultrasonic welder with continuous sealing attachment for hog ring welting of nonwoven fabric.

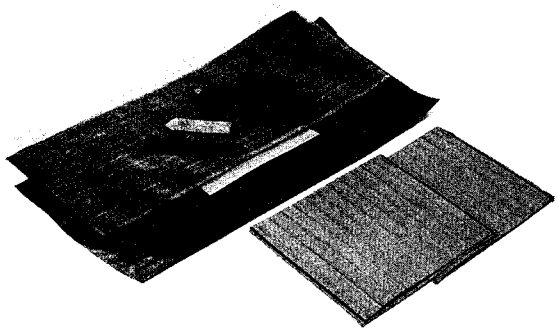

Figure 4. Fabric and film sealing: battery separators and edge cut and sealed upholstery.

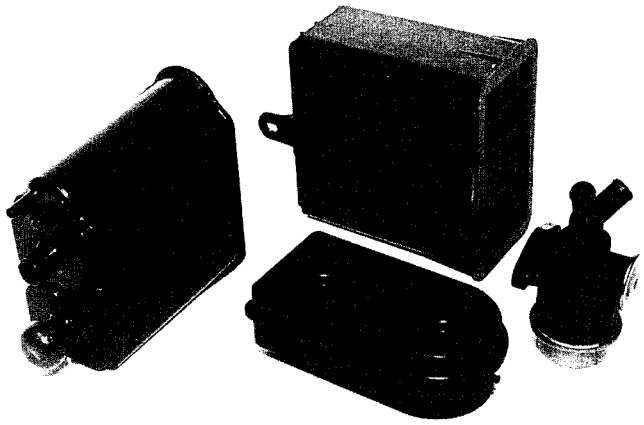

Figure 5. Vibration welded parts of nylon: vapor emission control canister, brake fluid reservoir, air diverter valve.

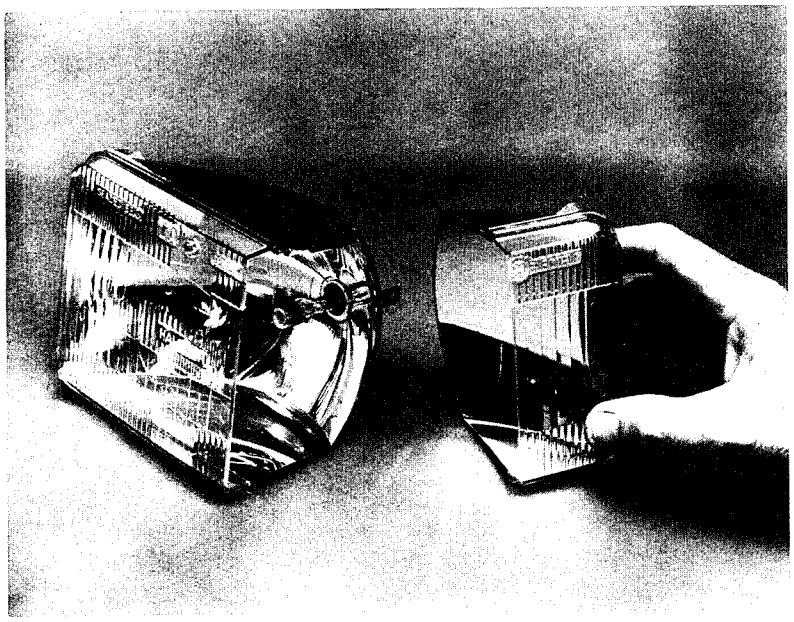

Figure 6. Vibration and ultrasonic welded halogen headlamps of polycarbonate.

HEAT WELDING OF MOULDINGS AND PROFILES IN THE AUTOMOTIVE INDUSTRY

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1. INTRODUCTION

The constantly increasing use of plastics for automotive parts inevitably leads to the problem of replacing the more complicated components - which presently are made of metal - by plastics as well. Due to its economic way of manufacture, thermoplastic materials are preferrably used. It frequently is not possible, however, to manufacture complicated, technical components in one operation due to the procedure of blow moulding, extruding or injection moulding, and assembly of two or more parts to one component is necessary. In the past these parts were assembled by screws, rivets, flanges etc. i.e. mechanically. The metal elements and seals required for the assembly represented additional problems in regard to the chemical and mechanical creep resistance. Furthermore, the assembly process is rather time-consuming and therefore inefficient.

Welding revealed to be a comparatively more elegant way of assembling parts of thermoplastic materials. Thermoplastic materials used for automotives are mainly high-frequency-, ultrasonically- or heat welded.

HF-welding is limited to sheets or foils which are welded to seat covers, door linings etc. Due to its welding procedure, ultrasonic welding is limited to small injection moulded parts made of relatively rigid materials with low absorption factor. As to the time required for the assembling process, heat welding of thermoplastic materials is inferior to ultrasonic welding, it is on the other side,however, nearly unlimited in regard to size and material type of the components to be assembled. It recently is also possible to weld certain groups of different material types together. In the following heat welding is explained in detail.

2. PROCEDURE

Heat welding of thermoplastics requires a hot plate for plastification of the fusion faces. Transfer of the heat can be assured either by contact or radiant heating. This hot plate is mostly made of aluminium, is electrically heated and electronically controlled. The hot plate's working surface is adapted to the shape of the component's fusion faces. In order to avoid melted material to adhere to the hot plate's working surface during contact heating, the hot plate can either be covered with teflon foil, three-dimensionally shaped hot plates are teflon coated.

The components to be welded are put against the hot plate. During the first stage of the heating process, a relatively high pressure is applied to guarantee displacing of the plasticized material, thus ensuring the components to be entirely adjacent to the hot plate. This process refers to the designation "matching" in the shown drawing. After completion of this stage, heating time commences and the pressure applied by the component to the hot plate is released to allow the heat to penetrate the material and create a sufficient amount of plasticized material necessary for welding. Subsequently the components to be assembled are removed from the hot plate, the hot plate itself withdraws from the working area - the necessary time is designed as "change-over time" - and finally both components are pressed together and welded by applying a pre-determined pressure. This welding pressure is continuously applied during the entire cooling time. As soon as the temperature in the fusion area drops below the crystalline melting point of partially crystal materials and below the softening point of amorphous materials, the welding pressure can be released and the welding process is completed. Fig. 1 illustrates the different stages of the welding cycle:

Following parameters are of importance for an optimum weld:

- the h o t p l a t e t e m p e r a t u r e depends on the material to be welded and is set by means of a special temperature controller. Equal temperature distribution on the hot plate working surface is very important.
- the h e a t i n g p r e s s u r e practically corresponds to the welding pressure, i.e. the pressure during matching process is relatively high to allow the fusion faces to quickly adapt to the hot plate contours. As soon as this is achieved, the pressure is released during heating time, either by means of stops of by control operation.
- during h e a t i n g t i m e the fusion faces remain in contact with the hot plate, without pressure, thus the fusion faces are plasticized without displacing the melted material.
- the c h a n g e - o v e r t i m e i.e. the period between heating and welding process, is to be kept as short as possible to avoid the plasticized material to cool off excessively.
- the j o i n i n g p r e s s u r e depends on the material viscosity and on the component's wall thickness. Materials with low viscosity, such as polyamids require a pressure of approx. 0.5 kg/cm^2, polyethylene and polypropylene approx. 1 - 2 kg/cm^2, PVC approx. 7 kg/cm^2 and materials of high-molecular weight require a pressure of approx. 20 kg/cm^2.
- j o i n i n g o r c o o l i n g time represents the time after welding.
- the w e l d i n g p r e s s u r e is maintained during this period of time. Additional cooling is not recommended.

Above parameters have to be met to obtain optimum weld quality. They only can be exactly observed and reproduced with welding machines of high-quality design.

3. WELDABILITY OF PLASTICS

Almost any kind of thermoplastic materials can be heat welded (with the exception of PTFE). The welding factors achieved range from 0.6 to 1, i.e. from 60 - 100% of the material strength. Materials containing fillers show reduced weld strength, this can be compensated by increasing the fusion faces. Furthermore, different material types can be assembled by heat welding, for instance is PMMA frequently welded to ABS. As a general principal, however, only the same material groups can be welded, i.e. partially crystal plastics among each other and amorphous plastics among each other.

4. DESIGNS OF FUSION AREAS

The requirements welded component and weld have to meet vary according to their application. A maximum of mechanical strength as well as hermetic seal or good cosmetic appearance represent the essential demands on the

weld. Different designs of the fusion area were developped to meet the various requirements.

4.1 Normal Butt Weld

The top picture of fig. 2 shows the normal butt weld mainly used for assembling technical parts where the visible weld flash is not disturbing.

4.2 Weld Covered on One Side

This form of the weld is chosen when the component to be welded does not have to meet any special requirements, but for optical reasons the weld flash needs to be invisible on one side. As shown in the figure, only half of the wall thickness is welded, whereas the rest serves as protruding lips which are merely joined. The groove between welding and joining faces takes up the weld flash.

4.3 Weld Set Back

In special cases, e.g. for tail lights or blinkers for cars, requiring a totally invisible weld flash, the fusion faces can be set back - as shown in fig. 2, picture 3.

4.4 Weld with Lap

Manufacturers of containers such as starter batteries frequently demand covered welds, i.e. non-visible welds. A covering lap (shown in fig. 2, bottom) provided at the lid edge, protrudes the weld. Small aligning pins at the bottom of the lid and welding ribs in the lid guarantee perfect meeting of the fusion faces even when deformed.

5. WELDING MACHINES

Heat welding of components of thermoplastics in high volume production requires welding machines which completely exclude any individual influence of an operator, i.e. semi- or fully automatically working machines. Loading and unloading of the components in semi-automatic machines is done manually, the welding process itself is performed entirely automatically. Fully automatic machines carry out loading, welding and ejecting of the welded parts in fully automatic operation.

When selecting the appropriate machine for production of a determined component, the machine's ability to guarantee reproducible welds and thus uniform weld quality is to be taken in account in regard to machine design and electro-pneumatic and hydraulic control. Shape and handling of the components to be welded decide the question of horizontally or vertically working machines.

In practice, semi-automatic machines are used for welding parts in small quantities. According to dimensions of the parts, multiple-cavity toolings can be employed allowing welding of several parts at a time. Loading time can be saved by using special loading tools, which are loaded by the operator during the automatic operation of the machine. After completion of the welding process, the parts are transferred to the machine and the loading tool is ready to be re-loaded.

For high-volume production, turntable welding machines in semi- or fully automatic design are available. Heating and welding process are carried through in two different working stations which results in shorter cycle times and increased output. Fully automatic infeed of the components in these machines is possible and further working operations such as testing, filling etc. can be integrated in the machine cycle. The following examples of application refer to further alternatives of machine types.

6. EXAMPLES OF APPLICATION

6.1 Welding of Gasoline Strainers

The gasoline strainers of polyamid, shown in fig. 3 are heat welded in high volume production. The parts are assembled by a simple butt weld with visible weld flash. The high output rate requires a semi-automatic welding machine, working horizontally with a double impression tooling and loading unit. The operating sequence corresponds to the description in point 5. Subsequent to welding the parts are ejected from the tool and leave the machine on a slide mounted to the machine. Output rate is 16 parts per minute.

6.2 Welding of Cool Fluid Reservoirs (fig. 5)

Cool fluid reservoirs of approx. 600 x 400 mms consist of two or three injection mouldings which are assembled by heat welding on a machine similar to the model shown in fig. 4. Holding tools mounted to the carriage of the machine maintain and align the components in their final position, which are clamped by vacuum and by mechanic system. The components are joined by a butt weld with visible weld flash, cycle time for one welding operation amounts to approx. 50 seconds.

6.3 Welding of Radiator and Fan Housings

The radiator housing shown in fig. 6 is made of talcum-filled polypropylene and consists of three parts. Assembly requires two welding operations. During the first operation - with machine type shown in fig. 4 - both heater halves are assembled, and in a second operation the fan housing is welded to the heater housing. Cycle time of the first operation is one minute, of the second operation approx. 50 seconds. Single-impression tools are used. The special design of the fusion faces prevents a welding flash from appearing at the housing inside. For that reason the lips merely meet each other at the inside and the ribs at the outside are welded together thus avoiding noises to be produced in the housing's inside by the passing air.

6.4 Welding of Air Nozzles made of polyethylene (fig. 7)

These parts are again welded with machine shown in fig. 4. Due to their size, three nozzles can be welded in one welding operation. The components to be assembled are injection moulded, the fusion faces are three-dimensionally shaped in accordance with the nozzle shape. The hot plates have to show the same shape as the fusion faces. This problem was solved by using adaptor platens which correspond to the outlines of the fusion faces and which are mounted to the plane hot plates. One complete welding operation, i.e. three parts at a time requires a cycle time of one minute. The joint is a pure butt weld, with the welding flash being visible inside and outside.

6.5 Welding of Trim Strips

The trim strips shown in fig. 8 are made of extruded profiles of PVC, cut to length. Injection moulded end pieces have to be attached to the profiles under a certain angle. The profile size allows welding of several end pieces at a time. In the present case, a five-impression tool is used which permits squeezing of the welding flash during welding operation. After completion of the cooling time, the flash is removed thus eliminating subsequent treatment of the profiles. Five of these end pieces can be attached to the profile ends by heat welding in a cycle of one minute, the appropriate machine is similar to the machine model shown in fig. 4.

6.6 Welding of Starter Batteries

The material used for producing case and lid of starter batteries is almost exclusively polypropylene. Case and lid are sealed by heat welding with semi- or fully automatic welding machines, which are integrated in production lines. Quite frequently the normal heat welding is replaced by "high temperature welding", a procedure working with hot plate temperatures of about 350° C and extremely short heating times of approx. 5 seconds. The hot plate is uncoated and the residues on its working surface evaporate during the time of rest of the hot plate. The strength of high temperature sealed welds is inferior to the strength obtained with normal temperatures. The obtained values, however, are quite sufficient for starter batteries and do meet their demands on weld strength and hermetic seal. The type of weld shown in fig. 2 bottom, ie. with lap is mainly chosen. Aligning pins provided in the battery lid assure perfect aligning of the ribs in case and lid.

6.7 Welding of Tail Lights

Fig. 9 shows the tail light of an Opel Senator, the housing is made of ABS, the lenses from PMMA. Three lenses have to be welded to the housing. The welding area corresponds to the third example of fig. 2. For reason of easier handling, vertically working machines are used for welding this kind of components. The housings are placed in the bottom holding tool, the lenses are loosely put on the housings and automatically transferred to the top holding tools before welding operation can take place. After welding, the operator takes the lights out of the machine. Cycle time of one welding operation amounts to one minute, one pair of lights being welded simultaneously.

For welding high production rates loading devices in form of turntables can be installed in front of the welding machines, enabling the operator to place the components to be welded in the holding tools and to remove the welded parts out of the machine during the automatic operating sequence of the machine.

Small parts with very high production rates, such as blinkers, require the use of semi-automatic turntable machines with 4 working stations. In the first station the operator loads the holding tools with the components to be welded, in the second station the top parts i.e. the lenses are transferred to the top holding tool, followed by the heating process in the third sta-

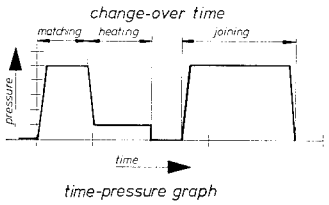
tion and the welding process in the fourth station. Here as well tools able to hold one pair of blinkers are used. Fig. 10 shows such a turntable machine.

6.8 Welding of Horns

The horns shown in fig. 11 consist of two ABS parts and one metal sheet. The metal sheet is flanged around the bottom part in the welding machine and both plastic parts are subsequently welded together. The extremely high production rate requires the use of a modified turntable machine with four-impression tooling allowing to flange, weld and automatically eject two pairs of horns at a time. The cycle time amounts to 20 sec., i.e. 12 horns per minute. The normal butt weld only creates a small weld flash which does not influence the horn's predetermined tone.

7. SUMMARY

Above examples only give a small review of the large application field of heat welding in high volume production. Optimum design of the components and use of high-quality welding machines guarantee economic production of plastic parts with perfect welds. Heat welding machines have to ensure entire reproduceability of their welding results. Heat welding is to a great extent independent of material and dimension of the components. Welding of tail lights of more than 1.2 m length for instance does not present a problem and these dimensions have not yet approached the limits of heat welding. The manufacturing staff can also easily understand the operating sequence and the welding machines can be designed according to the requirements the finished product has to meet and according to the desired efficiency.



time-pressure graph

Fig. 1

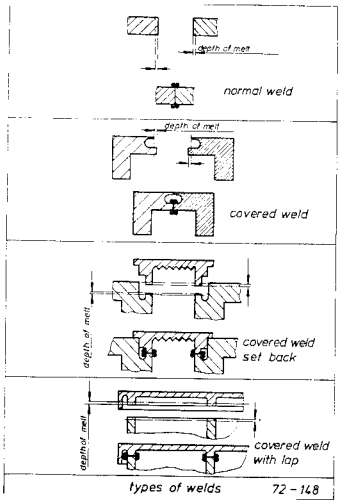


Fig. 2

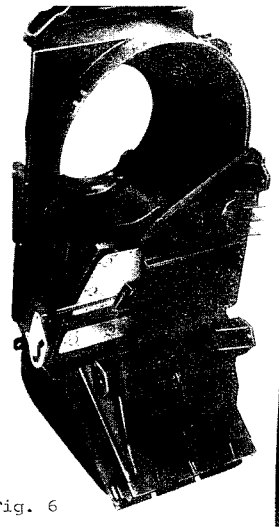


Fig. 6

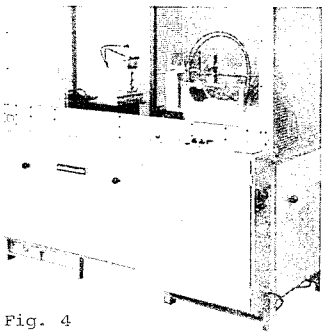


Fig. 4

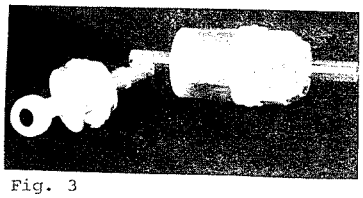


Fig. 3

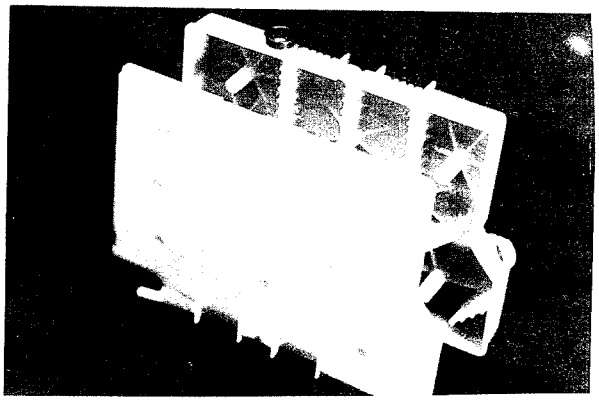
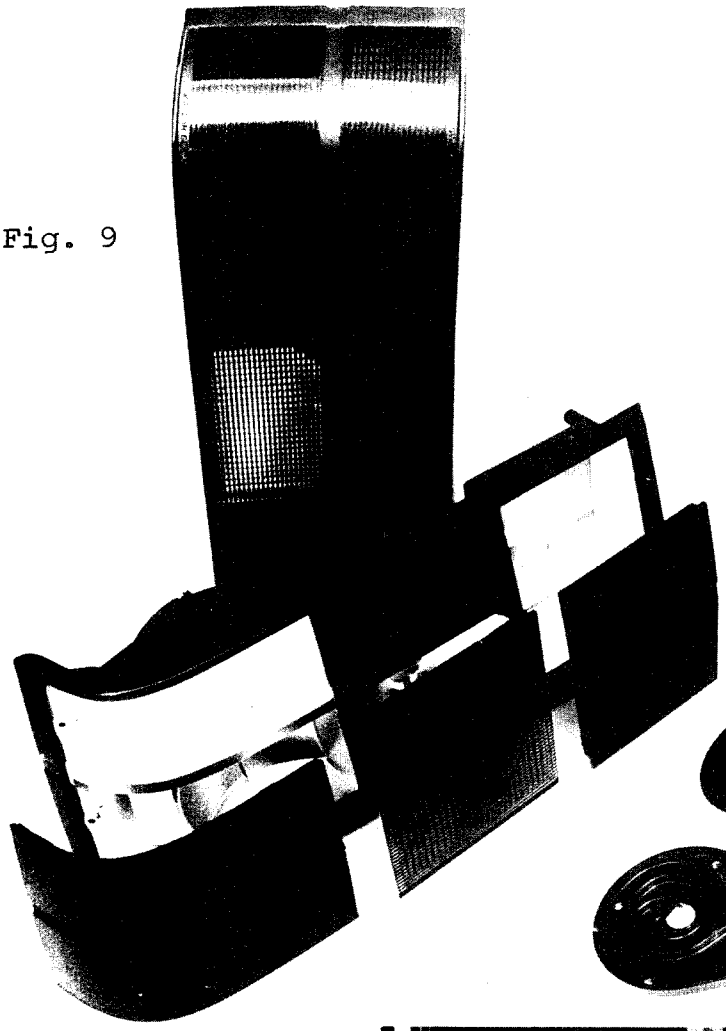


Fig. 5

Fig. 9



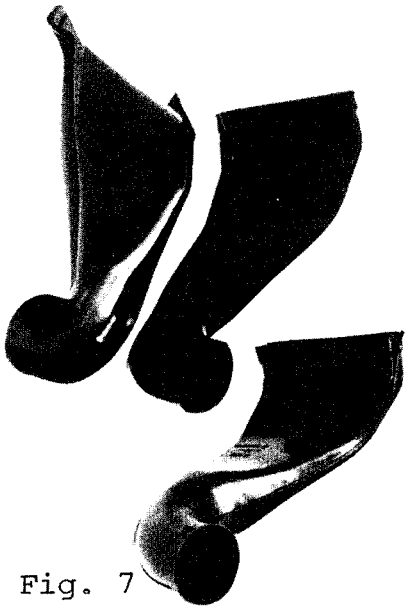
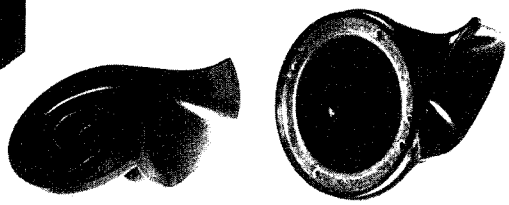


Fig. 7



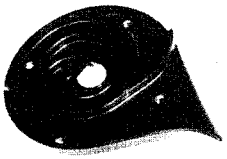


Fig. 11

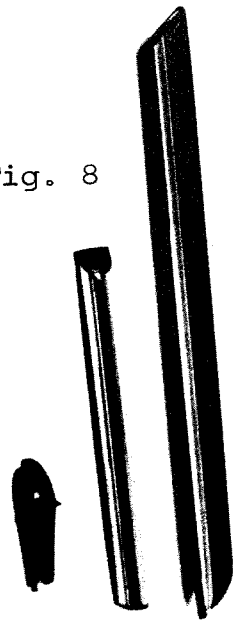


Fig. 8

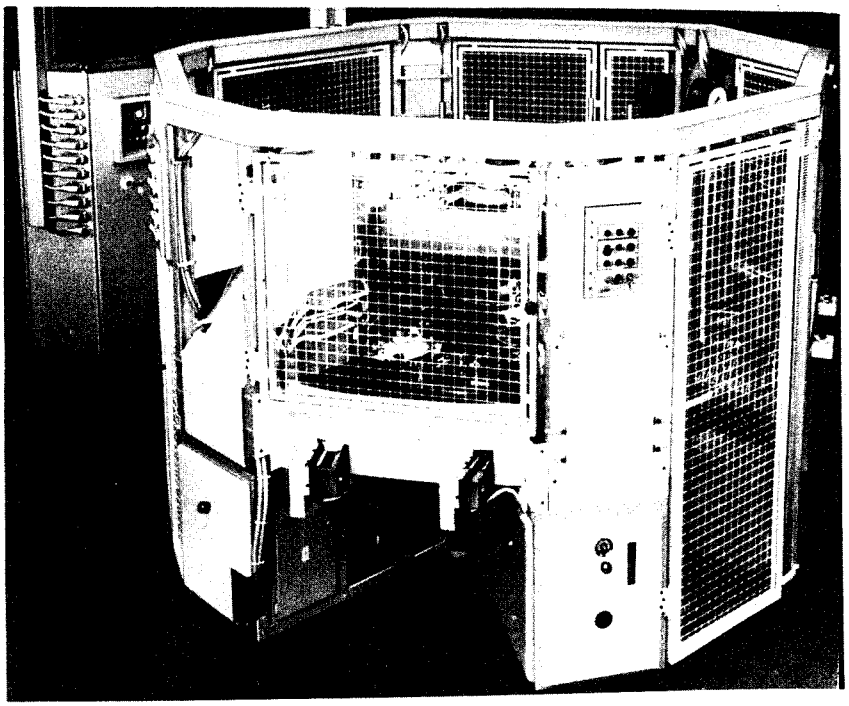


Fig. 10

TECHNIQUE FOR MEASUREMENT OF ELECTROSTATIC CHARGE IN AUTOMOTIVE FUEL TANKS

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I. INTRODUCTION

A safety factor which must be considered when filling any container with a hydrocarbon fluid is the generation of electrostatic charge and the possibility of an incendiary spark. When gasoline, a low conductivity fluid, is pumped through a filling station nozzle, static electricity is generated as a consequence of preferential adsorption of charge of one sign on surfaces of the pump and nozzle. Excess charge of the opposite sign travels with the fluid into the fuel tank. If enough charge is delivered and certain other conditions are met, there is a possibility of generating an incendiary spark. Thus, to insure safety even when substantial amounts of charge are involved, it is necessary to provide means to drain off charge in a controlled manner.

Polyethylene fuel tanks have been used on a number of vehicles for several years, and they have been free from problems due to uncontrolled static discharge. Apparently, one or more of the following factors preclude an incendiary spark: (1) the amount of charge introduced into the tank and its voltage are too low, (2) the charge is drained off through the conductive sender unit before it reaches dangerous levels, or (3) the charge is too immobile to supply the instantaneous discharge required for ignition. The purpose of the investigation described here was to devise means to measure the flow of charge during and after filling, and to use the methods in some realistic filling operations to evaluate the factors listed above. The results help explain the good safety record of polyethylene tanks, and suggest features of present tanks which should be included in future tanks. The methods can be employed to investigate tanks or plastic containers of a wide range of sizes and shapes.

II. EXPERIMENTAL

The total excess charge in a tank at any given time was measured in a Faraday cage apparatus, diagrammed in Figure 1, comprising two concentric boxes constructed from 1/8" aluminum with conductive screen ends to allow possible gasoline vapors to escape while yet maintaining electrical continuity. The outer box (30" x 30" x 42") functioned simply as a grounded shield to prevent interference from stray electrical fields. The inner box (25" x 25" x 36"), which was isolated from the outer box using foamed polyethylene blocks, served a a Faraday cage. The polyethylene tank (13-5/8" x 18-3/4" x 26" maximum dimensions) was mounted in the inner box using steel straps, such that its electrical environment, notably its capacitance to its surroundings (about 500 pF when half full), was comparable to that of a tank in a vehicle. The sender unit and the Faraday cage were then attached variously to ground, to a charge sensor, or to a voltage sensor, according to the nature of the experiment.

The charge and voltage sensors are diagrammed in Figure 2. The charge sensor consisted of a measuring capacitor, C_1, and a high impedence voltmeter; the charge, Q, delivered to the sensor is given by $Q = C_1 V_m$ where V_m is the indicated voltage. Since the greatest charge encountered in these experiments was 2.5 microcoulombs (uC), the meter indication was at most 2.5 volts using a 1.0 microfarad (uF) capacitor. The voltage sensor consisted of a capacitive voltage divider and a high impedence voltmeter; assuming the values of C_2 and C_3 used in these experiments, a meter voltage of 1 volt implied an electrostatic voltage of 714 volts. All capacitors were chosen for low leakage; polystyrene capacitors are satisfactory in this regard. The 14 pF high voltage capacitor was specially constructed for these experiments. It consisted of two 6.5 cm square copper plates separated by about 1 cm of K-Resin® (butadiene-styrene copolymer) dielectric, and its capacitance was measured with an impedence meter. A Keithley Model 610C electrometer, with an input impedence of 10^{14} ohm, was used as part of the high voltage sensor. Either the Keithley or an inexpensive follower amplifier (based on the Analog Devices model 515L FET input op amp) was used in the charge sensor. The analog output from either or both sensors was fed to a dual channel strip chart recorder. Care was taken to use coaxial leads in the high voltage sensor to preclude interference from stray fields.

Because some nonstandard fuel handling operations were employed in these experiments, the polyethylene tank was flushed with several volumes of nitrogen prior to the first gasoline fill as a safety precaution. Before initiating an experiment, the voltage and charge sensors were zeroed by momentarily shorting their leads to ground. Thereupon filling was commenced at rates up to 13 gal/min through an unleaded fuel nozzle. Charge and voltage were recorded during the filling operation and thereafter until they attained some constant value. After the experiment was completed, the fuel was forced by nitrogen pressure through the fuel intake system to a storage tank.

III. RESULTS

Measurement of Total Excess Charge

The total excess charge on a conductive object can be measured by connecting it to a charge sensor such as shown in Figure 2. However, this method is not applicable to nonconductive charged objects, because the charge cannot migrate to the sensor. It was initially observed by Faraday and confirmed by later investigations that if any charged object with charge Q is placed within a grounded conductive container, a charge -Q will be induced from ground onto the inner surface of the container. In our experiment, a charge sensor (with a finite but small voltage drop) was connected between ground and the shield. A charge -Q flowing from ground to the shield is equivalent to a charge +Q flowing from the shield to ground; thus the system acted as if the total excess charge within the tank had flowed to ground even though it still remained in the tank. (The argument is equally applicable with the signs of all charges reversed.)

Figure 3 shows the result of measurement of the total excess charge delivered in a 15 gallon fill. In this experiment, the sender unit was not grounded and the Faraday shield was connected to a charge sensor. Negative charge accumulated at a more or less constant rate as long as the gasoline was being pumped; after the pump was stopped, the charge maintained a constant value of about -1.75 uC.

Measurement of Charge Delivered to the Sender Unit

When a tank is properly mounted in a vehicle, the sender unit is not isolated but rather is electrically attached to the auto frame which can absorb and dissipate the charge safely. Figure 4 shows the time course of charge delivered from the sender unit to ground through a charge sensor. A bit of positive charge was registered initially, but thereupon the charge went negative in a manner reminiscent of the earlier experiment. However, unlike the previous experiment, the charge did not stop flowing immediately when the pump was stopped; -1.45 uC flowed while the pump was on and an additional -0.1 uC flowed after it was shut off. The current which persisted after the pump had been turned off resulted from the fact that the charge in the gasoline migrates to the sender unit slowly due to the low conductivity, 1.5×10^{-10} $ohm^{-1}m^{-1}$, of the gasoline. Nevertheless, in this experiment less than 10% of the charge remained in the tank when the pump was turned off, indicating that the sender unit is effective at removing charge.

Measurement of Voltage and Charge

In the third experiment, the sender unit was ungrounded, as in the first experiment and its voltage was monitored during filling and for a short time thereafter. The sender unit was then connected to ground through a charge sensor, and the charge was monitored. The results, displayed in Figures 5 and 6, show that when filling was commenced, the voltage first went positive and after a few seconds reversed and went negative, attaining and holding a value of -2400 volts when the pump was turned off. This result and other experiments have been interpreted to indicate that the reversal of signs is due to the superposition of two effects: delivery of a net negative charge from the fill nozzle and charge separation between the sender unit and the gasoline due to turbulent flow of the gasoline around the sender unit. When the charge sensor was connected to the sender unit, the voltage instantaneously dropped to zero. Simultaneously, the charge trace jumped to about -.06 uC and then began a slow approach to -0.8 uC. The immediately available charge is that which is stored in the sender unit as a consequence of its capacitance relative to its surroundings. The slowly available charge comes from the remainder of the tank and must migrate through the relatively low conductivity gasoline.

IV. DISCUSSION

It is generally agreed [1] that there is a minimum electrostatic energy required to ignite a hydrocarbon-air mixture; below that minimum the region traversed by the spark does not reach the kindling temperature. Under the conditions best suited for ignition, the minimum energy is about 0.2 millijoules (mJ); under most conditions a higher energy is required. The electrostatic energy, U, generated in the experiments described above has been calculated according to $U = Q^2/2C$ or $U = QV/2$, depending on which combination of the tank capacitance, C, the charge, Q, or the voltage, V is available. The results of these calculations are given in the table:

Estimated Electrostatic Energies

Calc. No.	Experiment Recorded In	Method Of Calculation	U(mJ)
1	Fig. 3	$U = Q^2/2C$ total Q	3.1
2	Fig. 4	$U = Q^2/2C$ total Q	2.6
3	Fig. 4	$U = Q^2/2C$ Q remaining when pump is turned off.	0.01
4	Fig. 5	$U = QV/2$ total Q	1.0
5	Fig. 5	$U = QV/2$ rapidly available Q	0.055

The total energy in the tank after filling with the sender unit ungrounded was 3.1 mJ (calculation (1)), which is substantially above the minimum ignition energy. The amount of energy delivered to the tank with the sender unit grounded (calculation (2)) was comparable in magnitude, but most of it was removed safely to ground during the filling operation. The amount of energy remaining in the tank when the pump was turned off was 0.01 mJ, only 5% of the minimum ignition energy, a safe level.

The consequences of an ungrounded sender unit are shown in calculation 4 and 5. The total energy available was 1.0 mJ, but only 0.055 mJ of it was available immediately when the sender unit was grounded. (Allowance has been made for energy stored in the 14 pF capacitor.) An energy of one millijoule released over several seconds would not ignite a flammable gas mixture, since the energy would be diffused over a relatively large region during the discharge, and the kindling temperature would not be attained. The instantaneously available energy, which might be effective in causing ignition, amounted to only 28% of the minimum ignition energy. These calculations indicate the advisability of grounding the sender unit at all times, but even when it was ungrounded in our experiments, it could not have been the source of an incendiary spark. (Because of the amount of charge delivered to a tank is independent of whether it is plastic or metal, it is likewise important to insure that electrostatic charge introduced into a metal tank reaches ground safely in spite of paint, rust, and corrosion, so that it does not collect on the tank wall and discharge unsafely to ground.)

The results reported here are thought to be realistic in terms of tank construction and environment as well as gasoline and pump. However, our experience has shown that there are marked differences among gasolines, and there may also be marked differences among tanks and pumps. These are factors which could be evaluated in greater detail using the methods described here. For the present, we can say that for one realistic combination of gasoline, pump, and tank (1) the amount of electrostatic energy in an ungrounded polyethylene tank reached levels which could ignite a suitable hydrocarbon-air mixture if all of the energy were brought instantaneously to a discharge point, but (2) the energy was spread throughout the volume of the tank, and only a small fraction of it could be brought instantaneously to a discharge point, and (3) under normal conditions, the sender unit is electrically connected to the auto frame and it thus provides a means for reducing the total amount of charge in the tank at any given time.

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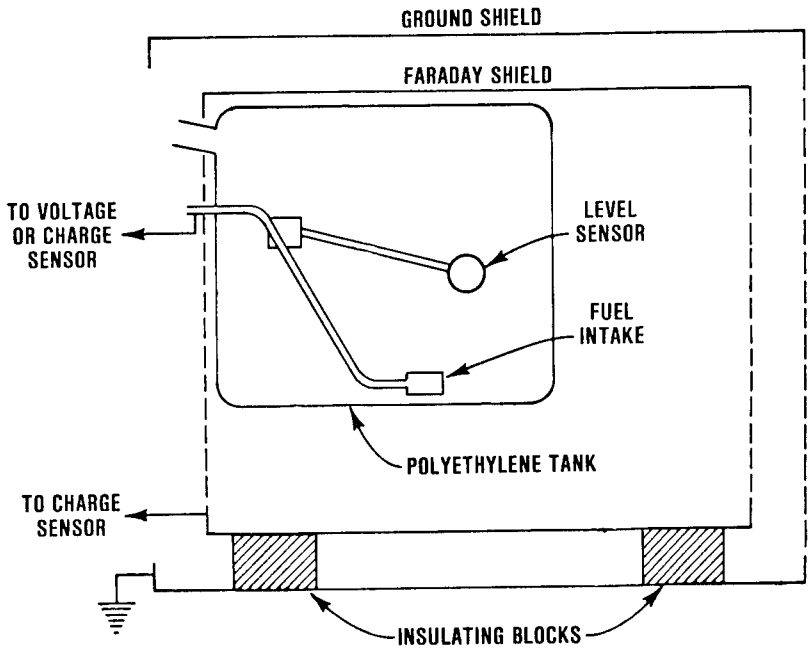

FIGURE 1: SHEMATIC DRAWING OF A POLYETHYLENE TANK IN THE FARADAY CAGE APPARATUS.

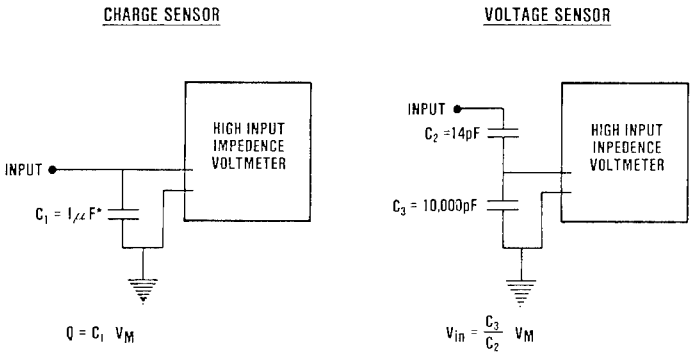

FIGURE 2: SCHEMATIC DRAWING OF CHARGE AND VOLTAGE SENSORS.

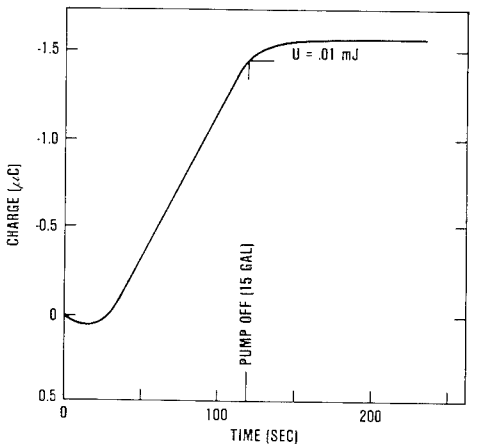

FIGURE 4: CHARGE DELIVERED TO THE SENDER UNIT DURING AND AFTER FILLING.

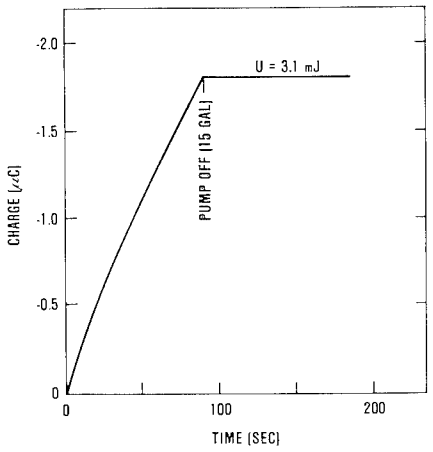

FIGURE 3: TOTAL EXCESS CHARGE DELIVERED TO A POLYETHYLENE TANK WHEN THE SENDER UNIT IS NOT GROUNDED.

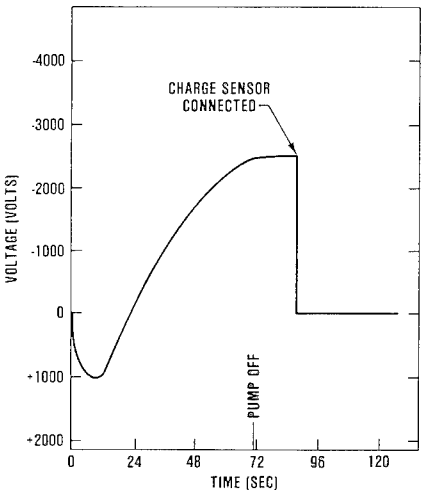

FIGURE 5: VOLTAGE ON UNGROUNDED SENDER UNIT DURING AND AFTER FILLING.

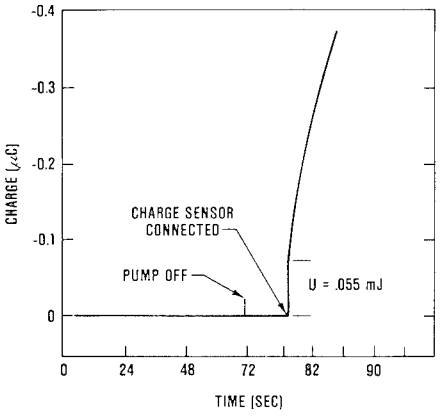

FIGURE 6: CHARGE AVAILABLE FROM SENDER UNIT WHICH HAS BEEN UNGROUNDED DURING FILLING.

INTERIOR USE OF PLASTICS ON EUROPEAN AUTOMOBILES

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INTRODUCTION

Nowhere in the automobile have plastics made a greater impact than in the interior. This publication will attempt to illustrate the historical background and discuss the future development of plastics for use in the interior of automobiles in Europe.

With the current tendency towards smaller vehicles it would seem likely that before all too long trends similar to those pervading in Europe will also be discernible in automobiles produced in the USA.

FROM COACH BOX TO COCKPIT

Let us begin with the coach box. The coachman was a powerful individual, whose full-time occupation called for the exertion of considerable muscle power. He was required to control the horses, handle the reins, sound the horn, use the whip and apply the brake in addition to being responsible for proper repair and feeding of the horses.

Coach journeys were normally full of adventure and extremely fatiguing for the passengers. Mankind has always dreamed of being driven, of faraway places and adventurous journeys. The invention of the automobile gasoline engine considerably advanced the prospects of realizing such a dream as compared to the age of the horse-drawn coach.

With increasing improvements in vehicles and automobile technology in addition to a better road network the number of activities required to control a vehicle increased steadily though they did not require the same degree of effort as had been necessary on the coach box. The driver's seat of a VW Kübelwagen illustrated in Fig. 1 together with the steering system and dashboard shows just how little information and how few controls are really necessary.

In this case the vehicle concerned was designed with a view to fulfilling a particular function with primary importance being attached to military requirements and little emphasis being placed on driver comfort.

After 1945 the trend reverted back to the construction of passenger vehicles initially on the basis of pre-war designs.

From 1950 onwards distinct progress was made at a very rapid rate in regard to vehicle operation and driver comfort. "The well being of the driver" was improved by the introduction of heating and ventilation, better seats, steering and braking aids, automatic transmission and other features making for easier control. The driver and steering wheel are now surrounded by the wipe/wash control mechanism, direction indicator, horn, light switch, headlamp flasher, rear window wiper control, dipping rear view mirror, internally adjustable outside mirror, radio and additional instruments which not only indicate speed but also the number of miles per trip, oil temperature, time of day etc. Fig. 2 shows the skinned foam instrument panel of the VW Type 1600 used in the midsixties.

THE DRIVER'S SEAT - A WORKPLACE

Ergonomic conditions are now checked with greater care and given consideration in the design stage. Fig. 3 shows how for drivers of differing size and sex the required controls must be at a correct and at the same time comfortable distance from the driver and how the position of the steering wheel with respect to the seat and pedals must satisfy ergonomic requirements. Drivers cover longer distances with their vehicles and should not be suffering from fatigue when they reach their destination despite the fact that more control tasks have to be performed than when the motor car was first introduced. As Fig. 4 shows the driver of a passenger vehicle must depress the clutch roughly 508 000 times in the course of 100 000 kilometres in addition to braking 313 000 times and starting the engine 15 000 times etc. It is clear that driving must be regarded as work despite the many labor saving features introduced.

If consideration is now also given to the actuation forces involved it once again becomes clear how much care is necessary when developing vehicles to gear the necessary actitivies to one another. On average a steering wheel is actuated with a torque of 2 Nm; given a steering wheel diameter of 400 mm this amounts to 5 N on either side when steering a vehicle. A similar situation is encountered with pedal forces, whereby the braking forces are of primary importance since they effect the safety of the vehicle.

PRESENT SITUATION AND OUTLOOK FOR THE FUTURE

There are specific reasons why the use of plastics in vehicle interiors is just now being discussed in a new light. If the developments of recent years are considered, then the following can be viewed as the "catalysts":

- o growing desire for comfort and ease of operation
- o new safety regulations and legal provisions
- o changed situation in the energy and raw material sector.

THE ADVANCE OF COMFORT

Comfort is not only a prime feature of vehicles, since appartments, houses, public buildings, hospitals etc. are also displaying an increasing degree of luxury. Without doubt a general goal and desire of mankind is to create something comfortable and at the same time technically perfect. This desire is being increasingly transferred to the automobile in which we spend a great deal of our time. People want to feel at home in their vehicles whether during driving, in traffic jams or when waiting. Despite the energy crisis the percentage share of more powerful vehicles has increased. Price increases and raw material/crude oil shortages could not prevent the share of vehicles in the 1500 - 2000 cm^3 range from increasing constantly. These increases between 1973 and 1978 were roughly 25 % to more than 35 %.

Moreover, as Fig. 5 shows, the percentage share taken up by vehicles in the range above 2000 cm^3 has risen from 5 to above 12 %. A trend is also discernible if consideration is given to vehicle equipment in the individual price categories. The Passat for example, with a production rate of roughly 1000 vehicles per day, exhibits the following breakdown (Fig. 6):

Custom-version:	15 %
Delux-version:	70 %
Grand Lux-version:	15 %

If the prices of these vehicles are considered and the Custom-version is taken as 100 % then the Delux-version costs 105 % and the Grand Lux-version 113 %. Naturally, it is not only the interiors of these vehicles which differ, but they do play a large part. The task involved is increasingly becoming one of matching in terms of shape and color. This in turn influences material and production, paintwork and parts. As Fig. 7 shows taking the VW Golf as an example the number of model and equipment combinations is also increasing. The VW range has expanded considerably over the years as shown in Fig. 8. As compared to 8 models in 1960 there were 32 models in 1977 with a corresponding range of versions and options.

If the total number of Golf models produced each day (roughly 2700) is compared, it will be established that on a monthly average only 2.5 vehicles are absolutely identical. Once again it is naturally not only a question of differences in terms of comfort

producing this wide variety, since the different types of vehicle also reveal a higher degree of motorization, better tires, bad weather package etc.

VEHICLE SAFETY - NOT JUST A CONTEMPORARY FEATURE

The legislation did not invent the vehicle safety requirements, but they have contributed to improved comparability of vehicle safety by way of their specifications and investigations. Realization of the necessary degree of safety has consistently increased on the part of the legislators and automobile manufacturers.

Even prior to the publication of vehicle safety specifications the VW Type 1600 illustrated in Fig. 2 had a padded dashboard and padded windscreen pillars. This dashboard immediately met all requirements of USA standards.

Standard developments for worldwide distribution are however made extremely difficult by the ever increasing safety regulations which also vary from country to country. Fig. 9 illustrates the increase in vehicle safety-related legislation from 1969 to 1976 in various countries. The excesses to which this can lead are shown in Fig. 10 by way of the stack of paper required for registration documents alone for Australia.

Plastics make a considerable contribution towards complying with all legal requirements aimed at the interior of vehicles, since in recent years success has been achieved in improving materials to such an extent that splintering does not occur even with rapid shaping.

ENERGY AND RAW MATERIALS

To date raw materials were only selected from the point of view of improving operability and optimizing costs. In the future, however, additional requirements will also have to be taken into consideration. To achieve the set goal energy will have to be saved during driving and not only will consideration habe to be given to light-weight construction, but also to the energy consumption of the manufacturing process.

Fig. 11 illustrates the specific energy consumption of the production stages when manufacturing a mid-sized vehicle. Roughly 9000 kWh are required for producing the raw materials and approximately 2200 kWh for manufacturing the vehicle. It is evident that particular importance must be attached to the raw materials. The extent to which light-weight construction is then appropriate must be the subject of precise considerations. Further comments on this topic will be passed at the end of this paper.

PLASTICS - THE HELPFUL AIDS

When discussing the use of plastics in vehicles, major significance is given to the interior since two thirds of all plastics used in automobiles are substitutes for felt, damping materials, textiles and trimming materials. Only a third replace metals, with a major portion thereof being used for controls in the vehicle interior. Fig. 12 shows that plastics are used above all in the interior with less than one third being utilized for external applications.

If a comparison is made of the cost share for vehicle production the selection of material assumes particular importance (Fig. 13). The ratio of 53 % material costs to 30 % production costs shifts significantly in case of plastics towards the direction of material costs. This higher percentage share (70 %) of material costs in the plastics sector as opposed to 50 % for metals was precisely the factor which triggered the enormous increase in the use of high polymers for automobiles between 1958 and 1968 as a result of the major drop in material prices for plastics (Fig. 14). The pure production costs (20 %) for the manufacture of plastic parts are 10 % below those in the metals sector (30 %).

By way of example the cost of the majority of plastomers (thermoplastics) dropped in this period by 50 %.

Fig. 15 shows the price trend for various plastics and their products during the oil crisis. The price level trends at present point to a continued progressive development.

Equivalent price increases are also apparent in the metals sector; however, in view of the fact that in absolute terms material cost increases are sharper than wage increases, the situation may take a turn in favor of metals at some time or other for the above-mentioned reasons. In the future designers will have to give increased consideration to these facts when selecting materials.

Moreover it remains to be seen whether the excellent prerequisites which existed for the use of plastics as a substitute product in 1968 can ever be repeated.

THE MATERIAL COST OF PLASTICS FAVORED THE DEVELOPMENT OF A PLASTIC FUEL TANK

It was however precisely the degressive price trend at the time with regard to high polymers which was a contributory factor towards commencing work on the development of a plastic fuel tank some 13 years ago. This application is not to be considered as an example of the direct utilization of plastics in vehicle interiors, but it serves admirably to illustrate how impulses must be given in good time if an alternative material is to be used for a product.

As early as 1973 the Passat Variant was the first VW car to feature as standard equipment a 55 litre tank (including 6 litre reserve) made from high-density polyurethane. Since then more than 800 000 such tanks with a net weight of 3.7 kg each have been blow moulded on portal-type machines (Fig. 16). Such tanks are thus 1.4 kg lighter and hold 5 litres more than a comparable sheet metal tank.

The plastic fuel tank is approved practically worldwide. The current situation with regard to raw materials calls for cautious planning. The development only came about however as a result of specific teamwork between the automobile manufacturers, suppliers of raw materials and manufacturers of machinery. It was not just important to develop and test the plastic fuel tank, the preparation of production and the guarantying of constant quality were also major factors.

Today some 6 years later the major advantages listed at the time of the plastic fuel tank as opposed to the sheet metal version such as greater design freedom - increased fuel volume, lower weight, no danger of corrosion, better thermal insulation and improved safety test behavior still speak in favor of its successful use.

In the meantime the Kautexmaschinenbau GmbH, Bonn-Holzlar/Germany in conjunction with Ford Australia, Ford, Cologne and the BASF, Ludwigshafen has completed development of two further plastic fuel tanks with capacities of 76 and 79 litres respectively. Since the beginning of the year the fuel tanks have been in production at the Ford Motor Company of Australia Ltd., Campbellfield, Melbourne plant. The automatic machine blow moulds 20 tanks per hour which are then completed in separate fixtures by attaching an additional part using friction welding.

CONSIDERATIONS OF THE INDIVIDUAL AREAS OF THE INTERIOR

The dashboard zone makes the most lasting impression on the driver. In particular designers will have to give thought to the future of dashboards bearing in mind the fact that electronics will also be gaining a position of considerable influence.

Thus for Maserati's prototype "Boomerang" the Italian designer, Georgetto Giugiaro housed all instruments and displays in the steering wheel rim to improve readability in the various driving phases whilst leaving the spokes on the outside (Fig. 17).

In another design, namely the "Asso di Picche" for Audi/Karmann the instruments and displays are located on a transverse dashboard with a cylindrical cross-section as shown in Fig. 18. Even in today's practice, some highly futuristic details can be found for example in the Citroen Visa in Fig. 19. The standard arrangement has undergone a basic change with the controls being housed in a newly invented "satellite".

Keeping however to the current European level, we find for instance that delux models feature a padded dashboard. The production process involves the insertion of a support made from wood fiber moulding material or sheet metal into a mould containing a vacuum formed ABS (acrylonitrile butadiene styrene) sheet which is then foam backed.

For reasons of economy the injection moulded dashboard supports customary in the USA have still not achieved the breakthrough in Europe. The Rabbit produced in the USA also has a dashboard comprising a wood fiber moulding material as backing (resin-bonded or formed in situ) and a sheet made from a PVC/ABS polymerizate, which is backed with semi-rigid polyurethane foam as padding.

The VW Golf, Ford Fiesta and VW Polo also have dashboards made from plastomers (thermoplastics) not covered with sheeting. Polyphenylene oxide (Noryl) has proven particularly suitable at the same time meeting the requirements of the US specification. The production conditions must however be strictly adhered to if fracture resistance is to be guarantied.

To make production more economical and eliminate the frequently demised "cheap plastic effect" of injection moulded dashboards, newly developed versions are featuring wood fiber moulding material laminated with foam sheeting even in the A-category (DeLux and Grand Lux models). This type of instrument panel is being instigated at VW with the notchback Jetta (Fig. 20).

The basic design of a dashboard "made from wood fiber moulding material laminated with foam sheeting" is illustrated in Fig. 21.

GOOD SEATS PROVIDE COMFORT

Throughout the VW Group seats made of polyurethane foam (high resilience) have been used to complete satisfaction. The foam seats are mounted on a three-legged tubular seat provided with a sheet metal pan which prevents the driver from submarining in the event of an accident. The introduction of forces is such that the seat belt can also be attached to the seat without any great problem. Such attachment to the seat has likewise become a general feature throughout the VW Group (Fig. 22). In view of the fact that this type of attachment offers major advantages, it is being put to ever more frequent use in all European vehicles.

SIDE AND DOOR PANELLING, SEAT COVERS AND FLOOR PANELLING CONTRIBUTE TO THE HOMELIKE CHARACTER

In Europe, door panels are currently still manufactured by adding side padding, armrests, door pockets, handles etc. to the embossed hardboards laminated with foam sheeting. Blocks of plastic moulded in one piece with integrated armrests and door pockets as shown in Fig. 23 are generally only used for rear side panelling and are primarily manufactured from wood fiber moulding material laminated with foam sheeting in a manner similar to dashboards. Large, moulded, single-piece door panels such as those produced in the USA using injection moulding methods are only seldom encountered in Europe.

Developments are however in the offing which will permit further progress in this sector as well by way of improvements to the wood fibre moulding materials and the processing techniques involved. Fig. 24 provides a comparison of the Jetta side panelling and door panelling which indicates this difference extremely clearly. Highly intensified developments are in progress in this field and the progress made has been convincing with the result that in coming years the use of single-piece, intricately-shaped door panels serving as a "door handle - armrest - door pockets" combination can likewise be expected in Europe.

New on the market is polypropylene filled with wood flour which is available as a board-shaped semi-finished product manufactured by extrusion. Single-piece side panels are then produced by thermoforming. As opposed to resin-impregnated wood fibre mats, such polypropylene should make for simpler and more environmentally sound handling as well as improved shaping potential together with shorter cycling times. The stylists will find themselves confronted with new economical possibilities with textile lamination in particular offering interesting applications for lightweight delux fittings. Fig. 25 shows a development example, namely a door panel with a backing made from polypropylene filled with wood flour covered with 2 mm PVC foam sheeting.

As yet these parts are still not in use as door panels, but Fig. 26 shows the tail gate panelling of the Passat Variant which is shaped from this material and painted and has been in use for many years.

Fig. 27 gives a schematic view of a moulding method for processing polypropylene filled with wood flour; the technology applied is comparable to that of normal sheet metal working: the press is preceded by a heat-up zone and the heated material is then routed into the cooled mould. Lamination material such as carpeting of sheeting is then supplied cold, using the transfer method or by way of insertion into the mould. The heat content of the polypropylene filled with wood flour is sufficient for forming and attachment to the carrier material. No additional bonding agent should be necessary for knitted fabrics and standard carpets in order to provide mechanical anchoring. PVC sheets require a bonding agent in the form of synthetic resin adhesives (thermoplastic adhesives) or mechanical jointing methods, e.g. fleece or fabric attached using polyurethane adhesives.

COMPARISON WITH ALTERNATIVE MATERIALS

Visible and concealed shaped interior trims made from phenolic resin-bonded wood fibers, fiber boards or cardboard are used in the automobile industry. The annual requirement in Europe is roughly 70 000 t.

The manufacturers of polypropylene filled with wood flour make particular reference to the following advantages of their product as opposed to wood pulp:

- improved shaping potential;
- low moisture intake;
- can be laminated with sheets and carpeting in one operation during the shaping process;
- problem-free manufacture of smooth and grained surfaces.

It should however be remembered that the painting of such polypropylene trims is still problematic. A positive feature is that the waste produced after cutting can be reused since the material involved is a plastomer (thermoplastic).

A cost comparison was prepared for manufacturing a passenger vehicle side panel laminated with 2 mm PVC foam sheeting. The surface area of the part was 0.8 m²; the comparison is illustrated in Fig. 28. By reducing 7 operations (wood fiber) to 3 an advantage in terms of price of roughly 8 % in favor of polypropylene filled with wood flour is achieved in each case with the use of a twin mould. This advantage is not convincing at first sight. It must however be noted that the productivity ratio of manufacturing facilities for moulded wood fiber material and polypropylene filled with wood flour is 1:3. If an index is formed for mould costs, the necessary investment and the area required referenced to the yield per shift, the relationships illustrated in Fig. 28 result, which should clearly indicate the cost advantages. In this case the results of further developments must be awaited.

WHAT ARE THE TRENDS AS FAR AS THE HEADLINING IS CONCERNED

Headlinings in Europe normally consist of a cut-to-size PVC sheet with sewn-in wire bracing which is mounted on the assembly line and secured by bonding. The edges must be matched and cut to size.

The desire for a technically more elegant solution, the creation of better prerequisites for complying with safety specifications as well as for a reduction in time spent working on the assembly line and a stylistically more elegant solution are the reasons why efforts are being made to employ prefabricated headlinings. Economic considerations do not however as yet permit a decision in favor of the prefabricated headlining presupposing the technical possibilities and materials available today.

A whole series of developments are still necessary in this field; a further drawback is that in some cases the headlining is heavier. The most significant progress has been made by Renault whose prefabricated headlining is made from three layers as shown in Fig. 29.

The moulding process comprises 2 phases:

1. phase at roughly 180 °C when the shell is cured
2. phase at 80 °C when the material is moulded on.

The parts must be transported with extreme care, since the danger of deformation is considerable and moisture leads to reduced dimensional stability.

Fiat is also extremely active in this field currently employing three different types of prefabricated headlinings. The first step was a prefabricated headlining on a foam-moulded expanded polystyrene carrier. The special features of this headlining are as follows:

- An air gap of 2 - 3 mm between the roof skin and foam carrier precludes the possibility of temperatures in excess of 90 °C around the foam.
- The side facing the passenger compartment has a full recovery surface in the form of a 2.5 mm thick PVC/polyurethane cushioning layer thus concealing any possible pressure points in the rigid foam.
- Initial development parts only require low expenditure: roughly 20 000 DM are required for the mould.

This headlining is a standard feature of the Fiat 131. Fiat also has as standard a prefabricated headlining, the carrier material of which is made from moulded, resin-impregnated cotton fleece laminated with foam sheeting or a top fleece.

Today there is a pilot test fleet of the VW Golf GTI on the road with similar prefabricated headlining (Fig. 30). This development is not yet completed, since the weight of 3.5 kg appears excessive and the development requires further improvement.

Fiat has recently made further developments which have also been put into practice. These designs resulted in a considerably lighter prefabricated headlining with a 4-layer structure. Starting from the roof, the first layer is a sound-absorbing polyehtylene foam sheet, being followed by a corrugated board carrier and polyethylene foam sheeting, flame-laminated with a sheet of PVC. The fact that the materials can be flame-laminated also permits continious production of prefabricated headlinings on a large scale.

Here too, the process still requires further improvement in terms of production and costs. Other carrier materials are however also possible, such as wood fibers or extruded plastic sections. In the long term there is no doubt whatsoever that prefabricated headlinings will be indispensable.

THE GREAT PROBLEM - COLOR COORDINATION

If the interior of an automobile is to have a homelike look, color coordination is a major factor. A particular advantage of plastics is that they can be directly dyed and do not require special painting. This applies particularly to the bright colors used in the consumer durables industry. Difficulties are encountered with the highly nuanced interiors of passenger vehicles. Color coordination poses particular problems for the following reasons:

- Various raw materials are used
- The production processes differ widely
- Suppliers and batches differ
- Production has an extremely great influence
- Aging is very difficult to control

Past endeavors were aimed at doing away with labor-intensive painting work. This was however not possible; on the contrary, the volume of painted plastic parts has constantly increased. This volume will continue to increase in the same manner in coming years until the trend towards a more brightly colored automobile interior makes the breakthrough. The advantages of paint, as described in the following, are to be given particular heed:

- There are scarcely any restrictions on coloring with varying degrees of gloss
- Color constancy from batch to batch is easily achieved by way of shading
- Rapid changes of shade are possible
- Parts can be given multi-color finishes
- Plastic parts are protected against aging due to the effect of light
- Plastics which are not fade-resistant can be used
- The scratch resistance of certain plastics, e.g. TPE is increased
- Filled plastics can be used

Recycling is possible which has a positive effect not only from the point of view of reduced costs but also in regards to waste disposal

In the design stage care must of course be taken to ensure that the parts present no problems for painting, since a high pigment price (prices up to 150 DM/kg are not unusual) shifts the cost picture in favor of painting, in view of the fact that the pigment component in paint is far less than that in plastics. This trend is further enhanced in the case of greater wall thicknesses as the weight of the plastic increases.

In contrast to the USA where painted plastics have been used in vehicles for many years there are scarcely any painting facilities in Europe. There is also the question of whether more recent developments cannot be employed to greater advantage, for example, electron beam hardening for painted plastics.

One thing is certain: the European automobile industry and its suppliers will have to actively involve themselves with painting and construct painting facilities. This will however require a very high level of investment.

The term "lightweight construction" is today often used in conjunction with the automobile industry to illustrate that less fuel is consumed in running a vehicle.

As already mentioned material selection was to date chiefly based on the self-regulating principle of cost minimization with endeavors simultaneously being made to optimize the properties of components.

Where energy savings are concerned, however, other criteria must also be considered.

Future consideration will have to be given increasingly to the following points, all of which presuppose sparing use of energy and raw materials:

- o lightweight construction making full use of material properties
- o improvement in long-term behavior (value retention and assured continued use)
- o energy saving production of basic materials
- o energy saving production processes
- o energy saving operation (i.e. lightweight construction)
- o recycling
- o decrease in waste-related problems

The problems involved in saving energy and protecting reserves of raw material cannot however be solved by vehicle designers alone. The State and the economy as a whole must also play their part. Considering, however, that the materials used in the interior of automobiles are already substitutes for lightweight materials such as textiles and upholstery, it will in the future only be possible to reduce weight by way of pinpointed-material utilization for components such as pedals, seats, gear shift mechanism etc.

SUMMARY

The prerequisites for the use of plastics in the interior of automobiles have changed somewhat in the course of time. With regard to further development, positive features in favor of plastics are increased comfort, reduced weight and energy/raw materials savings. Endeavors must still be made if legal specifications are to be complied with; this would not however appear to be an insurmountable problem. The upward price trend does however bring negative aspects to bear.

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Actuation frequencies in VW passenger vehicles over a distance of 100 000 km (62 500 miles)

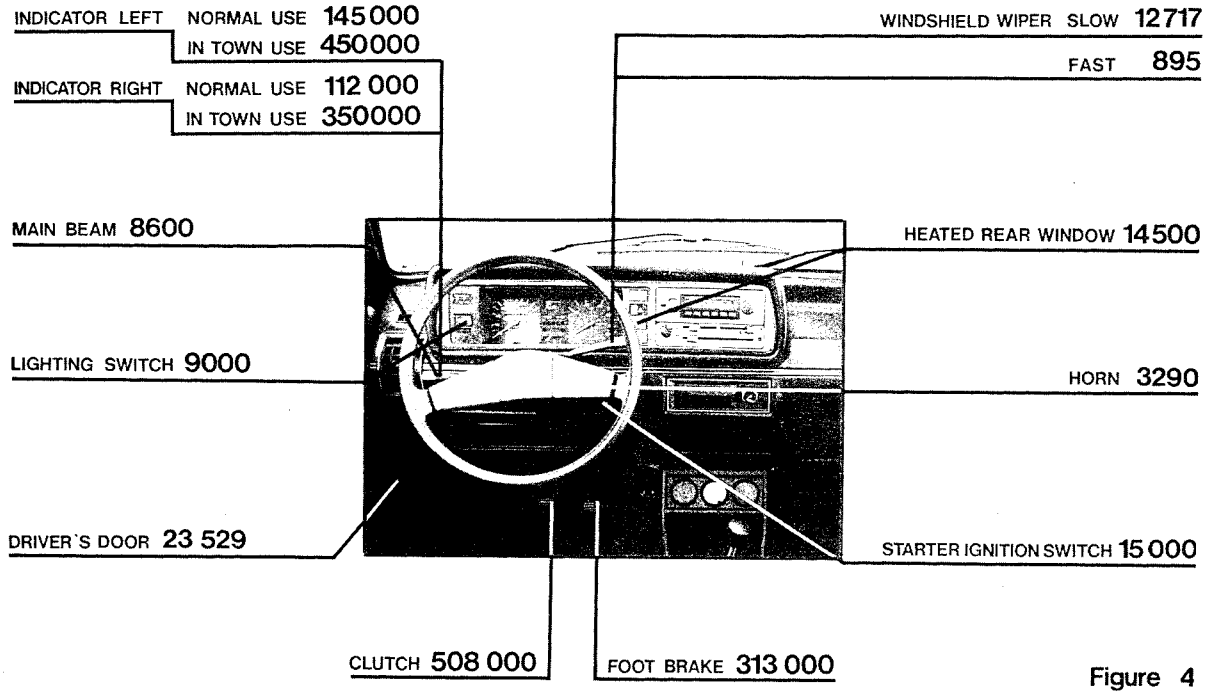


Figure 4

Extent of automobile equipment

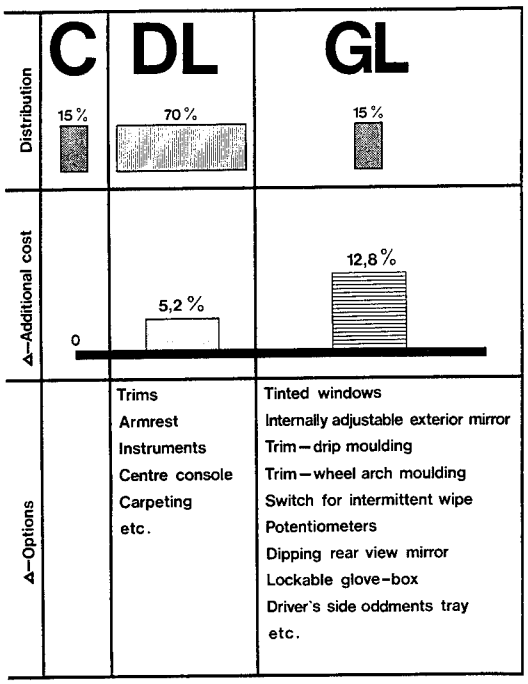


Figure 6

Plastics in VW Golf

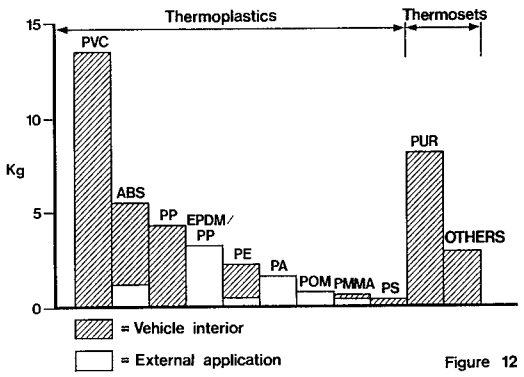


Figure 12

Comparison of VW type range

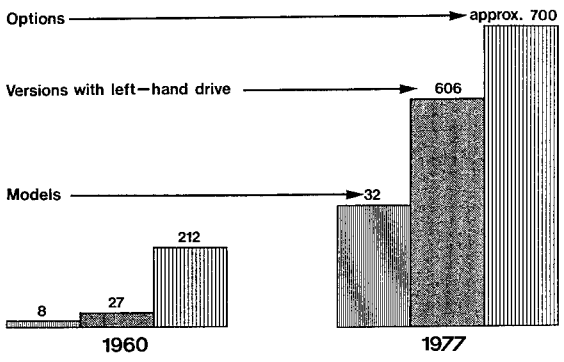


Figure 8

Percentage of costs for a new car

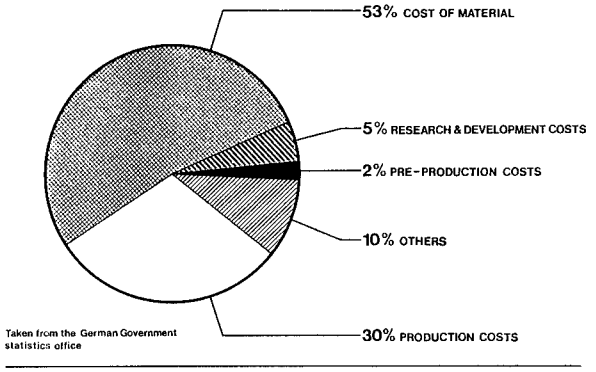
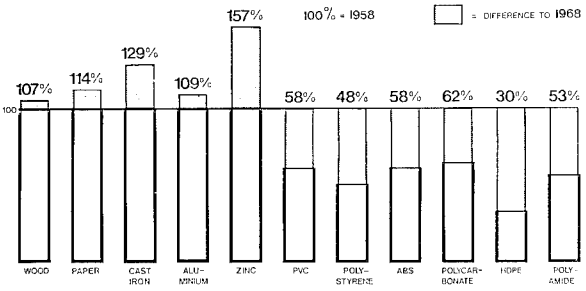


Figure 13

Price comparison of different materials

Figure 14



Basic design of a dashboard made from wood fibre moulding material laminated with foam sheeting

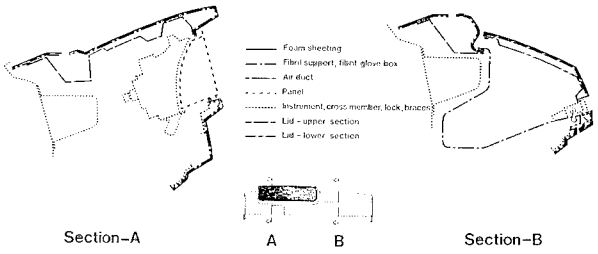


Figure 21

Cost development related to plastics, plastic parts and machines for production between Jan. 1973 to Feb. 1974

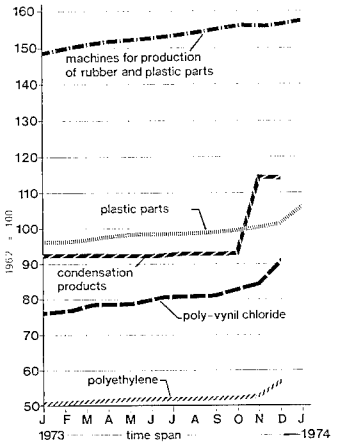


Figure 15

Schematic representation of moulding process for polypropylene filled with wood flour, BASF [81]

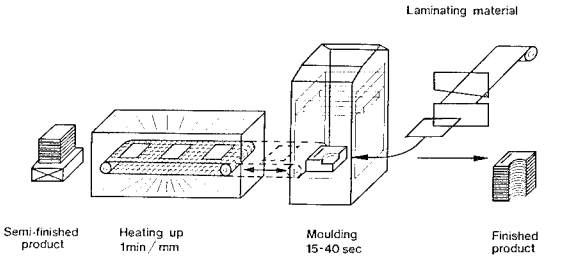
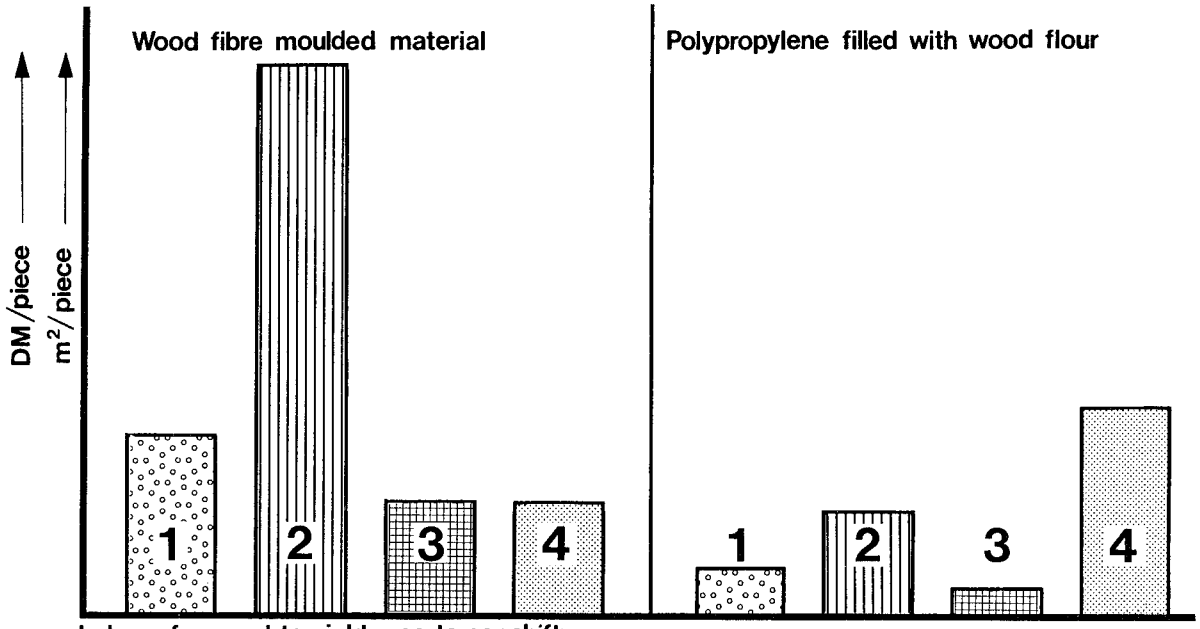


Figure 27

Cost comparison for a laminated passenger vehicle side panel with carrier made from wood fibre moulded material and alternatively polypropylene filled with wood flour [8]



Index referenced to yield = parts per shift

1=mould costs 2 = capital costs 3 = area requirement 4=material costs

Figure 28

Vehicle headlining [5]

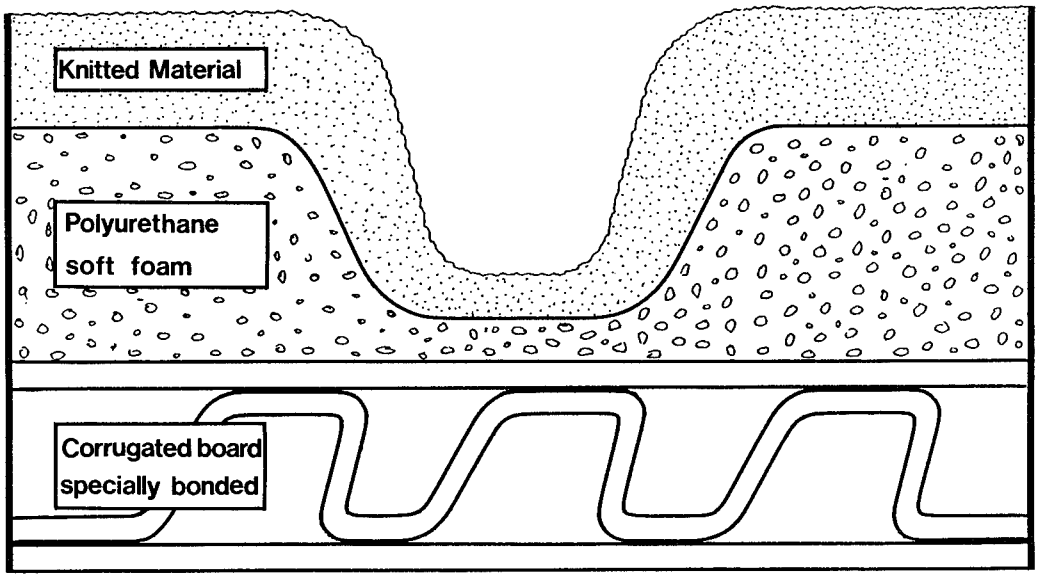


Figure 29

XMC^{R}-3 COMPOSITE MATERIAL—STRUCTURAL MOLDING COMPOUND

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ABSTRACT

The development of high strength fiber glass reinforced plastic materials has provided the design engineer with new capabilities in his search to obtain improved product performance. XMC^{R}-3 composite has been added to a family of fiber glass reinforced molding compounds that can be processed into structural shapes through the use of heated matched-metal dies and hydraulic presses. The XMC composites are generally distinguished from other molding compounds by their very high percentage of directionally oriented, continuous fiber glass (up to 80% by weight) which is incorporated into thickenable, thermosetting resin systems using filament winding techniques and programmed winding angles. The controlled addition of chopped fiber glass to this process (replacement of some continuous fiber glass) provides XMC-3 composite sheet material which demonstrates improved molding characteristics, a 4-5 fold increase in strength perpendicular to the direction of primary reinforcement, and only a 20-25% reduction in strength properties parallel to the direction of primary reinforcement.

An XMC-3 composite containing 50% continuous glass fibers and 25% chopped fiber glass by weight has typical properties of 75,000 psi tensile, 125,000 psi flex, 5.5×10^{6} psi modulus parallel to the direction of primary reinforcement and 10,000 psi tensile, 23,000 psi flex, and 1.1×10^{6} psi modulus perpendicular to the direction of primary reinforcement. Because of this, the ability to resist torsional loads in beam-type application has been vastly improved.

The development of XMC-3 composites has extended the workable range of composites for structural RP applications. The ability of these composites to be shaped into complex configurations, resulting in weight savings of 50 to 60%, will be of much value to automotive manufacturers.

HYBRID GRAPHITE FIBER COMPOSITES FOR THE AUTOMOTIVE INDUSTRY

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Mgr, Automotive Marketing
Graphite Fibers

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AEROSPACE DIVISION
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INTRODUCTION

Hybrid graphite fiber composites have received much attention from the automotive industry over the past several years. While this initial exposure has generated interest by virtue of the potential weight reduction, many pertinent issues have been raised concerning the use of graphite fiber. Issues such as cost effectivity, availability, producibility, and long-term durability are some of the key questions to be answered before high-volume use will be considered. In view of these requirements, material and component suppliers are actively pursuing: (1) new material forms for high-volume production, (2) a more extensive design data base, (3) a better definition of processes required to achieve production rates, (4) refinements in component designs to yield cost-effective construction, and (5) extended test programs of prototype parts to establish service life characteristics.

Requirements placed upon the Transportation Industry to become more fuel efficient have served as a catalyst for investigation of new, lighter-weight materials. Not only has this brought about the examination of fiber-reinforced composites, but it has spurred more efficient use of metals. Vehicle downsizing, more efficient engine and drive line systems, and aerodynamically cleaner body designs are all providing significant improvements in reduced energy consumption. Within the materials category, plastics and fiberglass composites offer direct savings in weight, as well as cost, and represent materials of familiarity to the auto industry. Hybrid graphite composites probably offer the greatest potential weight reduction approach; however, they also present the greatest challenge in meeting cost constraints and producibility. No doubt these materials are viewed as a "final approach" and will find their place in selective structural applications as more and more weight reduction is required. Like any change involving new and untried materials, it will take time to resolve issues and gain the needed confidence. This will only happen through continued industry backing of development and test programs. The major goals are, therefore, to develop the required material forms and necessary data base and to demonstrate the required manufacturing processes and economics for its use.

RAW MATERIAL FORMS

Graphite fiber materials available today fill a broad matrix of forms from which hybrid composites are constructed. A basic fiber (Table I) can be selected having high strength (400 to 450 ksi) and a typical modulus of 30-34 ksi or high modulus (50-55 Msi) and strengths of 300-350 Msi. The high-modulus fiber is currently much more expensive, but future projections indicate prices at more competitive levels.

Graphite fibers (Table I) are generally available in bundle sizes (filaments per tow) from 3000 (highest price) to 40,000 (lowest price). This latter fiber has only recently become available and has been developed primarily for the automotive market. The 3000 and 6000 filament tows are generally used in the manufacture of woven fabrics, although 6000 filament tow is being considered in the manufacture of hybrid XMC*. The more standard 10,000 filament tow is being used in hybrid SMC, pultrusion, and filament winding.

In addition to type and bundle size, the fibers are available in various forms (Figures 1 and 2) such as continuous, chopped, woven, and resin-impregnated. These forms have been developed and tailored to fit various processes for final part manufacture. Continuous fiber, packaged on individual spools or in boxes, offers a lower-cost approach to part manufacture through filament winding and pultrusion because no intermediate conversion costs related to a material form are needed. Sized fiber and beamed fiber are used to manufacture sheet type molding compounds for compression molding. This form does require intermediate conversion costs; however, projections for high volumes indicate potential $.50 per pound conversions, which is low compared with that required for the fabrics and resin-impregnated tapes shown in Figure 2. These products find wider acceptance in the aerospace and leisure markets primarily because of the more specialized products required by these markets.

*PPG trademark.

BASIC PROPERTIES

Programs are underway to characterize new hybrid material forms for the automotive industry. The all-glass, all-Kevlar, and all-graphite structural composites have been well characterized through aerospace and industrial programs. Studies are now focusing on hybrid forms of SMC, XMC, and injection-molding compounds. The key tradeoff involves properties and economics.

In the design of prop shafts, leaf springs, control arms, various torsion rods, crossmembers, etc., basic composite properties (Table II) are considered the building blocks to final construction. While numerous other properties are required for each design case (such as compression, shear, fatigue, impact), only tensile strength, modulus, and density are presented for this comparison. Because the various component designs are tailored through fiber selection and orientation to achieve maximum efficiency and minimum cost, several orientations are presented to illustrate the available choices. A particular design, such as a hybrid composite prop shaft, might use unidirectional graphite fiber and multidirection ($\pm$ 45°) fiberglass in combination. The graphite provides bending stiffness, while the glass is designed to carry the torsional loading. The numerous possibilities for tailoring a specific construction are obvious.

The influence of graphite fiber addition to all-fiberglass construction can be seen in Table III for unidirectional combinations. These examples assume intraply mixing of fibers where the strengths are based on graphite fiber strain limitation. The all-fiberglass and all-graphite values are less than those given in Table II due to lower fiber volumes and the resin systems used. (Values in Table II reflect higher performance epoxy resins.) Improvements in fiber loading and compression moldable polyester will increase the values shown. The primary advantage of graphite fiber addition involves improved stiffness -- a 40% addition of graphite fiber increases stiffness by 96%. Recognition of this trend is important when making initial material selections for preliminary design analysis.

Interply hybrids, which are representative of SMC and XMC compression molding compounds, are similar to a sandwich construction. This includes combinations of chopped glass and continuous glass or graphite fiber. Several examples are summarized in Table IV. As noted previously, work is continuing in this area to provide better material characterizations and economics to establish tradeoff benefits. The first three molding compound materials shown provide a base reference to all-glass construction. By replacing a 40% continuous, 20% random fiberglass material with a 12% continuous graphite, 48% random fiberglass construction, strength is increased by 60% and stiffness is increased by nearly 90%. As expected, relatively small additions of graphite fiber reinforcement yield proportionally greater increases in strength and stiffness. The first three hybrid combinations are more indicative of the SMC process, while the fourth represents an XMC type material with continuous fiberglass core and graphite outer layers.

These are just a few of the forms being examined today to identify potential products for the automotive industry where economics will be established as a function of material characteristics and processibility. Other materials being considered include injection molding compounds with various combinations of fiberglass and graphite reinforcement, improved property thermoplastic sheet material for hot forming or stamping, and reinforced reaction injection molding (RIM) material.

APPLICATIONS AND RAW MATERIALS

As previously discussed, there are many forms of raw materials and many possibilities for combining these materials to achieve properties tailored to each particular application. For several years, applications have been under development with these materials to examine potential weight savings and economic feasibility. Several of these applications are summarized relative to the raw material used, basic construction, and manufacturing process. This section addresses relative material costs, potential weight savings, and potential for future economic payoff.

While 20 to 30 applications with hybrid graphite composite construction are being evaluated today, many issues must be answered before these will reach limited production status. Figures 3 through 7 illustrate several of the applications being considered. In general, graphite fiber content is below 20% by weight to minimize material cost. Further, the high-strength fiber is used primarily because it is the lower cost material and it offers significant improvements in stiffness (as well as strength) over the more commonly used fiberglass.

As low-cost, high-modulus fibers are developed, more use will be made of these fibers where the estimated cost delta is 20% over high-strength fiber. Since graphite fiber is used primarily for stiffness, the higher modulus fiber will yield lower raw material costs (60% higher stiffness than the high-strength fiber).

Filament winding, compression molding, and pultrusion have all shown a potential for high-volume manufacture. Production winding machines have been designed to produce over 30 prop shafts per hour. Multiple machines could double or triple this rate. Automated compression molding lines are being considered to reduce the current 3 minute mold cycle time to less than 1 minute. Pultrusion lines currently run at 75 feet per hour with relatively complicated shapes. Faster speeds with multiple machines and multicavity dies could produce sufficient stock material to satisfy production demands.

Two approaches are being considered for the prop shaft design (Figure 3) -- the graphite/fiberglass hybrid and the graphite/aluminum (or steel) hybrid. The first approach includes high-strength graphite fiber in combination with E-glass fiber. These shafts are manufactured by the filament-winding process using multiple spools of continuous fiber. Metal sleeves are wound in to provide the interface for welding to yokes. The majority of material is low-cost fiberglass. Resin is applied during the winding process to minimize conversion costs. The overwrapped metal approach currently uses high-modulus fiber in resin-impregnated tape form. While the majority of material is aluminum or steel, the cost of resin-impregnated tape makes this approach less economical. Another approach would be to machine-lay the fibers in a wet-lay process, thereby eliminating the more costly prepregging step.

Several approaches are being considered for the manufacture of leaf springs (Figure 4). These include compression molding, filament winding, and pultrusion. The example shown uses compression molding of glass/graphite resin-impregnated tapes. For the heavy truck applications, a hybrid composite spring pack is combined with a steel top leaf for attachment purposes and economics. By virtue of the compsoite tape form used, these assemblies are yielding high premium levels. Further work must be done with lower-cost hybrid molding compounds having shorter processing cycle times to achieve the desired lower premiums.

The rather complicated bracket configuration (Figure 5) is compression molded with a form of sheet molding compound developed by Armco Composites. The potentially low conversion cost to produce this material form, which uses chopped fiberglass and continuous graphite fiber (sized with a polyester compatible resin and beamed to a 12 inch width), makes this approach economically attractive. While mold cycle time is approximately 3 minutes, improved molding compound resins are being considered to reduce this cycle time. For production, multiple dies with semiautomated material feed lines can provide the means for achieving high production rates. This single application is expected to demonstrate numerous other bracket type applications by virtue of the potentially low premiums and high weight savings over cast metal parts.

While the pultruded bumper (Figure 6) has had difficulties in maintaining fiber placement during the pultrusion process, it does represent a viable application and processing approach in achieving lightweight structural beam components. This application uses a minimum amount of continuous graphite fiber to achieve the desired beam bending stiffness. The part is designed for 5 mph impact standards. Other beams having similar impact functions are being investigated for the pultrusion process. In some cases, all-glass construction may be required to achieve the desired higher deformation strain energy more typical of a ductile metal. The tradeoff is apparent when considering required strength versus required strain energy. A second approach using the compression molding process of sheet molding compounds is being considered for bumper backup beams.

The final example shown (Figure 7) includes a transmission support crossmember which uses a small amount of continuous graphite fiber to achieve the required spring rate in combination with continuous glass XMC for compression molding. This application has the potential for weight savings in excess of 70% over the current steel part and a projected premium of less than $1.00 per pound of weight saved. The fiberglass meets gross beam bending requirements as well as critical shear stresses generated from torsional loads.

FUTURE ECONOMICS

The automotive industry has claimed for several years that graphite fiber prices must fall below $10/lb to be economically feasible. Fiber price forecasts since 1976 have indicated prices will fall below this level when volume exceeds one million pounds per year. This forecast trend is illustrated in Figure 8; estimated timing when the volumes could occur is shown in Figure 9. These figures do not reflect the aerospace market, which should exceed the million pound level by 1981-1982 primarily for higher priced fiber products. This trend reflects a best estimate for the automotive market and the lower cost commercial graphite fibers and is based on several limited production programs occurring in 1981-1983.

While economic feasibility of any given component is dependent upon raw material cost, producibility, and added value for weight reduction, the potential unit cost of raw material must be reviewed as a function of construction and volume to establish baselines for material selection. Figure 10 illustrates the potential unit costs of fibers, steel, and aluminum. Three hybrid graphite constructions are considered: 10, 20, and 30% graphite (balance includes % glass, % resin). As shown, unit price of raw material runs from $1.80 - $3.80 per pound at the one million pound volume of graphite fiber which is estimated for 1985. On a cost per unit volume basis, these prices are $.12 - $.24 per cubic inch. Considering the reduced weight of components (50-70% weight reductions), a $2.0 - $4.0 per pound raw material comes very close to being economically competitive with metal construction at less than $1.00 per pound premium on weight saved.

Another important factor is the long-term effect of escalation. While the percent of graphite used in the examples shown runs from 5% to 30%, graphite fiber is responsible for 20-60% of the cost of the part under current low-volume projections. However, allowing for higher volumes and escalation of all other material and labor cost through 1985, for example, the relative cost of the graphite drops to 10-40%. Since the major cost component (graphite fiber) is dropping in price, the net effect is an overall lower escalation. An example of this projection is shown in Figure 11 for the hybrid composite prop shaft compared with a two-piece, all-metal part.

While a big factor for this example is the removal of the center bearing assembly, this trend reveals the potential for direct cost savings (no premium) and a weight savings in excess of 50%. The spread given for the two-piece steel reflects minimum price for highest volume sizes, while the upper price reflects the lower volume sizes. The spread for hybrid composite shafts reflects minimum and maximum use of graphite fiber. The upper limit includes graphite fiber at a constant $18 per pound; the lower limit includes graphite as a function of projected volume. As shown in Figure 11, a crossover in cost is projected when the potential production rate of 100,000 to 200,000 prop shafts occurs.

Although most applications considered as examples here show no crossover trend prior to 1985, they do show the reduced rate of escalation (Figures 12, 13, and 14), which yields a potential for reduced premium on weight saved (under $1.00 per pound). For the bracket (Figure 12), a $1.00 premium is projected for 1985 (one million pounds fiber), after which the premium drops to around $0.60 per pound saved. The upper limit reflects a slow market growth for which the fiber price remains at $18 per pound.

For the transmission support crossmember (Figure 12), the potential weight savings is 16 pounds out of the total 22 for the metal component. This is an ideal situation for hybrid composite construction because it can be tailored to satisfy local stiffness constraints (localized spring rate at transmission attach point) without penalizing the total crossmember length with unnecessary material. The metal part uses a standard gage steel tube of a thickness required for the localized stiffness. The hybrid design using 5% graphite reinforcement has across-the-board potential for under $1.00 per pound premium on weight saved, while the 10% graphite hybrid does not fall below the $1.00 per pound premium until volume reaches the estimated production level in 1983. This application assumes the use of graphite/polyester prepreg tape in combination with continuous glass polyester molding compound where the price of graphite prepeg starts at $30 per pound and decreases to $16 per pound by 1985.

The hybrid graphite leaf spring (Figure 13) shows no strong potential for low premium on weight saved for the current design (max graphite) or processing method (compression molding with prepreg tape). If the current graphite prepreg tape requirement can be reduced from 13 pounds to 7.0 pounds (minimum graphite

design), the forecast premium is reduced significantly. However, unlike the other three examples which include estimated manufacturing costs, this comparison only includes raw material prices. Therefore, the premiums shown will increase proportionally by the manufacturing costs. If the springs can be produced by filament winding or pultrusion, the potential for an acceptable premium level is much greater because conversion costs to prepreg tape are not required.

These applications are typical of the areas being investigated today. Hercules recognizes that current costs discourage many within the industry from commiting to programs with specific target production dates. However, for these examples we have not considered a potential for secondary weight savings based upon the primary or direct weight savings. In many cases, a direct component weight reduction can lead to further reductions in adjacent or other supporting components. Further, no consideration has been given to the value of weight reduction relative to potential CAFE penalty for not meeting MPG requirements due to excess vehicle inertial weight. Nor has the value of reduced life cycle costs relative to reduced fuel consumption and potentially higher fuel costs been evaluated. In the future, as higher gas mileage is required and as fuel costs increase, the overall added value for weight reduction will have more significance and may well justify the premiums forecast at this time.

SUMMARY

Hybrid graphite fiber construction is currently viewed as a final approach to maximum weight reduction. However, as the issues are resolved and better understanding and higher confidence in its use is achieved, wider acceptance is anticipated. Continued development and refinements in the raw material forms will lead to more efficient and economical introduction into currently used fiber-reinforced molding materials. More complete characterizations of the properties and processibility of these hybrid materials will provide better options for the material selection. Basic data available today have shown the potential for improved structural characteristics. Further studies are required to fully assess the economic potential. Automotive industry interest and support are vital to the success of this new material. Until this support develops, the acceptance and increasing use by aerospace, industrial, and leisure industries will ensure continuing growth and raw material price reductions. However, the automotive industry clearly represents the greatest potential for high-volume consumption and, therefore, the greatest driving force for achieving the necessary low-cost material.

Table I - Fiber Types and Bundle Size

	Strength (ksi)	Modulus (Msi)	Density $_3$ (lb/in.^{3})
High strength	400-450	30-35	0.064
High modulus	300-350	50-55	0.067

Bundle Size	Application
3,000	Fabric
6,000	Fabric, XMC
10,000	Prepreg
12,000	Prepreg, SMC, F.W.
40,000	SMC, Pultrusion, F.W.

Table II - Basic Composite Properties

		Tensile Strength ksi (MPa)	Tensile Modulus Msi (GPa)	Density lb/in.^{3} (g/cm^3)
Uni-dir (0°)	graphite	220.0 (1517)	20.0 (138)	0.056 (1.55)
	fiberglass	160.0 (1104)	5.6 (39)	0.072 (1.99)
Bi-dir (0,90)	graphite	122.0 (838)	10.7 (74)	0.056
	fiberglass	75.0 (518)	3.6 (25)	0.072
Multi-dir (±45°)	graphite	20.0 (138)	2.5 (17	0.056
	fiberglass	22.0 (152)	1.6 (11)	0.072
Isotropic (0, ± 45, 90)	graphite	88.0 (604)	6.9 (48)	0.056
	fiberglass	48.0 (330)	2.6 (18)	0.072

*Nominal 60% fiber volume, epoxy resin

Table III - Unidirectional Graphite/Fiberglass Hybrids

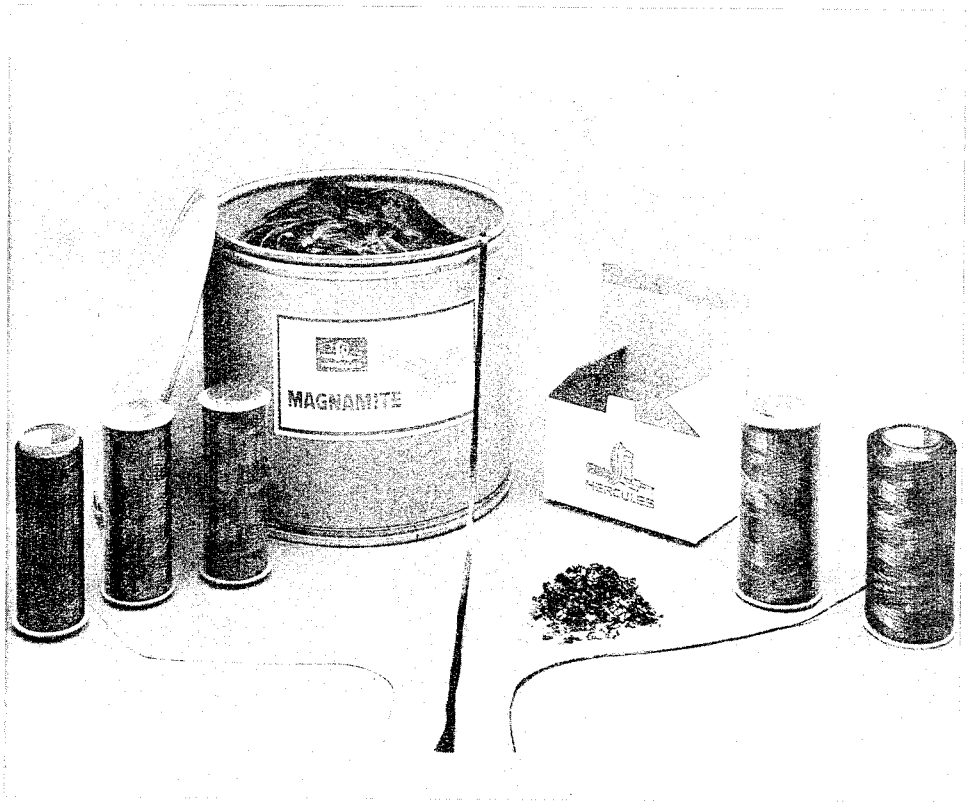
	Tensile Strength ksi (MPa)	Tensile Modulus Msi (GPa)	Density lb/in.^{3} (g/cm^3)
All fiberglass	87.0 (600)	5.6 (39)	0.072 (1.99)
Graphite/fiberglass			
20/80	87.4 (603)	8.3 (57)	0.069 (1.91
40/60	116.0 (800)	11.0 (76)	0.066 (1.82)
60/40	143.0 (986)	13.6 (94)	0.062 (1.71)
80/20	172.0 (1186)	16.3 (113)	0.059 (1.63)
All graphite	200.0 (1379)	19.0 (131)	0.056 (1.55)

*Nominal 50% fiber volume, polyester resin

Table IV - Molding Compound Materials

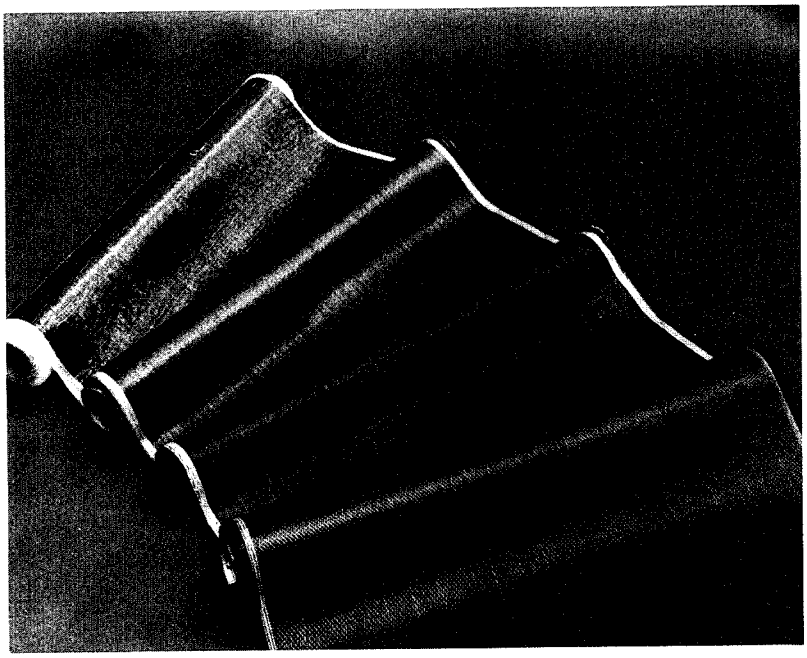
	Tensile Strength ksi (MPa)	Tensile Modulus Msi (GPa)	Density lb/in.^{3} (g/cm^3)
(Molding compound sheet)			
All fiberglass			
Random 60%	30 (207)	2.5 (17.3)	0.072 (1.99)
Continuous (unidir) 60%	70 (483)	5.5 (38.0)	0.072 (1.99)
Continuous (40%) random (20%)	50 (345)	4.0 (27.7)	0.072 (1.99)
Graphite/fiberglass			
Graphite (12%) random glass (48%)	80 (552)	7.5 (51.9)	0.069 (1.91)
Graphite (15%) random glass (45%)	90 (621)	8.0 (55.3)	0.068 (1.88)
Graphite (20%) random glass (40%)	100 (690)	9.5 (65.70	0.067 (1.85)
Graphite (20%) cont ±15° glass (40%)	120 (827)	10.5 (72.6)	0.067 (1.85)
All graphite			
Continuous (unidir) 60%	190 (1310)	16.0 (110.6)	0.056 (1.55)

Note: Assumed construction, graphite face sheets - fiberglass core



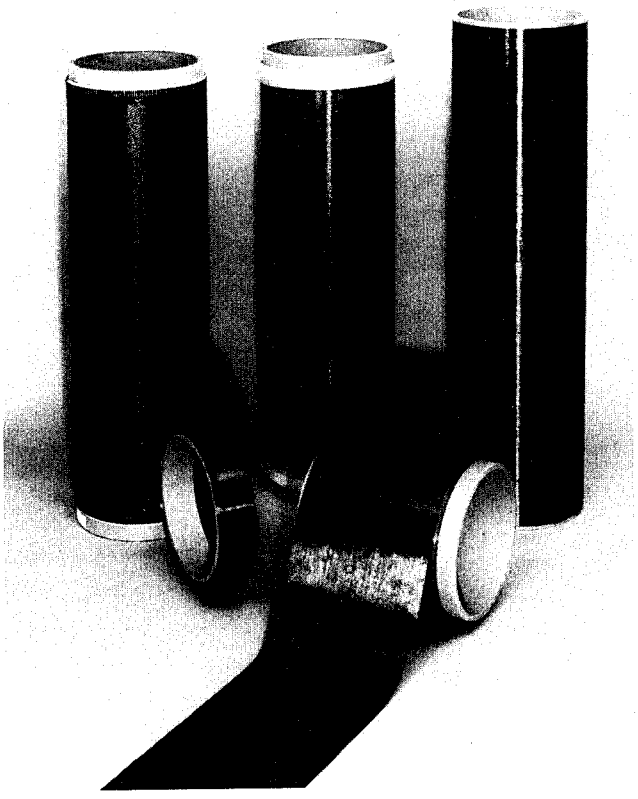
CONTINUOUS	CHOPPED
SPOOL, BEAM, BOX	MILLED 1/4 MM
SIZED, UNSIZED	1/8 IN., 1/4 IN.,
HIGH STRENGTH, HIGH MODULUS	1-2 IN. SIZED
FILAMENT WINDING	INJECTION MOLDING
PULTRUSION, PREPREG	

Figure 1. Graphite Fiber Products



WOVEN, KNIT, MAT

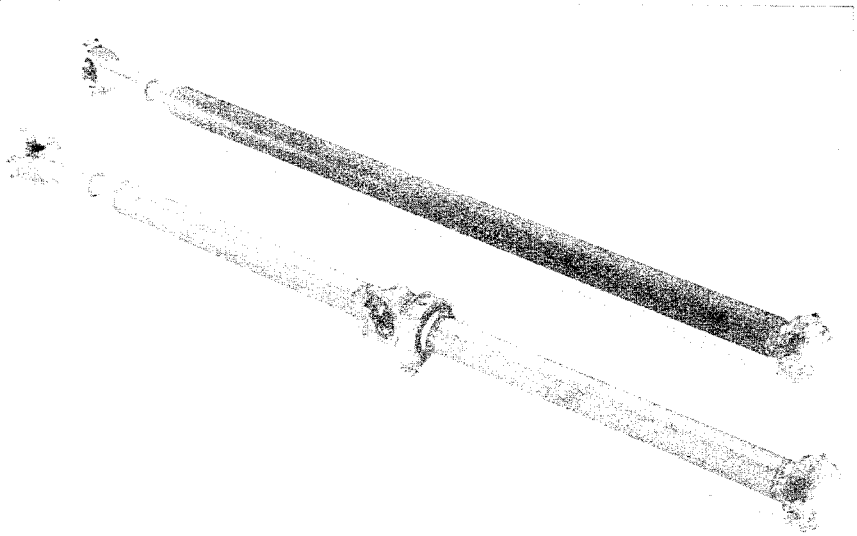
BIDIRECTIONAL
UNIDIRECTIONAL
RANDOM
MFG. COMPLEX CONFIGURATIONS



RESIN IMPREGNATED

UNIDIRECTIONAL, MULTI-
DIRECTIONAL
EPOXY, POLYESTER, VINYLESTER
1/4 IN. TO 48 IN. WIDE
PART MANUFACTURE
TAPE WRAP, LAYUP

[illegible]



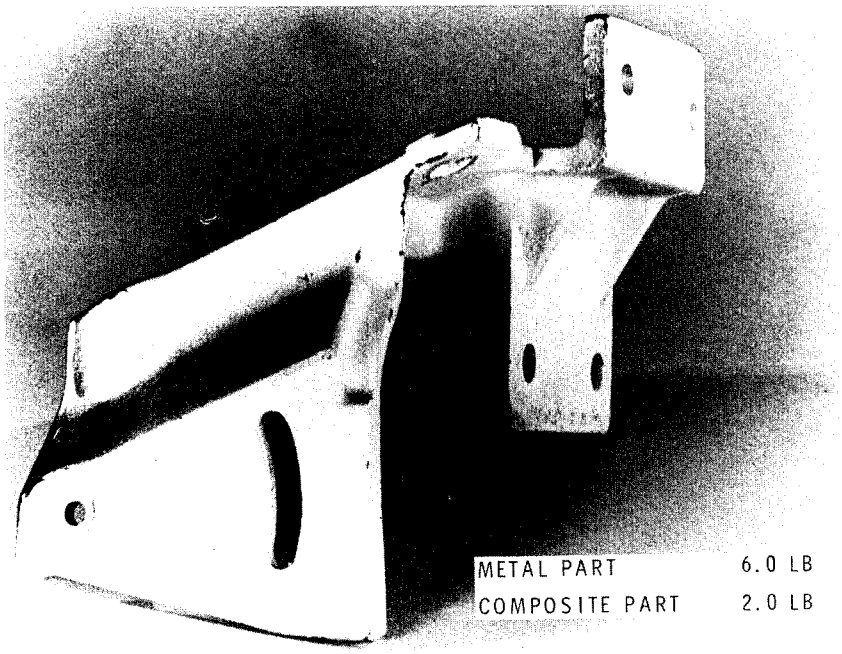
	HYBRID GL/GR	HYBRID GR/METAL
MATERIAL:	HIGH STR GRAPHITE/ E-GLASS/METAL	HIGH MOD. GR./Al
CONSTRUCTION:	14% GR/38% FI/21% RES/27% MET.	6% GR/4% RES/90% Al
PROCESS:	FILAMENT WIND	TAPE WRAP

MATERIAL: HIGH STR. GRAPHITE/E-GLASS/METAL

CONSTRUCTION: 16% GR/26% GL/28% RES/30% METAL

PROCESS: COMPRESSION MOLD

Figure 6. Hybrid Leaf Spring



MATERIAL: HIGH STR. GRAPHITE/E-GLASS

CONSTRUCTION: 27% GR/43% GL/30% RESIN

PROCESS: COMPRESSION MOLD

MATERIAL: HIGH STR. GRAPHITE/E-GLASS

CONSTRUCTION: 5% GR/45% GL/50% RESIN

PROCESS: PULTRUSION

Figure 6. Composite Bumper

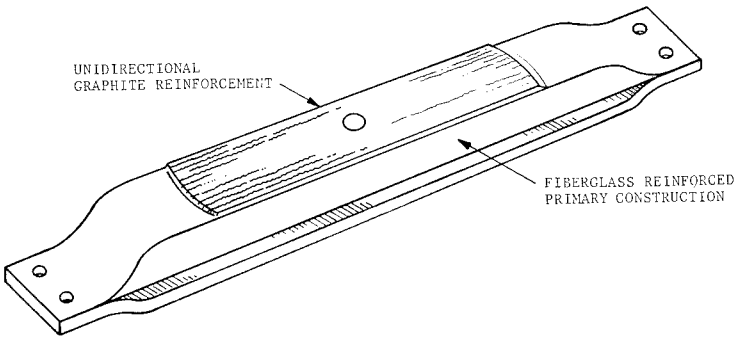


Figure 7. Hybrid Transmission Support

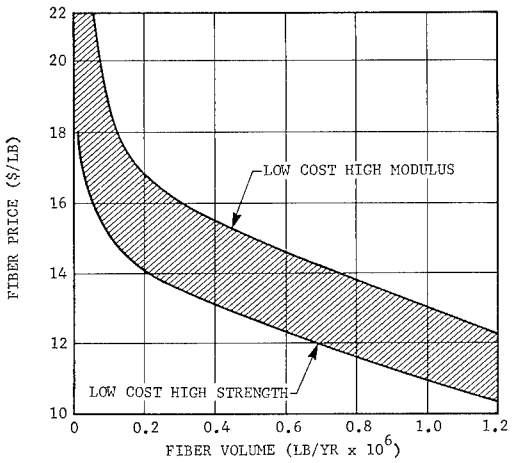


Figure 8. Fiber Price/Volume

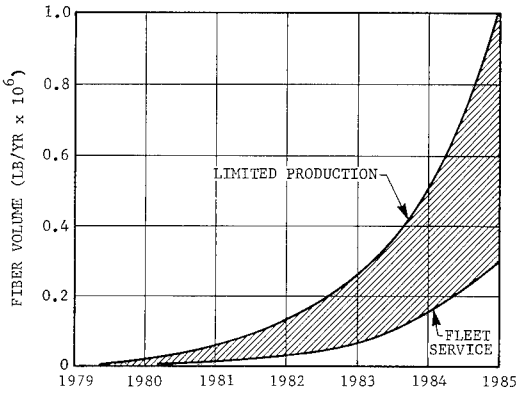


Figure 9. Potential Volume/Year

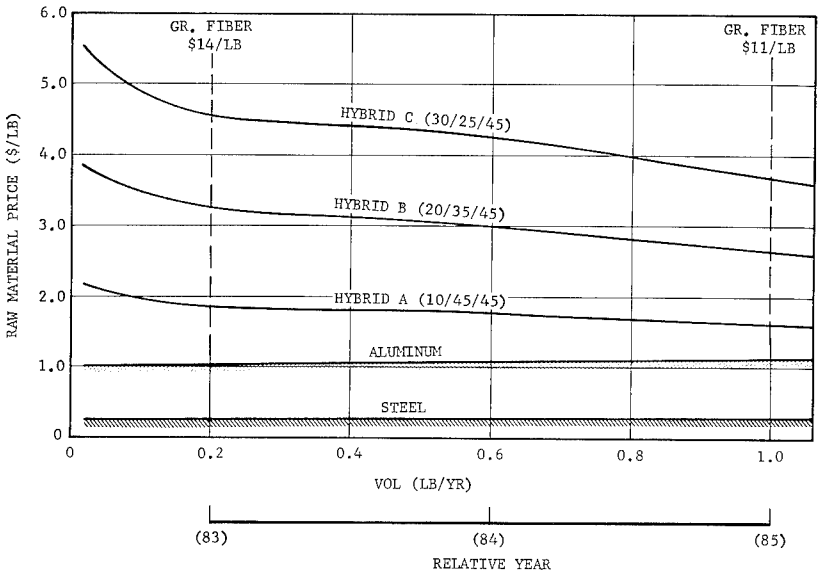


Figure 10. Raw Material Price

GRAPHITE FIBER PRICE		
1979	$18/lb	5000 lb
1981	$16/lb	50,000 lb
1983	$14/lb	200,000 lb
1985	$11/lb	1,000,000 lb

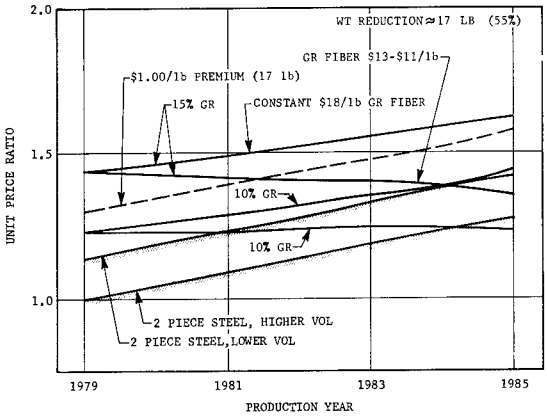


Figure 11. Prop Shaft Economic Potential

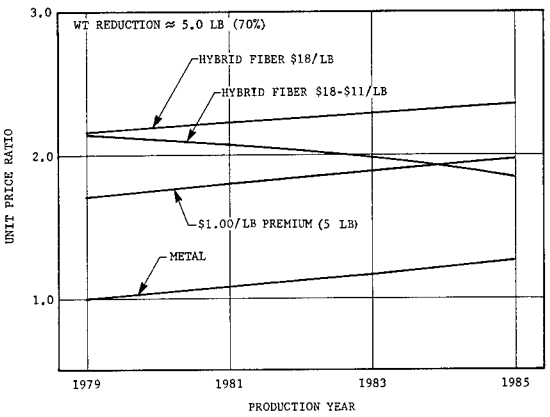


Figure 12. Bracket Economic Potential

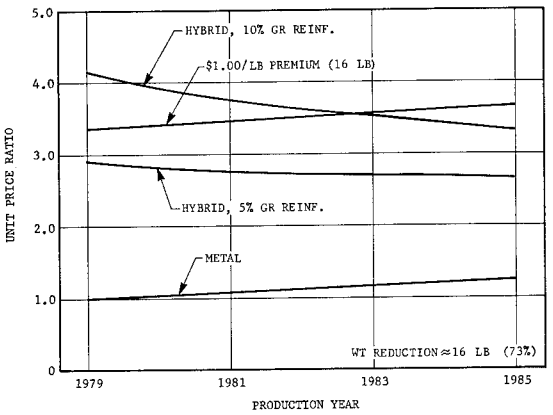


Figure 13. Crossmember Potential Economics

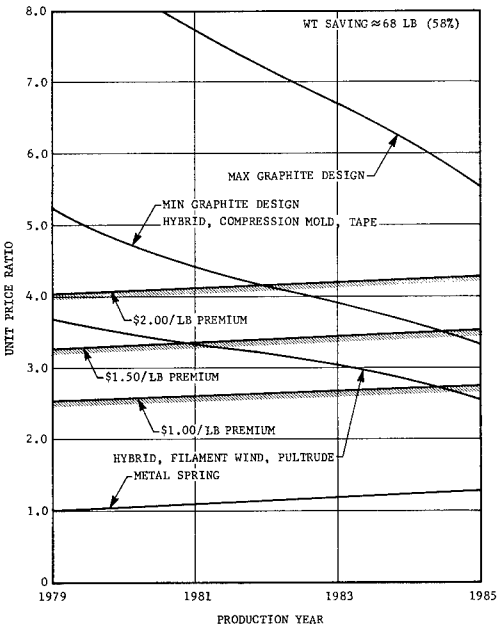


Figure 14. Leaf Spring Economic Potential

FAST CURING EPOXY RESIN SYSTEMS FOR THE FILAMENT WOUND DRIVESHAFT

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Introduction:

One of the future applications of carbon fiber under consideration by the automotive industry is the composite light truck driveshaft. This particular application is cost effective and is not being considered solely as a weight saving replacement. This is a result of the fact that the light truck composite driveshaft will be one piece thus eliminating the added cost of the coupling joint currently used with the two piece metal shaft. The composite shaft will be approximately 68 inches in length and 3.8 inches in diameter. With yokes attached, the shaft will weigh 17 pounds compared to the current metal shaft which weighs 37 pounds.

The composite driveshaft is a dramatic example of fiber reinforced plastics technology. It will have several advantages over the conventional shaft currently in use. These include: 1. A one piece construction which minimizes mechanical problems, 2. reduced noise, 3. reduced tendency to vibrate, 4. increased resistance to corrosion.

The composite system used also provides a good example of how hybridization with glass can make a carbon fiber application more viable. Carbon fiber will be used in only limited amounts in order to impart the necessary stiffness to the shaft.

Prototype shafts built at our facility are made by a filament winding technique. The filament winding procedure uses an epoxy resin specially formulated to meet the variety of needs required for the production and use of the composite driveshaft. An epoxy resin was chosen since it was felt that this type of resin would be necessary to meet the temperature and environmental resistance requirements of the driveshaft. The criteria set by the automotive maker is for adequate thermal resistance at 121°C and for maintaining acceptable performance after immersion in boiling saturated salt water for 24 hours. The other requirements for the resin system include low cost, fast cure and adequate levels of tensile and impact strength. These properties relate to the end use requirements of the drivesharft.

In order to process properly the resin must also have certain handling characteristics. The primary requirements for use as a filament winding resin are for the proper viscosity and pot life at the winding temperature. A resin viscosity of ca. 1500-2000 cps (1.5-2.0 Pa.sec.) is desired for the driveshaft winding application. Lower viscosities of about 500 cps (0.5 Pa.sec.) are frequently used for filament winding but during a high speed process these low viscosities may result in excessive amounts of resin being expelled from the fiber. Thus a slightly higher viscosity minimizes this occurrence while still allowing for adequate fiber wetting. Pot life of the resin system must be such that shafts may be wound without significant advancement of the resin occurring in the resin bath.

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The outline of resin requirements indicates that many of the features desired are contradictory. The system must be fast curing but must nevertheless have adequate pot life. It must have low viscosity but also must have good thermal resistance. Materials that provide improved high temperature performance are often solid or high viscosity materials. In the past, pipe has been filament wound using epoxy systems but these systems were slow curing requiring a cure cycle of several hours followed by a post cure. These systems are inadequate for the driveshaft application.

Results and Discussion

We have formulated a resin system which meets all of the criteria mentioned. Properties have been obtained on the resin system from castings as well as composite systems prepared from either carbon fiber or glass.

In Table I is an outline of the basic features of our driveshaft resin system designated "A". Viscosity of the system is approximately 2000 cps at an elevated temperature of 55°C. Pot life is dependent on batch size, decreasing with increasing quantity. This feature necessitates the use of a limited batch size which periodically is replenished with a freshly mixed material. The system wets both glass and carbon fibers adequately. Initial Tg of the resin is 171°C which is reduced to 150°C after a 24 hour water boil. The resin system cures very rapidly. Four minutes at 184°C are sufficient to completely develop resin properties. No post cure is necessary.

The last feature is shown more clearly in Table II which indicates filament winding resin properties as a function of cure time. Complete resin properties are achieved using a four minute cure at 184°C. The use of a low level of accelerator reduces the cure time to two minutes at 184°C. In this case as well it appears that a high percentage of composite properties are obtained from the initial short cure. (A small increase in heat deflection temperature is observed after a cure time of seventeen minutes.)

In order to obtain property information on composite systems made with the resin material we prepared panels made from 0° filament wound sheets. The sheets were made from either Celion®6000 carbon fiber or from "E" glass and then layed up in a panel configuration. Curing was done in a hot mold and press at 164°C using a short cure cycle of five minutes as discussed previously. Obviously panels made in this fashion do not replicate the filament winding construction. However, it was felt that this procedure gave a meaningful estimate of the composite properties that could be obtained with the new resin system.

The properties obtained on the panels prepared with carbon fiber are shown in Table III. Flex and interlaminar shear properties are shown as a function of temperature. In addition, data is given for the system after 24 hour immersion in boiling water as well as boiling saturated salt water. The salt solution is designed to simulate a severely corrosive system that might be encountered by

the driveshaft under extended operation. Flexural strength and interlaminar shear strength are the key composite properties affected by the nature of the interface. Since environmental conditioning exerts its most severe affect on composites at the fiber-resin interface, these properties would be the most appropriate to monitor.

Examination of the data indicates a limited reduction in properties for the conditioned materials tested at 121°C while those properties obtained at 177°C show more significant reduction from the comparable dry properties. Despite the property reductions observed, the level of properties maintained after 24 hour conditioning in boiling water and saturated salt water still appears to be adequate at 150°C. It is also clear from the data obtained that the presence of salt in the conditioning bath does not result in any further deterioration of composite properties over that observed with boiling water.

In Table IV, composite properties obtained on panels prepared from filament wound "E" glass sheets are shown. In this case, property reduction at 121°C after 24 hour boiling water conditioning is substantial although actual levels of properties maintained still appear to be adequate. At 150°C, property reduction is severe enough to cause plastic failure in the testing of shear specimens. Properties obtained after 24 hours conditioning in boiling salt water solution are very similar to those observed after boiling water conditioning.

Based on the results obtained with the all glass composites, we formulated an additional system designed to provide improved composite properties at elevated temperature after environmental conditioning.

The properties obtained on the carbon fiber composite prepared from the improved resin system, designated System "B", are shown in Table V. Very little difference is observed in properties before and after conditioning between this system and System "A". A lower level of flex strength is seen at 121°C after conditioning. Properties at 177°C after conditioning are virtually identical. Of greater interest is a comparison of the System "A" glass reinforced composite with that prepared from System "B". The latter system, as shown in Table VI, shows improved property levels in flex at 121°C as well as flex and shear at 177°C after conditioning. The value of the interlaminar shear strength at 177°C after conditioning has been significantly increased and plastic failure is not observed in the testing of the shear specimens.

Additional testing of composite specimens was also done after much more extensive environmental conditioning than a 24 hour treatment. This initial procedure can only assess the response of the resin system to limited environmental attack. It is well known from work done with aerospace epoxy resin systems that composite coupons take several days in boiling water to reach an equilibrium condition.[1]

In Table VII, composite flex and shear properties at 121°C were determined for both Systems "A" and "B" after seven days conditioning in boiling saturated salt water. The final column in the table indicates the percent change in shear strength observed when the property value obtained after seven day conditioning was compared with that obtabined after 24 hour conditioning. It is immediately apparent that the all glass composite system prepared from System "A" is the only material undergoing significant reduction in shear value during the longer environmental exposure. However, the composite still maintains an adequate level of shear strength after the conditioning period. Flex values were only minimally changed for this system by the extended treatment. Properties of the carbon fiber composite prepared from System "A" as well as properties of the carbon fiber and glass composites prepared from System "B" experienced only a limited reduction in properties when compared to those values obtained after the 24 hour conditioning. Thus even after this severe conditioning treatment, properties at elevated temperature for these systems still appear to be maintained at adequate levels.

Conclusions

A low cost, low viscosity, rapid curing epoxy resin system has been formulated for the filament winding of carbon and glass fiber composite systems. Composites prepared from the systems examined show adequate flex and shear properties at an elevated temperature of 121°C even after extended environmental conditioning. The resin system appears to be suitable for the filament winding of composite driveshafts as well as other filament winding applications.

Acknowledgments

The authors would like to acknowledge the invaluable help of David Suarez, Jim Sabo and Hector Zabaleta who prepared the resin castings and composite panels used in this work.

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TABLE I

FILAMENT WINDING RESIN SYSTEM "A"

VISCOSITY:	1500 - 2000 cps (1.5-2.0 Pa.sec.)
POT LIFE:	260 min. at 55°C (70g)
	30 min. at 55°C (3Kg)
Tg (dry casting)	171°C
Tg (casting after 24 hour water boil)	150°C
CURE:	Four minutes at 184°C

NO POST CURE REQUIRED

LOW COST

TABLE II

CAST RESIN PROPERTIES AS A FUNCTION OF CURE TIME [1]

Resin	Cure Time (Min.)	Rockwell Hardness "M" Scale	Heat Deflection Temperature (°C)	Flexural Strength KSI (MPa)	Flexural Modulus KSI (MPa)
	4	108	152	16.95 (117)	455 (3137)
System	9	108		16.58 (114)	449 (3096)
"A"	14	106		16.55 (114)	446 (3075)
	19	107	152	15.75 (109)	441 (3041)
System	2	111	145	18.98 (131)	489 (3372)
"A"	7	111		19.03 (131)	495 (3413)
+	12	109		17.82 (123)	473 (3261)
Accelerator	17	109	150	17.40 (120)	468 (3227)

1. Curing was done in a circulating air oven at 184°C.

TABLE III

COMPOSITE PROPERTIES OF 0° FILAMENT WOUND SYSTEM "A"/CELION® 6000 [1]

Conditioning Procedure	Test Temperature (°C)	Flexural [2] Strength KSI (MPa)	Flexural [2] Modulus MSI (GPa)	Interlaminar Shear Strength PSI (MPa)
None	22	268 (1848)	20.2 (139)	14,700 (101)
(Dry)	121	190 (1310)	19.3 (133)	9,800 (67.6)
	150	154 (1062)	18.8 (130)	7,800 (53.8)
Wet	22	(?)185 (1276)	19.5 (134)	13,700 (94.5)
(24 Hr. Immersion	121	187 (1289)	19.3 (133)	7,800 (53.8)
in Boiling Water)	150	124 (855)	17.8 (123)	6,600 (45.5)
Wet	22	238 (1641)	19.4 (134)	13,600 (93.8)
(24 Hr. Immersion	121	171 (1179)	19.4 (134)	8,300 (57.2)
in Boiling Saturated	150	128 (883)	18.0 (124)	6,900 (47.6)
Salt Water)				

1. Compression mold curing was done using a hot mold and press at 177°C. A 12 x 11.4 inch panel was made using contact pressure for 0.5 minutes followed by 100 psi (0.69 MPa) for 4.5 minutes. The panel was then removed hot.

2. Fiber volumes are normalized to 62%.

TABLE IV

COMPOSITE PROPERTIES OF 0° FILAMENT WOUND SYSTEM "A"/"E" GLASS[1]

Conditioning Procedure	Test Temperature (°C)	Flexural[2] Strength KSI (MPa)	Flexural[2] Modulus MSI (GPa)	Interlaminar Shear Strength PSI (MPa)
None	22	222 (1531)	6.43 (44.3)	13,300 (91.7)
(Dry)	121	142 (979)	6.03 (41.6)	8,400 (57.9)
	150	110 (758)	5.75 (39.6)	4,800 (33.1)
Wet	22	182 (1255)	6.34 (43.7)	12,000 (82.7)
(24 Hr. Immersion	121	117 (807)	5.92 (40.8)	7,200 (49.6)
in Boiling Water)	150	84 (579)	5.02 (34.6)	3,100[3] (21.4)
Wet	22	204 (1407)	6.31 (43.5)	12,700 (87.6)
(24 Hr. Immersion	121	132 (910)	6.12 (42.2)	7,500 (51.7)
in Boiling Saturated	150	97 (669)	5.56 (38.3)	4,200 (28.9)
Salt Water)				

1. Compression mold curing was done using a hot mold and press at 177°C. A 12 x 11.4 inch panel was made using contact pressure for 0.5 minutes followed by 100 psi (0.69 MPa) for 4.5 minutes. The panel was then removed hot.

2. Fiber volumes are normalized to 62%.

3. Plastic failure was observed.

TABLE V

COMPOSITE PROPERTIES OF 0° FILAMENT WOUND SYSTEM "B"/CELION® 6000 [1]

Conditioning Procedure	Test Temperature (°C)	Flexural[2] Strength KSI (MPa)	Flexural[2] Modulus MSI (Gpa)	Interlaminar Shear Strength PSI (MPa)
None	22	255 (1758)	19.3 (133)	14,500 (100)
(Dry)	121	176 (1213)	18.8 (130)	9,800 (67.6)
	150	158 (1089)	18.4 (127)	8,000 (55.2)
Wet	22	208 (1434)	18.2 (125)	13,500 (93.1)
(24 Hr. Immersion	121	136 (938)	17.8 (123)	8,300 (57.2)
in Boiling Water)	150	124 (855)	17.2 (119)	6,600 (45.5)
Wet				
(24 Hr. Immersion	22	208 (1434)	18.4 (127)	13,800 (95.2)
in Boiling Saturated	121	151 (1041)	17.0 (117)	8,500 (58.6)
Salt Water)	150	128 (883)	16.8 (116)	6,900 (47.6)

1. Compression mold curing was done using a hot mold and press at 177°C. A 12 x 11.4 inch panel was made using contact pressure for 0.5 minutes followed by 100 psi (0.69 MPa) for 9.5 minutes. The panel was removed hot.

2. Fiber volumes are normalized to 62%.

TABLE VI

COMPOSITE PROPERTIES OF 0° FILAMENT WOUND SYSTEM "B"/"E" GLASS[1]

Conditioning Procedure	Test Temperature (°C)	Flexural[2] Strength KSI (MPa)	Flexural[2] Modulus MSI (GPa)	Interlaminar Shear Strength PSI (MPa)
	22	211 (1455)	6.40 (44.1)	13.600 (93.8)
None	121	148 (1020)	6.24 (43.0)	8,300 (57.2)
(Dry)	150	117 (807)	5.69 (39.2)	7,200 (49.6)
Wet	22	181 (1248)	6.31 (43.5)	13,200 (91.0)
(24 Hr. Immersion	121	134 (924)	6.46 (44.5)	7,300 (50.3)
in Boiling Water)	150	101 (696)	5.60 (38.6)	5,800 (40.0)
Wet	22	197 (1358)	6.26 (43.2)	13,300 (91.6)
(24 Hr. Immersion	121	143 (986)	6.01 (41.4)	7,700 (53.1)
in Boiling Saturated	150	107 (738)	5.63 (38.8)	7,100 (48.9)
Salt Water)				

1. Compression mold curing was done using a hot mold and press at 177°C. A 12 x 11.4 inch panel was made using contact pressure for 0.5 minutes followed by 100 psi (0.69 MPa) for 4.5 minutes. The panel was then removed hot.

2. Fiber volumes are normalized to 62%.

TABLE VII

ELEVATED TEMPERATURE (121°C) COMPOSITE PROPERTIES

AFTER EQUILIBRIUM ENVIRONMENTAL CONDITIONING [1]

Resin	Flexural[2] Strength KSI (MPa)	Flexural[2] Modulus MSI (GPa)	Interlaminar Shear Strength PSI (MPa)	Percent Change[3]
System "A"				
"E" Glass	123 (848)	5.96 (41.1)	5,300 (36.5)	-29
Celion 6000	--	--	7,600 (52.4)	- 8
System "B"				
"E" Glass	120 (827)	5.96 (41.1)	7,100 (48.9)	- 8
Celion 6000	139 (958)	17.31 (119)	7,600 (52.4)	-11

1. Seven days in boiling saturated salt water.

2. Fiber volumes normalized to 62%

3. Percent change compared to value obtained after 24 hour conditioning in saturated salt water.

DYNAMIC PERFORMANCE OF VINYL ESTER RESIN COMPRESSION MOLDED HIGH STRENGTH COMPOSITES

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INTRODUCTION

Detroit is employing new and imaginative technology to comply with the escalating Corporate Average Fuel Economy (CAFE) standards mandated by Federal Regulations. The automobile producers are meeting the challenge via several methods: downsizing, as evident in the models now on the market; corresponding reduction in engine and drive train size; introduction of front-wheel drive vehicles to replace existing models; greater availability of diesel engines for popular models; and substitution of lighter weight materials. High strength low alloy (HSLA) steel; aluminum and magnesium have reduced the weight of many components. Light weight reinforced plastic composites (RP/C) are increasingly used because of dual energy savings: (1) the raw material to finished component energy consumption of RP/C parts is less than that of conventional metal components and (2) use of light weight RP/C components can dramatically improve a vehicle's fuel economy.

The use of RP/C parts from sheet molding compounds (SMC) -- less than 35% fiber glass -- is well known in the automotive and transportation industry. Although the long term performance of these parts is important, most applications are primarily appearance parts with only minimal structural requirements. Here, the dynamic load-bearing performance of the RP/C is not a major concern.

In the last three years, automotive companies, custom molders, fiber glass companies, and resin suppliers have devoted extensive effort to develop high strength molding compounds (HSMC) with higher levels of fiber glass. The most promising of these systems, which are usually denoted R-50 and R-65, contain 50% to 65% fiber glass in the form of 1" chopped, randomly oriented fibers. These systems are developed specifically for structural applications; thus, to replace well-established metal technology, detailed static and dynamic performance data for high strength RP/C is required by the design engineer.

The Dow Chemical Company has been extensively involved in the development of HSMC systems based on DERAKANE* 790 Vinyl Ester Resin. The chemistry of thickenable vinyl ester resins has been reported previously.[1]

Briefly, the two main advantages of vinyl ester resins are derived from: (1) the design of the epoxy backbone which provides the flow, toughness and excellent performance characteristics over a wide range of temperatures; and (2) the terminal vinyl unsaturation which allows rapid free radical curing reaction with peroxides.

STATIC PROPERTIES

The static properties of vinyl ester resin based HSMC composites have been extensively studied and previously reported.[2] The mechanical properties of six key formulations are shown in Figures 1, 2 and 3. Tensile and flexural properties were determined using ASTM Methods D-638 and D-790 at temperatures of -20, 72, 212 and 302°F.

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The room-temperature static properties of an RP/C material are determined primarily by glass content.

A decline in static properties exists at elevated temperatures. The relative importance of glass level also diminishes at elevated temperatures, as the elevated temperature performance of the resin itself assumes an important role in determining the static properties of the RP/C.

The effect of the filler level of the RP/C is clearly demonstrated in Figures 1, 2 and 3. Although the industry discusses the components (glass, resin, filler) of the system in terms of weight fraction, these materials actually function on a volume fraction basis. While holding the glass weight percent of a system constant, the addition of filler improves both the modulus and overall high temperature static performance of the RP/C; thus, while the glass weight percent is held constant, the addition of filler serves to increase the glass volume percent of the system. In addition to lowering the cost of the composite, $CaCO_3$ filler also contributes to improved molding rheology. The use of filler allows better glass carry while molding and prevents the formation of glass-rich and resin-rich areas in the composite.

STATIC CREEP

The design engineer is often interested in the long-term static creep of RP/C structures. Static creep was determined for DERAKANE 790 vinyl ester resin based HSMC composites by Materials Technology, Inc.[3], using ASTM Method D-2990. Figure 4 shows that creep under long term loading does occur at stress levels as low as 10,000 psi (68.9 MPa). As the stress level is raised, the percent elongation at time zero (0) increases but the rate of creep is identical at all stress levesl. Creep data at a fixed stress level, 13,750 psi (96.0 MPa) and varying temperature is shown in Figure 5. The rate of creep of the material is greater at 93.3°C, suggesting that the rate of creep is a function of temperature. Importantly, the creep behavior of DERAKANE vinyl ester resin based RP/C structures follows an extremely predictable pattern, as shown by the straight line plots on semi-log scales.

DYNAMIC PROPERTIES

The automotive design engineer is interested in much more than the static performance of RP/C materials. The room-temperature static properties of an HSMC composite are largely determined by the glass content of the system. However, the dynamic properties are controlled by the type of resin used in the HSMC system. Design calculations are based on the long-term dynamic performance of the material.

FATIGUE

Tension-tension fatigue properties were determined at room temperature and 200°F for both R-50 and R-65 formulations and the respective S-N curves are shown in Figures 6, 7, 8, and 9. The cyclic stress was input as a sinusoidal wave with the minimum stress of 5% of the ultimate tensile strength (UTS); the maximum being the stress level shown in the figures.

The fatigue tests for the R-50 composite at room temperature and both systems at 200°F were performed by Terra Tek.[4] The room-temperature fatigue tests for the R-65 RP/C were performed by Dow Chemical[5] using the same test procedures as Terra Tek.

The S-N curves show the room-temperature endurance limit of the R-50 and R-65 systems to be, respectively, 47% and 42% of UTS. These levels correspond to 12,000 psi (83 MPa) and 12,500 psi (86 MPa). As shown in Figures 8 and 9, the elevated temperature (200°F) endurance limit of the R-50 material is 42% of UTS; the 200°F endurance limit of the R-65 RP/C is 36% of its UTS. These correspond to 9300 psi (64 MPa) and 9800 psi (68 MPa). The endurance limit is reached at approximately 10^6 cycles in all four cases.

Interestingly, when superimposed, the 200°F S-N curves for both the R-50 and R-65 systems appear nearly identical. This suggests that elevated temperature properties of an RP/C material are determined by the resin and not the glass content of the system. Thus, the same type of S-N curve would result at 200°F at any glass level, provided vinyl ester resin is used in all systems. This same effect is noted in the static physical properties at elevated temperatures, suggesting that both static and dynamic elevated temperature physical properties are determined by the resin matrix.

Similar S-N curves are observed for both the R-50 and R-65 systems at room-temperature. The fatigue endurance limit of an HSMC composite is determined by the resin matrix, not the glass content of the system.

Specimens that withstood 10^6 cycles were tested for residual strengths. The room-temperature specimens retained 75-100% of their original UTS, while the 200°F specimens were found to retain 95-100% of their original UTS when tested at 200°F.

The loss in dynamic modulus was monitored during the development of the S-N curves. The modulus decay of R-50 at 45% of UTS is shown in Figure 10 for both room-temperature and 200°F. Although a loss in modulus is observed, the room-temperature specimens still retained 85% of their original modulus after 10^6 cycles. The 200°F specimens retained 97% of their original modulus after 10^6 cycles. Samples tested at much higher cyclic stresses which failed before 10^6 cycles still showed excellent retention of the modulus.

IMPACT STRENGTH

Impact strength is one of the key performance requirements for RP/C systems designed for many automotive applications, such as bumpers, intrusion beams, crash members, wheels or other parts subject to direct impact. Throughout the industry, it is becoming apparent that traditional impact tests like Izod, Charpy, tensile impact, high rate tensile and dropping weight are not realistic tests of a material's behavior during impact. High-rate impact testers, such as the instrument developed by Rheometrics, Inc.[6], provide the controlled-rate capabilities of high-rate tensile testers with the test-specimen versatility of dropping weight testing.

Variable rate impact tests were performed on DERAKANE 790 RP/C systems containing 40, 50 and 65% fiber glass. The impact test used 6" x 6" flat plaque specimens; a 1/2 diameter impacting head with a 2" diameter backing support. Three replicates of each composite were run at 1, 3, 5, 7 and 10 mph at room temperature.

The strain rate at which impact failure for vinyl ester based composites changes from an elastic mode to a brittle mode is between 5-7 mph. This value is fairly high and points to the suitability of vinyl ester based RP/C for a wide variety of structural automotive applications.

CONCLUSION

DERAKANE 790 vinyl ester resin high strength RP/C systems is a leading candidate for a wide range of structural automotive applications. The excellent static properties of these systems is widely known. However, the room-temperature static properties are largely a function of the glass content of the system. The dynamic properties and elevated temperature static behavior of the RP/C system are largely controlled by the resin matrix. This paper expands the design data available to the automotive engineer. Static creep, fatigue and impact strength are examined for several widely used vinyl ester resin RP/C systems at a variety of temperatures. These superior dynamic properties are needed to insure long-term toughness and durability for a wide range of high strength structural automotive applications.

BIOGRAPHY

1. Dick Erratt is Project Manager of DERAKANE* Vinyl Ester Resins for High Strength Molding Compound (HSMC) in Resins R&D, Dow Chemical U.S.A. He received a B.S. in Chemical Engineering from Michigan State University in 1951. After five years in the U.S. Air Force, he joined Dow in 1956. His career at Dow has been in plastics R&D and in resins for Reinforced Plastics Composites (RP/C) since 1973.

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4. Ray Thomas is a Research Supervisor in Resins Research, Dow Chemical U.S.A. He received a bachelor's degree in Aerospace Engineering in 1967 from Georgia Tech. He worked as an Aerospace Structures Engineer until 1971 when he joined Dow in Resins Research. Since that time he has worked in the development of sheet molding compounds and high strength sheet molding compounds.

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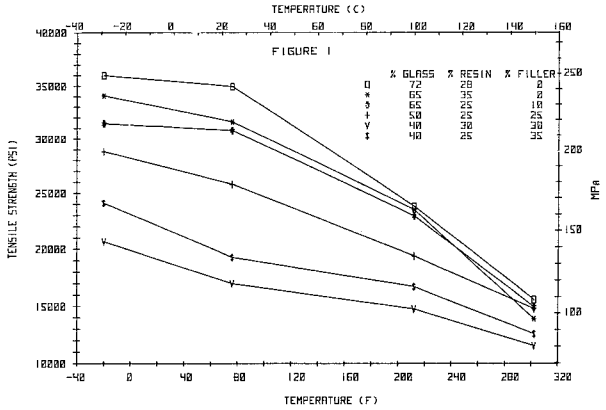
[3]Materials Technology, Inc., P. O. 7358, Ann Arbor, Michigan 48107.

[4]Terra Tek, 420 Wakara Way, Salt Lake City, Utah 84108.

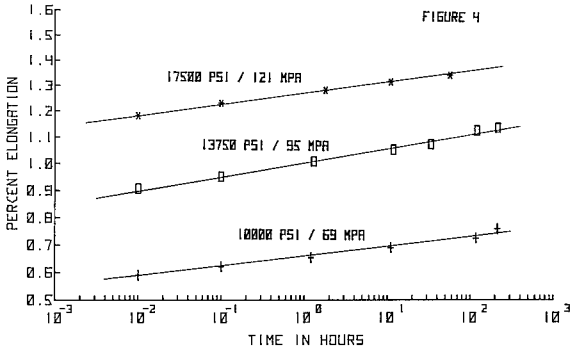
[5]Dow Chemical U.S.A., Resins Research and Development, Freeport, Texas 77541.

[6]Rheometrics, Inc., 2438 U.S. Highway 22, Union, New Jersey 07083.

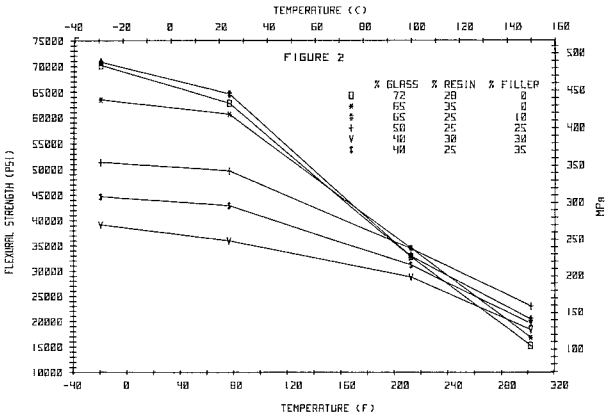
EFFECT OF GLASS LEVEL AND TEMPERATURE DERAKANE 790



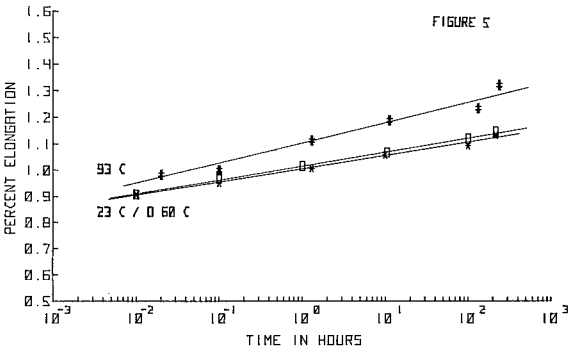
STATIC CREEP AT 23 DEG. CENTIGRADE
DERAKANE 790 R-50



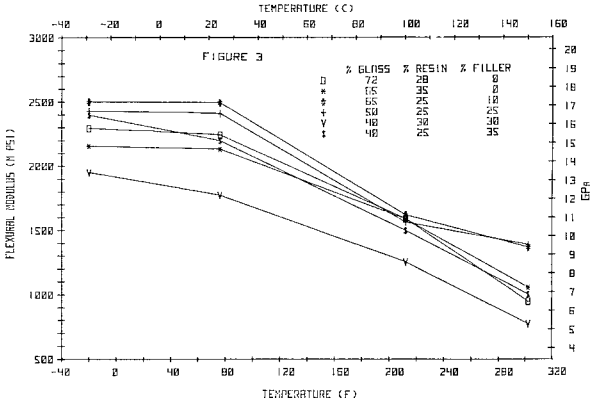
EFFECT OF GLASS LEVEL AND TEMPERATURE DERAKANE 790



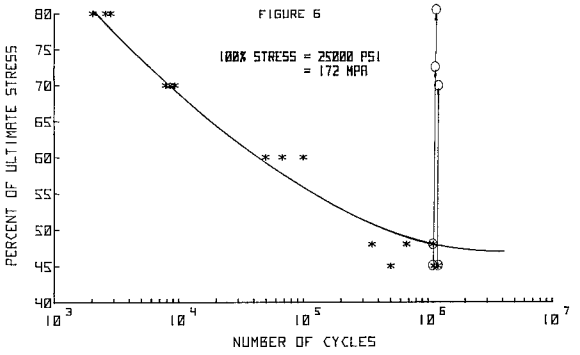
STATIC CREEP AT 13750 PSI STRESS
DERAKANE 790 R-50

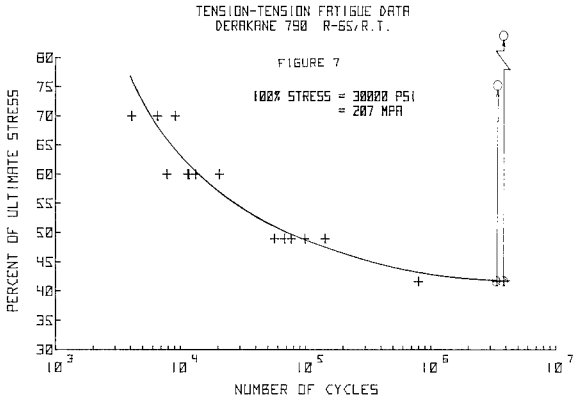


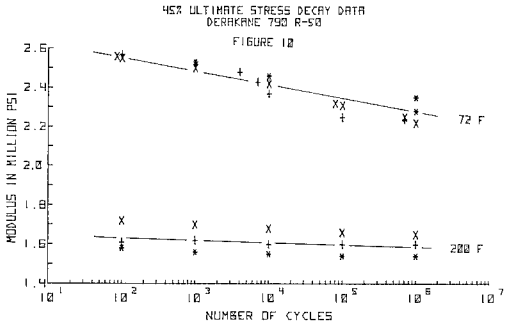
EFFECT OF GLASS LEVEL AND TEMPERATURE DERAKANE 790

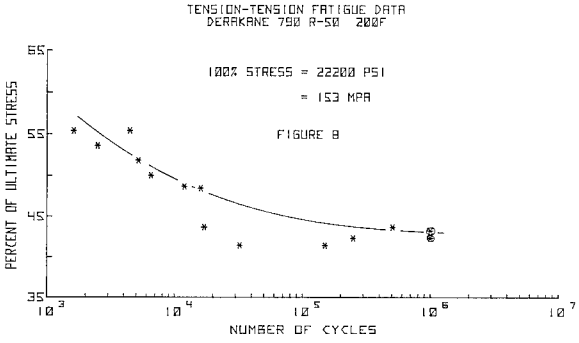


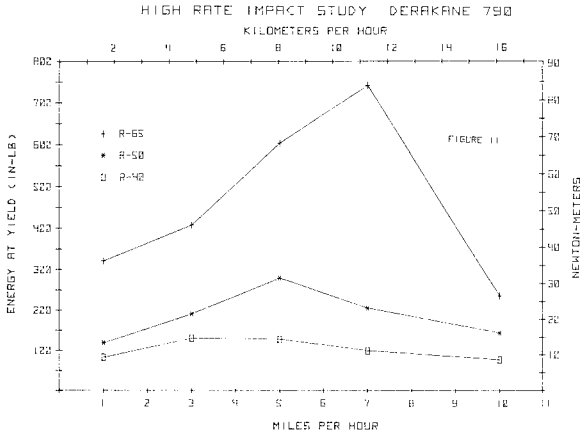
TENSION-TENSION FATIGUE DATA
DERAKANE 790 R-50/R.T.

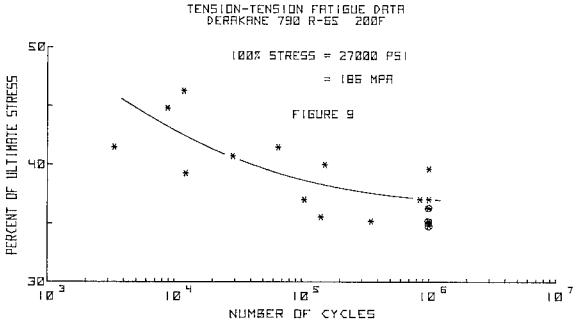


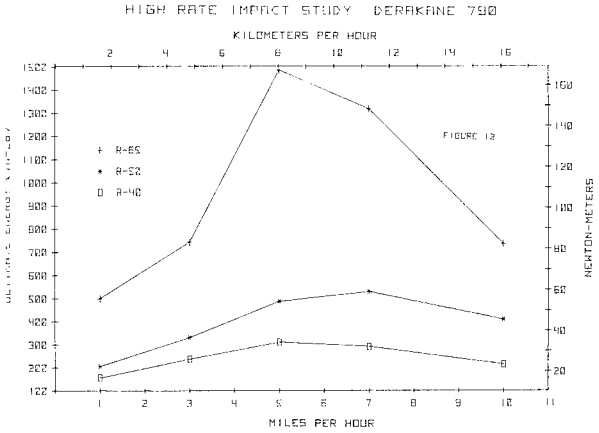

TENSION-TENSION FATIGUE DATA
DERAKANE 790 R-65/R.T.
FIGURE 7
100% STRESS = 30000 PSI
= 207 MPA
PERCENT OF ULTIMATE STRESS
NUMBER OF CYCLES


45% ULTIMATE STRESS DECAY DATA
DERAKANE 790 R-50
FIGURE 10
MODULUS IN MILLION PSI
72 F
200 F
NUMBER OF CYCLES


TENSION-TENSION FATIGUE DATA
DERAKANE 790 R-50 200F
100% STRESS = 22200 PSI
= 153 MPA
FIGURE 8
PERCENT OF ULTIMATE STRESS
NUMBER OF CYCLES


HIGH RATE IMPACT STUDY DERAKANE 790
KILOMETERS PER HOUR
+ R-65
* R-50
□ R-40
FIGURE 11
ENERGY AT YIELD (IN-LB)
NEWTON-METERS
MILES PER HOUR


TENSION-TENSION FATIGUE DATA
DERAKANE 790 R-65 200F
100% STRESS = 27000 PSI
= 186 MPA
FIGURE 9
PERCENT OF ULTIMATE STRESS
NUMBER OF CYCLES


HIGH RATE IMPACT STUDY DERAKANE 790
KILOMETERS PER HOUR
+ R-65
* R-50
□ R-40
FIGURE 12
NEWTON-METERS
MILES PER HOUR

REQUIREMENTS AND AVAILABILITY OF PLASTIC MATERIALS FOR AUTOMOTIVE USE THROUGH 1985

Charles H. Jenest

Arthur D. Little, Inc.
Cambridge, Mass.

Introduction

In 1978, about 1.7 billion lbs of plastic parts were used in the 9.2 million U.S.-produced passenger cars--an average of 180 lbs of plastic parts per car (up about 15 lbs/car over 1977); this year the amount of plastic per car will approximate 192 lbs. In 1985, assuming U.S. production of passenger cars at the same level as 1978, and about 250 lbs/car of plastic parts, the total in-place weight of plastic parts in all automobiles will total about 2.3 billion lbs. Although over a dozen different types of plastic are used in making a typical automobile, five types account for over 85%, by weight, of all the plastic parts: They are:

- Polyurethane (PU) -- a thermosetting material used principally in the form of flexible foam for seats, crash pads, and headliners and as solid elastomer for flexible front and rear end fascia.
- Polypropylene (PP) -- a rigid thermoplastic which is low in price and has good overall properties. Its uses include interior panels, door liners, fluid containers, fan shrouds, fender liners, and battery cases and trays.
- Acrylonitrile-butadiene-styrene (ABS) -- also a rigid thermoplastic with good strength and dimensional stability. It is used for such applications as instrument panels and grilles.
- Unsaturated polyester - UPE) -- a thermosetting material which is formulated with glass fiber reinforcement and fillers to make SMC (sheet molding compound) and BMC (bulk molding compound). The most important auto application is front end header panels. Other applications include heating and air conditioning ducts and housings, lamp housings and instrument panel parts.
- Polyvinyl chloride (PVC) -- can be compounded to be flexible or rigid depending on the particular use; most automotive uses require flexible materials. It possesses a degree of inherent flame resistance. Primary auto uses are upholstery materials and wire insulation.

Table 1 shows a breakdown of the use of plastic in the "average" 1978 U.S.-produced passenger car.

Molded plastic auto parts are made from compounds which consist of: (1) synthetic resins derived from primary petrochemicals (e.g., propylene), (2) chemical additives (e.g., plasticizers, colorants, antioxidants), (3) reinforcing materials (e.g., fiberglass), and (4) fillers. The flexible PVC compound used to make vinyl upholstery typically consists of about 50% resin, 40% plasticizer (to make the sheet pliable) and 10% other additives, mainly flame retardant, colorant, heat and light stabilizers and filler. On the other hand, the acrylic compound used to mold taillight lenses is over 95% resin content.

The quantities of plastic shown in Table 1 are amounts of in-place plastic parts; that is, they include chemical additives, reinforcing materials, and fillers, as well as the basic resins. Based on an overall yield factor of 90%, the actual requirement of plastic compound per car was about 200 lbs on average in 1978 or 1.8 billion lbs in total. This represented about 4.5% of the total use of all resin based compound for all uses in the U.S. last year. Including trucks and buses, the total automotive use of plastic compound in 1978 approximated 2.3 billion lbs. In 1985, this total will be double that of last year (up about 10%/yr).

In 1978, the weighted average price of the resins used in passenger car manufacture was about 50¢/lb. This was about one-third more than the average price paid by all manufacturers for all resins; automobile manufacturers require higher valued resins on average than other end-use industries. We believe that the real weighted average price--that is, the price, adjusted for inflation--for "automotive resins" will increase by about 1%-2% per year through 1985, when it will then approximate 55-60¢/lb (in constant 1978 dollars).

In 1978, the average price of the non-resin materials contained in the plastic compounds was likewise about 50¢/lb, and we believe prices of these materials will increase at a somewhat slower rate than those of the base resins over the next several years.

Primary Petrochemical Production Cost and Price

Over the next several years, most of the increased production of ethylene, propylene, butadiene, benzene and orthoxylene--the major primary petrochemicals from which the "automotive" resins are made--will come from new olefin plants which will use naphtha and/or gas oil as the major feedstock. We believe that U.S. prices of these feedstocks will go up at about the same rate as crude oil--about 6%/yr in constant 1978 dollars. Figure 1 shows the relationship of primary petrochemicals to the final automotive plastic parts.

Table 2 shows the 1978 pro forma production cost of ethylene in a new 1 billion-pound-per-year ethylene plant brought on-stream in mid-1977. The plant has about $200 million of fixed plant investment (FPI) associated with it; this does not include interest during construction, startup expenses or working capital. Naphtha, the raw material (feedstock), delivered at nearly 6¢/lb (about $15 per barrel) gives a raw material cost of about 18¢/lb of ethylene produced. The conversion cost in such a plant is somewhat over 7¢/lb, resulting in a production cost of roughly 25¢/lb, before adjusting for co-product credits (assuming an 80% operating rate).

However, when naphtha is used as the raw material in an olefin plant, several valuable chemical and fuel co-products are produced in addition to the main product, ethylene. The amount and types of co-products vary depending on the type of naphtha feedstock used and the processing or cracking conditions (e.g., temperature, pressure and time). In our typical example, somewhat over two lbs of co-products are produced for each pound of ethylene. About 30% by weight of the co-product is chemicals (propylene and butadiene), and 70% is made up of fuel or energy products--pyrolysis type gasoline fuel gas and fuel oil. Using estimated 1978 average market values, the net co-product credit calculates to somewhat over 16¢/lb of ethylene produced. When this co-product credit is subtracted from the estimated production cost of about 25¢/lb, a net cost of manufacture of 9¢/lb results. At a net sales price of about 13¢/lb for ethylene last year and a marketing, technical and administrative (MT&A) expense of about 8% of sales (1¢/lb), the operating profit derived from this typical new ethylene plant was about 23% of net sales in 1978 or about 12% of fixed plant investment. This compared with about 8% return on the replacement cost of FPI for the U.S. industrial chemical industry in 1978, assuming the replacement cost was 50% greater than the historical (book) cost.

Our 1985 forecast of primary petrochemical and resin prices are based on these assumptions: (1) that the real price of naphtha will increase at about 5% per year; (2) that the cost of constructing a 1-billion-pound-per-year ethylene plant for startup in mid-1984 will be about 2%/yr more than it was in our 1978 example--(e.g., $230 MM in 1978 dollars or about $390 MM in 1985

dollars at an 8% inflation rate); (3) that the cost to convert the naphtha will increase by about 3%/yr; and (4) that the co-product credit will increase to about 20¢-25¢/lb.

We expect the net price of ethylene to be about 17¢-20¢/lb (in constant 1978 dollars) in 1985, a real price increase of about 3% per year. If inflation averages 8% per year for the 1978-1985 period, the 1985 ethylene price in current dollars will be 30¢-35¢/lb.

RESINS

Polyurethanes

The urethane polymers are made from isocyanate and polyol chemical intermediates. They were first produced in Europe by Bayer and were introduced to the U.S. market 25 years ago by Mobay, initially owned jointly by Bayer and Monsanto but for several years now owned 100% by Bayer. In recent years the urethanes have been among the most rapidly growing plastic materials in terms of overall production. For example, output doubled over the past five years (15%/yr versus about 6.5%/yr for all resins taken together) and will grow at about 9-10%/yr through 1985. Major growth markets for the urethanes will be insulation products (e.g., rigid foam) and automotive parts. Eight companies now or will soon account for about 85% of total production for urethane chemicals (including Atlantic Richfield which will enter the market in 1981 or soon thereafter. The three largest are Bayer, Union Carbide, and BASF. In 1978, the total market value of urethane chemicals for all uses was about $1.3 billion (see Table 3). The corresponding value of the urethane in polymer form for U.S. consumption was about $2 billion. About 14% of all urethane polymer is now used in new automobile manufacture. Annual capacity for urethane chemicals will be about 4 billion lbs by 1982 and undoubtedly will exceed 5.3 billion lbs/yr in 1985. We expect the composite price of urethane chemicals to increase by about 2%/yr to roughly 50-55¢/lb in 1985. The equivalent price in resin form will be about $1-$1.10/lb.

Polypropylene

Polypropylene was introduced commercially in the United States in 1957 by Hercules (still the largest producer) after being discovered in Europe at research institutes by Prof. Natta in Italy and Prof. Ziegler in West Germany. Total PP production increased by about 8%/yr over the past five years and we expect it to average about 10%/yr over the 1978-1985 period. In 1978, production was up about 12% to about 3.1 billion lbs valued at about $900 MM. Total production of PP in 1985 should approximate 6 billion lbs. As a result of the existing and likely continuing overcapacity in PP, however, the average real price increase for this resin will not exceed 1%/yr through 1985, increasing by that time to about 35-40¢/lb. Although it will continue to lose some market share especially to the three new producers--Gulf Oil, Northern Natural Gas, and Solvay. Hercules will still account for about one-quarter of total PP capacity in 1982 (followed in size by Standard Oil of Indiana and Shell Oil) even though there will be 12 producers by that time (see Table 4). About 11% (36 lbs per car) of all PP sales were used in new car production as plastic parts in 1978, and this percentage will likely increase somewhat through 1985. In addition, about two lbs of PP fiber were used in the typical 1978 U.S.-produced passenger car.

ABS Resin

About 30 years ago, ABS plastic material was first offered commercially in the United States by Uniroyal. Last year, however, Uniroyal sold its ABS business to U.S. Steel. The production of ABS between 1973 and 1978 increased by about 5%/yr. We expect that the overall ABS market will grow 5-6%/yr on average over the next few years (it was up about 6% in 1978) but its increased use in automobile manufacture is expected to grow at somewhat less than this through 1985. At an average price of about 47¢/lb in 1978, ABS sells for about half again as much as PP resin on a 100% basis; ABS compound containing about 30% glass fiber, however, sells for only about 20% more than those based on PP (85¢/lb versus 70¢/lb).

Unlike the urethane chemicals and the PP resin industries, each of which have about a dozen producers, there are only six ABS producers in the United States. Borg-Warner and Monsanto are the largest, each with about 30% of the overall near-term capacity followed by Dow Chemical (see Table 5). In addition to the U.S. Steel acquisition of Uniroyal's ABS operation, Mobil Oil has recently taken over Dart Industries' ABS (and polystyrene) operation, and Goodrich sold part of its ABS business to Petrofina (Cosden Oil and Chemical). The rated industry capacity for ABS will approximate 1.9 billion lbs in 1982, and including Borg Warner's new plant the operating rate in 1985 should approximate 85-90%. On average about 31 lbs of ABS plastic parts were used to produce a typical U.S.-made 1978 automobile; this represented about 17% of the total weight of all plastic in the car, and this particular market accounted for about one-fourth of the total ABS industry sales (including exports) last year. Only the pipe market is as large as the automotive industry among the individual ABS resin markets. We estimate that the average price of ABS resin will increase by about 20% compared to 1978 and approximate 55-60¢/lb in 1985.

Polyvinyl Chloride

Although PVC is the fifth most important resin family used in automobile manufacture (now about 16 lbs of vinyl compound or 9% of all plastic in each automobile), this market represents only about 1 1/2% of total sales of PVC resin for all applications (including exports). There is virtually no opportunity for PVC-based products to replace other parts or materials in automobiles. Most of the PVC consumption is for vinyl coated fabrics for upholstery material, headliners, interior door coverings, sun visors and exterior roof material. We believe that with the continued decrease in the size of the average U.S.-produced automobile and the consumer preference for textile upholstery, the amount of PVC-based plastic material used per car will continue to decrease slowly in the future.

Overall demand for PVC resin increased at a rate of about 4% per year between 1973 and 1978, but in 1978 it was about 9%. Although PVC resin has been a commercial product for over 50 years, it continues to exhibit "remarkable" growth for a resin material that old. However, because of its wide spectrum of uses, we expect the PVC resin market to increase at about 7%/yr on average over the next several years. At $1.5 billion in 1978, the market value of PVC resin was exceeded only by that of low-density polyethylene ($2.1 billion) and polyurethane ($2 billion at the resin equivalent level) among the 40 or so different resin "families" sold commercially today for all uses. At 27¢/lb, PVC is the lowest priced plastic resin (on a weight bases) used in automobile production. However, on the more important basis of price per unit volume, PP (at about 29.5¢/lb last year) is the lowest priced resin since its density is only about two-thirds that of PVC resin.

There are 20 U.S. producers of PVC resin (including one in Puerto Rico). Union Carbide, the first U.S. producer in about 1927, has a relatively minor position in this industry today, while B. F. Goodrich with over a 15% market share has been the industry leader for several years and is "aggressively" expanding its vinyl capacity. Georgia-Pacific, a relatively new PVC producer, is also expanding its capacity very aggressively and will be the #3 supplier by 1982 (see Table 6). In 1985, the operating rate of the PVC resin industry should approximate 85-90% of rated capacity; by historical PVC industry standards, this is considered to be a high operating rate. We expect the PVC resin price to approximate 30-35¢/lb in 1985.

Unsaturated Polyesters

These thermosetting resins were first commercialized in the United States in 1942 by American Cyanamid (now a relatively small producer) to produce glass reinforced structural materials which could be used in place of scarce metals required for some of the implements of World War II. It was recognized that when this family of resins is reinforced with fiberglass, composite materials can be produced having higher strength-to-weight ratios than certain steels.

The initial large volume commercial market for these resins was boat hulls, and to this day marine products with about one-fifth of the market still rank third in importance for these resins after transportation equipment (mainly automotive) and the broad category of building and construction products (including pipes, tanks, architectural sheeting, and bathroom components) each at about one-quarter of the market.

Approximately 30 lbs of glass-reinforced polyester parts were used in 1978 in the production of the average American-built automobile, and about half of that was sheet molding compound. About 17% of the total plastic content of the automobile was polyester based, and the new passenger car market represented about 8% of the total market for UPE resins. The average price of these resins at 46¢/lb (all grades taken together) is about at the same level as ABS materials. By 1985, we expect the price of UPE resin to average 50-55¢/lb.

There are over two dozen producers of UPE type resins. Reichhold Chemicals has been the largest supplier for many years and accounts for about 18% of the market as shown in Table 7. In 1977, U.S. Steel acquired the polyester resin business of W. R. Grace and thus became the #2 supplier. In addition, U.S. Steel has a 90 million pounds-per-year capacity UPE resin plant under construction at Neville Island, Pennsylvania, and by 1982 will be essentially equal to Reichhold Chemicals in UPE resin capacity. Ashland Oil is the #3 producer of these resins, followed closely by PPG and Koppers. There is substantial excess rated capacity for UPE currently and this is likely to continue for the next few years. About 80% of all UPE resin is used in conjunction with glass fiber reinforcement, and (excluding Certain-teed) the three largest producers of reinforcement type glass fiber--Owens Corning Fiberglas, PPG and Reichhold Chemicals--are also among the major producers of UPE resin. The average price of glass fiber reinforcement (roving and mat) was about 60¢/lb in 1978 or about 30% more than that of polyester resin. Over the five years 1973-1978, the price of glass fiber reinforcement increased by only about 7%/yr (or about 1% per year less than inflation). We expect, however, that over the next few years, the price of glass fiber will increase on average at about the same rate as general inflation. In 1978, the total U.S. market for glass fiber used to reinforce all resin was about 600 million lbs valued at about $360 million; roughly 25% of this market was accounted for by the automobile industry.

Nylon

No other family of resins now accounts for as much as 5% by

weight of all plastic parts in an automobile except nylon. The term nylon describes a family of polyamide resins which was first commercialized about 40 years ago by Du Pont as fiber used to make women's hosiery and other textile products. A few years after the fibers were introduced, plastic molding and extrusion compounds based on nylon resins were introduced also by Du Pont which has remained the industry leader over these many years. Du Pont now accounts for nearly half of the total sales of nylon plastic materials used in automotive applications followed in sales by Monsanto and Celanese.

At about $1.20/lb in 1978 nylon resin sold for over twice the price of the average of all the "automotive" resins taken together and is the most important commercially of the so-called engineering thermoplastic materials. We expect the average price of nylon plastic to approximate $1.35-$1.45/lb in 1985. Other resins in this category which also sell at the $1+/lb level and which are used in making relatively small but important auto parts are polyphenylene oxide (PPO) based materials, polycarbonate, acetal and polybutylene terephthalate (PBT).

Currently, the average U.S.-made automobile contains about 9 pounds of nylon plastic (5% of the total plastic in the car), and in 1978 about 28% of the total nylon plastic market was accounted for by the automotive industry. We expect the amount of nylon per car to increase substantially by 1985. Table 8 summarizes the supply/demand/price situation relative to nylon plastic materials.

Approximate Production Costs of Selected Resins

Our estimates of current approximate resin production costs are based on plants constructed from about early 1975 to mid 1977 and producing specification material by year end 1977, approximately the same time period as for the ethylene plant discussed above. We have prepared approximate pro forma production cost estimates for polypropylene (PP) and unsaturated polyester (UPE) resin plants. These examples enable us to identify the major factors relating to likely cost increases for two of the most important "autmotive" resins--PP or UPE.

Polypropylene

We have selected a PP resin plant with a rated capacity of 200 million lbs per year. This is the approximate size of the new plant started up in 1978 by Northern Natural Gas and of those now under construction in the United States by Solvay and U.S. Steel. The largest single-site PP capacity in the industry is that of Hercules at Lake Charles, Louisiana, which is rated at about 700 million lbs/yr; however, this involves more than one "plant." The smallest plant is one that has been in existence for several years--that of Eastman Kodak--at about 140 million lbs/yr. Hercules has announced that it will add another 200 million lbs/yr of capacity at Lake Charles by the end of 1980, bringing the total there to about 900 million lbs/yr of PP resin.

We estimate that the fixed plant investment for such a 200 million-pound-per-year PP plant brought on stream in mid 1977 was about $55 million. As was true in the case of our ethylene plant example, this does not include working capital, interest during construction, or start-up expenses. We assumed an 80% operating rate, which was about typical for the PP industry in 1978 in this country; this resulted in the production of about 160 million lbs of an on-specification material. We have assumed a 95% yield in the polymer plant which requires about 5% excess propylene to allow for yield loss. In 1978, the delivered price of polymer grade propylene was about 11¢/lb, so the raw material cost for the PP was about 11.5¢/lb of resin produced. In chemical plants of this nature we assume the annual depreciation rate to be 10% of FPI, maintenance cost 4% of FPI, and local taxes and insurance 2% of FPI.
We estimate that the production cost of PP in such a plant was about 22¢/lb last year as shown in Table 9. According to the Society of the Plastics Industry, the average U.S. selling price of PP in 1978 was nearly 29.5¢/lb delivered, and the net price FOB producing plant was somewhat over 27¢/lb. Assuming the non-production costs (i.e., marketing, technical and administrative expenses) associated with this product were about 9% of net sales in 1978 (about 2.5¢/lb), the operating profit on this PP business was about 18% of net sales and about 15% of FPI.

Unsaturated Polyester Resin

Unlike PP, the manufacture of UPE resin is not capital intensive in the sense that a minimum economic sized UPE resin plant yields about three times more sales per dollar of FPI than does a PP resin plant. In addition the absolute fixed investment is only about 10% of that required for polypropylene resin.

Because of this, the UPE resin business is very competitive with over two dozen producers. Most of the new UPE resin plants constructed in the past few years have been in the range of 30-40 million lbs/yr, except for the U.S. Steel plant now under construction which will be rated at about 90 million lbs/yr.

A new UPE resin plant with a capacity of 40 million lbs/yr operating for the full year 1978 would have cost about $5 million in FPI. Four intermediate chemical raw materials are required to make this resin type--styrene, phthalic anhydride, propylene glycol, and maleic anhydride. These raw materials sold for about 19-31¢/lb delivered in 1978, and the average raw material cost was nearly 23¢/lb of general purpose grade UPE resin produced (the yield is essentially 100%). The conversion cost was only about 6¢/lb, resulting in a total production cost of about 29¢/lb as shown in Table 10. In 1978, the average delivered price of general purpose grade UPE resin was about 39¢/lb and the net sales value was about 36¢/lb. If the MT&A expense on this resin was about 10% of net sales, the operating profit was about 10% of net sales and about 22% of fixed plant investment.

Overall Resin Demand and Supply

We believe that U.S. resin capacity will be more than sufficient to serve the requirements of the automotive (and all other industries) through 1985. In 1978, the composite operating rate of that segment of the overall resin industry which is most important to the automobile industry was about 85% of nameplate capacity. This is considered to be a "normal" operating rate for the resin industry and one which yielded "good" profitability at last year's prices. We expect that in 1985 the comparable composite operating rate will also approximate 85%. Because of this projected "attractive" operating rate, we do not believe that overcapacity will keep the resin producers from increasing their prices to a degree somewhat in excess of the general rate of inflation; indeed, the total costs of the resin producers will increase at a rate faster than overall inflation. Table 11 summarizes our supply/demand estimates for the most important types of "automotive" plastic resins through 1985. We believe that the resin producers will in fact construct the additional capacity needed to meet the 1985 resin demand.

Table 1

IN-PLACE USE OF PLASTIC PRODUCTS IN THE AVERAGE U.S.-PRODUCED PASSENGER CAR - 1978

Type of Plastic Compound	Lbs/Car	% of Total
Urethane	43	24
Polypropylene	36	20
Acrylonitrile-Butadiene-Styrene	31	17
Polyester, Unsaturated	30	17
Polyvinyl Chloride	16	9
Nylon	9	5
Other[1]	15	8
Totals	180[2]	100

1. Includes: phenolic, acrylic, polyethylene, polyphenylene oxide, polycarbonate, polybutylene terephthalate, acetal, and miscellaneous.
2. Includes reinforcements, fillers, plasticizers and other additives. Excludes PP, nylon and other fibers, polyvinyl butyral (safety glass interlayer) and resin used for paints, adhesives and sealants.

Source: Arthur D. Little, Inc., estimates.

Table 2

APPROXIMATE PRO FORMA PRODUCTION COST OF ETHYLENE - 1978
(naphtha cracking process)

Rated Capacity: 1 billion lbs/yr
Production and Sales: 800 million lbs (80% operating rate)
Fixed Plant Investment: $200 million[(a)]

	¢/lb
Raw Materials	
3.1 lbs naphtha at 5.8¢/lb ($15/barrel)	18.0
Conversion Cost	
Plant Depreciation (at 10%/yr of FPI)	2.5
Fuel (at $2/million Btu)	1.1
Maintenance (at 4%/yr of FPI)	1.1
Local Taxes and Insurance (at 2%/yr of FPI)	0.6
All Other (Labor and Supervision, Labor and Plant Overhead, Other Utilities, Miscellaneous)	1.9
Subtotal	7.2
Grand Total	25.2
Co-product Credits	
0.4 lb propylene (chemical grade) at 10¢/lb	4.0
0.2 lb butadiene at 18¢/lb	3.6
0.6 lb gasoline (pyrolysis type) at 7.5¢/lb	4.5
0.7 lb fuel gas at 4.5¢/lb	3.2
0.2 lb fuel oil at 4.5¢/lb	0.9
Subtotal	16.2
Net Production Cost	9.0

(a) These are essentially 1976 dollars.

Source: Arthur D. Little, Inc., estimates.

Table 3

PRODUCTION, PRICE AND MARKET VALUE OF URETHANE CHEMICALS (1973-1985)

Year	Production (MM Lbs)	Average Composite Prices (c/lb, delivered)	Market Value (MM $)
1973	1,400	30	420
1976	2,200	36	790
1977	2,500	40[1]	1,000
1978	2,800[(a)]	45	1,260
1985	5,300	50-55	2,700

Producers	Annual Rated Capacities - at 12/81 (MM lbs) TDI[2]	MDI[3]	Polyol	Total	%
Mobay Chemical (Bayer)	225	300	280	805	20
Union Carbide			600	600	15
BASF Wyandotte	125	100	365	590	15
Olin	140		305	445	11
Dow Chemical	100		300	400	10
Upjohn		250	15	265	7
Atlantic Richfield		200		200	5
Rubicon (Uniroyal/ICI)	40	100	20	160	4
Others[4]	80		465	545	13
Totals	710	950	2,350	4,010	100

1. Composite price derived from TDI at 45c/lb, MDI at 46c/lb, and polyol at 37c/lb. Polyurethane resins sold as such were about 75c/lb in 1977.
2. Toluene diisocyanate (80/20 mixture).
3. Methylene Diphenyl diisocyanate (polymeric type).
4. Includes Allied Chemical, E. R. Carpenter, Owens-Corning Fiberglas, Du Pont, PPG, Reichhold Chemicals, Stepan Chemical, Texaco, and Witco Chemical.

(a) Upjohn estimates the 1978 U.S. demand for urethane resin at about 2 billion lbs. There is a significant net export of urethane chemicals.

Source: U.S. International Trade Commission (USITC), Chemical Week, and Arthur D. Little, Inc., estimates.

Table 4

PRODUCTION, PRICE AND MARKET VALUE OF POLYPROPYLENE RESIN (1973-1985)

Year	Production (MM Lbs)	Average Price (c/lb, delivered)	Market Value (MM $)
1973	2,161	19	410
1976	2,632	29.5	775
1977	2,747	30.5	840
1978	3,074	29.5	905
1985	6,000	35-40	2,250

Producers	Annual Rated Capacity - at 12/81 MM Lbs	%
Hercules	1,300	24
Standard Oil (Indiana)	745	14
Shell Oil (Royal Dutch/Shell)	585	11
Exxon	550	10
Atlantic Richfield	405	8
U. S. Steel (Novamont)	405	8
Gulf Oil	400	7
El Paso	300	6
Others (Eastman Kodak, Northern Natural Gas, Phillips Petroleum and Solvay)	665	12
Totals	5,355	100

Sources: The Society of the Plastics Industry, Inc., and Arthur D. Little, Inc., estimates.

Table 5

PRODUCTION, PRICE AND MARKET VALUE OF ABS RESIN (1973-1985)

Year	Production (MM Lbs)	Price (c/lb delivered)	Market Value (MM $)
1973	876	30	230
1976	1,003	44.5	445
1977	1,069	45.5	485
1978	1,134	47	630
1985	1,800	55-60	1,035

Producers	Annual Rated Capacity - at 12/81 MM Lbs	%
Monsanto	550	31
Borg-Warner[(a)]	530	30
Dow Chemical	300	17
U.S. Steel	230	13
Goodrich/Petrofina (Abtec)	110	6
Mobil Oil	55	3
Totals	1,775	100

1. Includes some styrene-acrylonitrile (SAN) resin capacity. In 1978 the production of SAN resin was about 120 MM lbs.

(a) Adding 150 MM lbs/yr by end of 1982.

Source: The Society of the Plastics Industry, Inc., and Arthur D. Little, Inc., estimates.

Table 6

PRODUCTION, PRICE AND MARKET VALUE OF POLYVINYL CHLORIDE RESIN (1973-1985)

Year	Production (MM Lbs)	Price (c/lb, delivered)	Market Value (MM $)
1973	4,562	15	685
1976	4,716	27	1,275
1977	5,253	27	1,415
1978	5,723	27	1,545
1985	9,400	30-35	3,055

Producers	Annual Rated Capacity - at 12/81 MM lbs	%
Goodrich[(a)]	1,350	15
Tenneco	1,000	11
Georgia-Pacific	915	10
Firestone	615	7
Diamond-Shamrock	605	7
Continental Oil	710	8
Borden[(b)]	530	6
Stauffer Chemical	420	5
Others (12 Companies)[1]	2,715	31
Totals	8,860	100

1. Includes: Air Products and Chemicals, Certain-teed, Ethyl, General Tire, Goodyear, Great American, Keysor, Occidental Petroleum, Pantasote, Rico Chemical, Shinetsu Chemical, and Union Carbide.

(a) Plans to add 1 billion lbs/yr by 1985.
(b) Will add 240 MM lbs/yr in 1982.

Source: The Society of the Plastics Industry, Inc., and Arthur D. Little, Inc., estimates.

Table 7

PRODUCTION, PRICE AND MARKET VALUE OF UNSATURATED POLYESTER RESIN (1973-1985)

Year	Production (MM Lbs)	Price (c/lb, delivered)	Market Value (MM $)
1973	1,051	22	230
1976	1,042	42.5	445
1977	1,060	43.5	460
1978	1,209	46	555
1985	2,300	50-55	1,315

Producers	Annual Rated Capacity - at 12/'81 MM Lbs	%
Reichhold Chemicals	350	18
U.S. Steel	345	17
Ashland Oil	175	9
PPG	155	8
Koppers	150	8
Cargill	120	6
Owens-Corning Fiberglas	100	5
Interplastics	100	5
Others (about 20 companies)[1]	490	24
Totals	1,985	100

1. Includes: Alpha Chemical, American Cyanamid, British Petroleum (Sohio), Dow Chemical, ICI, H.H. Robertson (Freeman Chemical), Rohm & Haas, and several Others.

Source: The Society of the Plastics Industry, Inc., and Arthur D. Little, Inc., estimates.

Table 8

PRODUCTION, PRICE AND MARKET VALUE OF NYLON RESIN (1973-1985)

Year	Production (MM Lbs)	Price (c/lb, delivered)	Market Value (MM $)
1973	205	80	165
1976	247	112	275
1977	254	116	295
1978	275	120	330
1985	600	135-145	840

Producers	Annual Rated Capacity - at 12/'81 MM Lbs	%
Du Pont	200	45
Monsanto	75	17
Celanese	40	9
Allied Chemical	30	7
Hoechst	20	5
Others[1]	75	17
Totals	440	100

1. Includes: Belding Chemical Industries, Bemis, Firestone, Henkel, Basische, Nypol, Rilsan (Elf Aquitaine), and Wellman.

Source: The Society of the Plastics Industry and Arthur D. Little, Inc., estimates.

Table 9

APPROXIMATE PRO FORMA PRODUCTION COST OF POLYPROPYLENE - 1978

Rated Capacity: 200 MM lbs/yr
Production and Sales: 160 MM lbs/yr (80% operating rate)
Fixed Plant Investment: $55 MM (essentially 1976 dollars)

	¢/lb
Raw Materials	
1.05 lbs of Propylene (polymer grade) at 11¢/lb	11.5
Conversion Cost	
Plant Depreciation (at 10%/yr of FPI)	3.4
Maintenance (at 4%/yr of FPI)	1.4
Operating Labor and Supervision	1.4
Utilities (incl. power at 20 Mills/kWh)	1.4
Labor and Plant Overhead (at 100% of Operating Labor and Supervision)	1.4
Catalysts & Chemicals, Local Taxes and Insurance, Finishing, Packaging, and miscellaneous	1.5
Subtotal	10.5
Total Production Cost	22.0

Source: Arthur D. Little, Inc., estimates.

Table 10

APPROXIMATE PRO FORMA PRODUCTION COST OF UNSATURATED POLYESTER RESIN-1978
(general purpose type)

Rated Capacity: 40 MM lbs/yr
Production and Sales: 32 MM lbs (80% operating rate)
Fixed Plant Investment: $5 MM

	¢/lb
Raw Materials	
0.30 lb Phthalic Anhydride at 23¢/lb	6.9
0.20 lb Propylene Glycol at 25¢/lb	5.0
0.10 lb Maleic Anhydride at 31¢/lb	3.1
0.40 lb Styrene at 19¢/lb	7.6
Subtotal	22.6
Conversion Cost	
Plant Depreciation (at 10%/yr of FPI)	1.6
Maintenance (at 4%/yr at FPI)	0.6
All Other Costs (utilities, operating labor and supervision, labor and plant overhead, catalysts and chemicals, miscellaneous)	4.2
Subtotal	6.4
Total Production Cost	29.0

Source: Arthur D. Little, Inc., estimates.

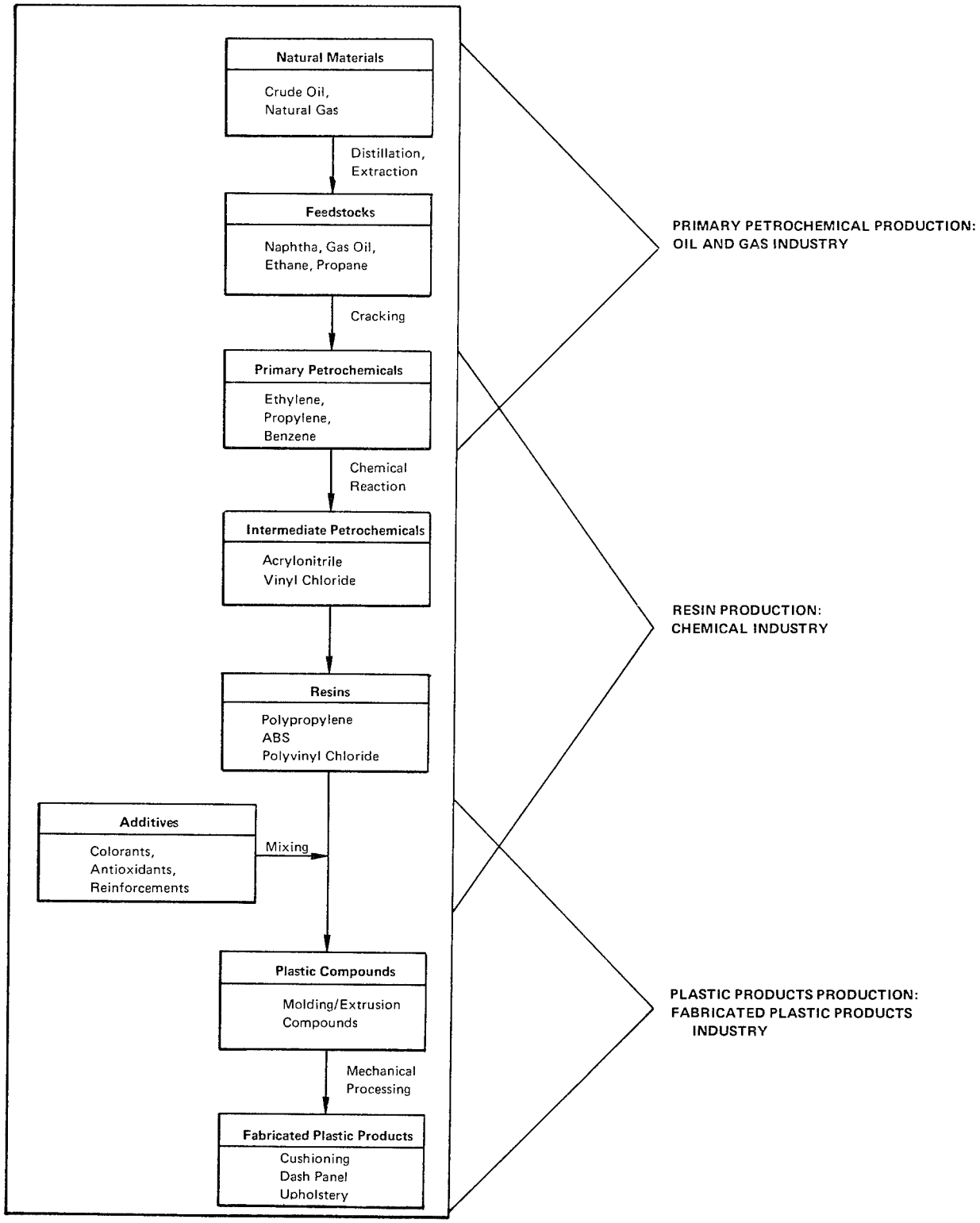
Table 11

SUPPLY AND DEMAND OF SELECTED "AUTOMOTIVE" RESINS (1978-1985)
(billion lbs)

Resin Type	1982 Rated Capacity (at 12/81)	1978 Production	1985[1] Demand	New Capacity Needed[2]
Urethane[3]	4.0	2.8	5.3	2.2
Polypropylene	5.3	3.1	6.0	1.8
Acrylonitrile-Butadiene-Styrene	1.8	1.1	1.8	0.3
Unsaturated Polyester	2.0	1.2	2.5	0.9
Polyvinyl Chloride	8.9	5.7	9.4	2.2
Nylon	0.44	0.28	0.60	0.25

1. Includes exports.
2. Based on an 85% operating rate.
3. Expressed as isocyanate and polyol chemicals from which most urethane plastic products are made in situ.

Source: The Society of the Plastics Industry, Inc., and Arthur D. Little, Inc., estimates.



Source: Arthur D. Little, Inc.

FIGURE 1 --- FLOW OF MATERIALS IN THE PLASTICS INDUSTRY

Arthur D. Little, Inc.

AUTOMOTIVE PLASTICS—EXPLORING THE LIMITS TO GROWTH

Robert Eller

Arthur D. Little, Inc.
Cambridge, Mass.

The biggest technical challenge the auto industry has faced in its history is meeting the fuel economy, antipollution and safety requirements which have been imposed on it. It will demand the single, most concentrated financial commitment to new production facilities, tooling, and engineering effort ever made by the automotive industry.

This investment which will reach $80 billion by 1985 will probably add $1000 to the cost of a typical American car. It must be made by an industry with a mature product whose annual domestic sales growth will probably be 2% per year or less and whose profit margins have shrunk to less than half of what they were in the mid-sixties.

To complicate matters, these challenges must be faced in an uncertain economic environment, in which record inflation and increasing gasoline prices, are reordering American social values.

Rising to the challenge is an industry which has been technologically conservative and has relied heavily on traditional materials and high volume production methods to provide its customers with reliable, low cost, personal transportation.

The plastics industry, which now sells about 5% of its output to the auto industry, has a vital role to play in helping the auto industry meet this challenge by substituting plastics for the traditional materials used by the automotive industry. The financial rewards for the plastics industry are potentially high and the impressive attendance at this SPE NATEC bears witness to the commitment to seeking those rewards.

If by Model Year 1985 we were to experience an increase in automotive plastics usage of 80 pounds per vehicle from the 1979 figure of 190 pounds per vehicle, it could mean an increase in plastic resin and component sales of almost 1 billion pounds. Such a conservative growth rate in automotive use of plastics represents an average increase of about 7% per year which is slightly below the 8-9% growth rate which we anticipate for the plastics industry as a whole over the next 5 to 6 years. Polyurethanes, thermosetting polyesters, and polypropylene will primarily benefit from this increase in use of automotive plastics. For these materials, it could be a period of extremely rapid growth, not only in poundage, but in materials performance and processing sophistication.

Detroit will demand the development of new, faster production technology, new materials combinations, a deeper understanding of property-structure relationships, the establishment of reliable quality control methods, and rapid progress in process control. The technical need exists; the potential for economic reward is there; and therefore the financial support for the required R&D effort will be found from within our industry or from the auto industry.

Judging by the response to the conference on Basic Research Directions for Advanced Automotive Technology which was held in Boston last February and the challenge given by President Carter to the auto industry to develop a 50 MPG car by the year 2000, the plastics industry can expect some significant government support.

Today, I would like to examine the current state of automotive plastics, the areas in which they could potentially grow, and explore some of the factors which could limit this growth. From this foundation, I hope to define some future technical directions for our industry.

WHERE DO PLASTICS STAND NOW

As shown in Table 1, interior applications heavily dominated the 190 pounds per vehicle used in 1979. Roughly half of the total 190 pounds were used in interior applications for such traditional plastics components as instrument panels, steering wheels, seat cushions, upholstery, and decorative trim. Urethanes, PP, ABS, and PVC were the dominant resins.

Exterior applications which are still in the earliest stages of growth represent only about 30% of current plastics usage. The current exterior applications are heavily dominated by the use of plastics for styling and non-structural components like grill opening panels. Mechanical, electrical, and under-the-hood applications represent the remaining 20% of the total.

1978 and 1979 might well be called the prediction years in which plastics poundage growth predictions were both abundant and varied as industry spokesmen, consultants, and the plastics press tried to assess the role that plastics will play in automotive weight savings.

Auto industry estimates for Model Year 1985 range from 250 to 330 pounds/car. Differences between the conservative 60-pound growth and the optimistic 140 pound growth prediction depend heavily on the assessment of the role of plastics in exterior body panels, structural members and energy absorption systems.

Plastic components like injection molded instrument panels, polyurethane foam seat cushions, polypropylene kick panels, blow molded duct work and even to some extent molded under-the-hood components, etc., were natural extrapolations of current materials and fabrication technology. Grill opening panels in SMC were barely technically acceptable solutions to a styling need.

In order to achieve any substantial increase in plastics usage, the next generation of components will require fast curing thermosets, stamping technology, well controlled reaction injection molding methods, and increased knowledge of glass fiber flow and resin rheology in order to achieve the full potential that plastics have for growth in these demanding applications.

HOW MUCH PLASTICS MATERIAL SUBSTITUTION IS NEEDED

In order to answer this question, the strategy of material substitution must be placed in perspective.

Simply stated, the auto companies want:

- To meet CAFE (Corporate Average Fuel Economy) environmental and safety regulations while providing customers with an essentially unchanged product line (high percentage of "big" cars, some luxury models and lots of profitable options); while at the same time
- Minimizing new investment, variable cost and technical risk.

Material substitution is only one of many strategies which the auto companies can use in meeting these objectives.

Among the most important of the other alternatives are (Table 2):

- Downsizing (which can result in weight savings of 400-900 pounds).

- Component redesign (using traditional materials).
- Improved powertrain performance (e.g., turbo-charging, improving accessory drives, four-speed transmissions, lockup torque converters, etc. which can improve fuel economy by 20% to over 1977 levels).
- Changing fleet sales mix to favor compact and subcompact models.

The advantages and disadvantages of these alternative strategies are summarized in Table 3.

Meeting CAFE by changing the fleet sales mix to a higher percentage of compact and subcompact models can be a relatively inexpensive strategy since it requires the redesign of fewer model lines. (Major shifts would however require new tooling investments.) It is a less desirable strategy since it minimizes opportunity to sell the more profitable larger cars. In capital-limited situations, it will obviously be employed and will act as a brake on the drive for increased plastics materials substitutions. Downsizing and powertrain improvements have major effects on CAFE but require large investments. To date it appears as if the risks of downsizing have been minor. The risks associated with powertrain improvements vary depending on the specific improvement.

The effect on CAFE of simply redesigning components in the original material is usually minor, except where it can be accompanied by substantial downsizing or where previous designs were extremely inefficient.

Plastics materials substitution can yield moderate fuel economy gains. Investment in new productive capacity and tooling are relatively small when compared to a new steel stamping operation or the investment for a new engine plant. Plastics fabrication capacity is usually modular and small increments in production capacity can be purchased without significantly penalizing production economics. This favors a continuous conservative entry for plastics rather than sudden increases in plastics usage.

The moderate fuel economy gains resulting from plastics materials substitution must be sought in rather small increments and with a variety of components, many of which demand either new processing technology (like RIM or stamping) or a substantial improvement in current production efficiency (like the efforts underway to automate SMC).

In our plastics materials substitution studies we have generally found that variable costs increase when the substitution is for relatively simple steel components (e.g., hoods). For parts which either have complex shapes or many subcomponents (e.g., doors, header panels, some oil pans), both weight and cost savings are sometimes possible.

Some of the factors affecting the cost (or the potential cost savings) of plastics material substitution for stamped steel are:

- The number of subcomponents in an assembly.
- Production volume (longer runs are generally unfavorable for plastics).
- Part complexity (which affects the number of "hits" and hence tooling and labor required for steel stamping).
- Design (flat, simple shapes favor steel).
- "Fat" factor in design with traditional materials (e.g., overweight seat frames are easier material substitution targets than highly engineered hoods).

Plastics materials substitutions in the future will present automotive designers with technical unknowns and product liability risks, especially when compared to the alternative strategies of downsizing and component redesign using conventional materials.

So relative to the other strategies that are available to Detroit, plastics materials substitution has the advantage of relatively low investment costs, but the disadvantages of higher costs (for some components) and increased technical risks in return for only moderate gains in fuel economy.

Downsizing can result in impressive weight savings. Downsizing of Intermediate sized 1978 cars resulted in weight reductions which averaged about 630 pounds. This is sufficient to reduce models at least one EPA Inertia Weight Class. Actual reduction in vehicle size only represented about 25% of this total weight saving. The major weight reduction resulted from component optimization and improving the design efficiencies (without material substitution) in chassis, powertrain, fuel and structural systems. All material substitutions accounted for only 20% of the total weight saved. As we can see from Table 4, plastics and aluminum were the main material substitution contenders and there were only moderate increases in their use, despite the big reduction in vehicle weight. As shown in Figure 1, the average increase in consumption of plastic in the average U.S. passenger car from 1977-1978 was only a modest 10 pounds.

Fuel economy gains through powertrain improvements (without necessarily affecting vehicle weight) are also an attractive alternative for Detroit. An estimate of some of these fuel economy gains is shown in Table 5. Potential gains of 30% (over 1977 fuel economy levels) would be possible if all of these powertrain improvements were to be implemented. These powertrain improvements are in varying stages of development. Advanced electronic controls which optimize engine and transmission operation are likely to be implemented before the late Eighties. Turbo charging and improvement of performance of accessories are somewhat closer. Additional increments of 5 to 8% are possible with tire redesign for higher pressure and body exteriors designed to reduce aerodynamic drag.

By combining primary and secondary weight reduction through downsizing, component optimization and redesign, total weight savings of 800-900 pounds are possible without substantial increases in plastics material substitution in major components. As shown in Table 6, such a weight reduction, in combination with drivetrain and other improvements, could achieve CAFE requirements without substantial plastics materials substitution. The question, however, will be whether (or on what time schedule) auto manufacturers can afford these relatively expensive approaches to meeting CAFE. When capital for downsizing and powertrain improvements is in short supply, materials substitution becomes a more viable alternative.

MATERIALS SUBSTITUTION COMPETITORS

Even when the material substitution option is adopted, plastics must compete with other materials as the substitute material.

As seen from the historical materials breakdown in Table 7, the important material substitution competitors to plastics are aluminum and alternative steels. The graph in Figure 1 shows the use of these competitive materials has increased at a faster rate than plastics. High strength steel usage in particular increased substantially in 1979.

Aluminum is extremely effective as a weight reduction material. Weight savings of 40-60% are possible. The forming methods and parts fabrication techniques are similar to those used for steel. The physical properties are well known. Painting is not a problem; design know-how has been developed.

The major problem with aluminum material substitutions is cost. In many components we have examined, aluminum substitution for conventional sheet steel often cost in excess of $1 per pound of weight saved. On the other hand, aluminum substitution for cast iron (for example, in intake manifolds and engine transmissions) can result in breakeven or only marginal cost increases. We have seen a number of these substitutions in 1979 models.

Because of the relative ease of adapting aluminum to existing designs in steel, it is probable that aluminum will be used for short term "quick-fix" situations where big weight reductions are needed to drop vehicle weight into a lower Intertia Weight Class. Design engineering time and manpower are valuable commodities and aluminum substitution can gain time to meet production schedules while redesign of components in less costly materials is underway. Aluminum seat frames, bumper systems, truck and deck lids have been used in 1979 models. Aluminum substitutions have been especially concentrated in 1979 luxury models in order to help meet CAFE requirements. As the U.S. fleet shifts to a higher percentage of smaller cars, these substitutions will be less fequent. Some 1978 aluminum uses went back to steel in 1979 for cost reasons. Aluminum does not appear to be a serious long-term contender for the sheet-type components (e.g., body panels) which are the important growth areas for plastics.

Alternative steels on the other hand should be viewed as serious materials substitution competitors for plastics. They are not lighter than steels currently used but they could be stronger and less expensive. Optimizing designs in steel is familiar to Detroit and entails less technical risk and uncertainty than redesign with plastics. The large increase in usage in 1979 models was in door panels, deck lids, frame assemblies, wheels and hood panels. Alternative steels of particular importance include:

- High Strength, Low Alloy (HSLA) - a family of steels which offers increase in tensile strength but no increase in modulus compared to carbon steel. In situations where their more limited formability does not restrict their use, HSLA steel can offer impressive weight savings, often at no cost increase over conventional hot rolled carbon steel.
- Black Plate - an extra thin, low carbon steel which can be used in double wall constructions for stiffness and sound insulation.

The challenge to examine existing steel designs for their weight reduction potential has resulted in new designs which save weight not only through thickness reduction but also through more efficient designs (less "fat") and improvement in fabrication methods. (Substitution of tube and coil steel seat frames for conventional stamped and welded frames is an example.) The characteristics of a number of proposed steel substitutions and their plastic competitors are shown in Table 8.

"INTERNAL" FACTORS LIMITING AUTOMOTIVE PLASTICS GROWTH

Until now, we have been examining external factors which could limit materials substitution in general and plastics material substitution in particular. Now let's look at some of the technical and economic characteristics of plastics themselves which are acting as a brake on their acceptance as the materials of choice. Table 9 is a listing of some of the "internal" factors which could have an effect on the growth potential of automotive plastics.

Plastics have penetrated into most of the "easy" automotive applications, those in which they are the only obvious choice or for which weight savings could be achieved at either cost savings or a moderate cost increment (instrument panels, lighting, fascia, fender liners, load floors are examples).

Detachable body panels like hoods, deck lids, fenders and doors are the next big plastics materials substitution targets. The role which plastics will play in detachable exterior panels is a major factor separating the conservative 1985 plastics usage estimates (250 pounds/car) from the optimistic predictions (300-330 pounds/car).

Table 10 illustrates, for typical 1985 cars, what the potential magnitude of substitution in these areas might be. Non-unitized Intermediate cars offer substantially greater material substitution opportunity than compacts, not only because they weigh more and are more profitable to sell but also because they are generally less efficiently designed. There is a significant difference in weight savings possible in a station wagon rear door versus a hatchback door, for example. If we accept that making big cars with good fuel economy ranks high in Detroit's objectives, then it will be in these models that plastics will find the most ready opportunity acceptance for body panels.

Acceptance of plastics for these components will be technically difficult. Plastics must compete primarily with steel in components for which:

- The structural requirements are severe.
- The physical properties of steel are efficiently utilized.
- Cost savings are difficult to achieve.
- The high investment for steel manufacturing plants has been made.
- Production rates are extremely high.
- Design know-how in traditional materials is well established.
- Finishing methods are satisfactory.
- Crashworthiness considerations can be a limiting factor.

From the perspective of 1979, reinforced RIM and SMC are the most technically advanced and most economically feasible of the various plastics for exterior body panels.

Table 11 shows how some of the important properties of these plastics compare with the competition. The strength penalty for using plastics is significant but the major limiting factor is stiffness. Fortunately, section modulus (stiffness) increases with the square of thickness and this allows plastic parts of reasonable thickness (0.125") and adequate stiffness to be made. These thicker wall sections add to cycle time and reduce the cost savings resulting from the lower specific gravity advantage offered by plastics.

The exact wall thicknesses required for plastic components is still an open question. (Based on current properties, 0.125" is the most common thickness of plastics candidate components.) When properties improve, when design requirements can be more precisely defined, when plastics process control is improved and when non-destructive quality control tests (such as X-ray and ultrasonic inspection techniques) become more reliable, the typical thickness of plastic parts will be reduced to 0.100" and possibly lower without increasing technical risk.

Weight savings are a relatively new subject in Detroit but variable costs have always been a sensitive subject. The relatively low productivity of plastics processes has been a major factor in pushing up variable costs for plastics. These have often offset the advantages of low tooling cost and low capital investment.

There have been impressive increases in productivity as a result of demand from Detroit. These have come and will continue to come from such improvements as:

- Automating press loading/unloading (SMC)
- More rapid curing systems (SMC/RIM)
- Use of multicavity and multistation systems
- Better understanding of resin and glass fiber flow characteristics (SMC, RIM, injection molded BMC)
- Development of stamping methods

Plastics productivity still has not matched the speeds of metal stamping (see Table 12). There is still room for improvement but recent advances, especially in SMC and stamping technology, have allowed us to approach steel stamping rates.

It is worth noting that even complex plastics components generally are made in a single step. Metal stamping, on the other hand, requires multiple "hits" (and therefore multiple presses and tooling) to fabricate complex parts.

For low annual production volume requirements (say 50,000 to 300,000 parts per year), the need for expensive multiple tooling for stamped steel parts adds substantially to production costs, thereby giving plastics a particular advantage for short run components. This was one of the factors which will allow stamped plastic oil pans to compete in low-production-run engines.

Estimates of variable costs of components is one useful tool for evaluating material substitution potential. Other factors such as technical risk, availability of design manpower, availability of suitable finishing methods, being equal, substitutions which add less than 40¢-50¢ per pound of weight saved are serious short- and long-term contenders. Exceeding this cost level generally dampens Detroit's enthusiasm especially when viewed against some of the other weight savings alternatives discussed earlier.

In the short term, when weight savings are essential to drop vehicle weight to another inertia weight class, substitutions costing considerably higher than 50¢ per pound of weight saved will be used.

Along with other raw materials, plastics will increase in price. We expect that these increases will be moderate and will not significantly alter the competitive posture of plastics versus metals.

In order to illustrate how the economics compare, I have prepared the rough estimate, shown in Table 13, of the variable costs and relative weights for a relatively simple 10-pound unfinished body panel. The comparison illustrates why HS steel is such an important contender. Modest weight savings are possible (in this case 10%) at no cost increase. The material, its design capabilities, tooling requirements, and production rate are familiar to Detroit. Technical risk is minimal.

Aluminum offers big weight savings with minimum risk but at high cost.

SMC weight savings are limited by its mechanical properties and high specific gravity. Costs per pound of saved weight are high. For SMC to appear attractive to Detroit, the target component in steel must be complex or be made from multiple components.

R-RIM offers the promise of better weight savings than SMC. This offsets its somewhat higher raw materials cost.

Finishing costs were left out of the comparison above because they warrant a separate discussion.

Productivity, eliminating customer complaints, quality of paint match and weathering of finishes are important Detroit concerns.

Off-line finishing is expensive and makes paint matching extremely difficult. Use of finishes based on resin systems, which are different from those used for steel, hurts uniform aging of the finish. Assembly production time in Detroit costs 30¢-50¢ per minute and, therefore, increased assembly costs for adding components at specialized positions along the assembly lines can quickly add to the cost of using a component.

For some assembly lines there simply is not enough physical space to bring specialized components to a new position for attachment. Handling between off-line painting locations and final assembly results in either high costs or damaged parts which require touchup. Production paint oven temperatures are high enough to require off-line painting of R-RIM components. Future oven temperatures are anticipated to decrease. Until they do, the need to paint body panels off-line will remain a significant limitation.

IN SUMMARY

Automotive plastics use will grow. The growth will be limited by the attractiveness of alternative weight saving strategies and by other material substitution candidates. Whether the growth will be modest (250 pounds per car in 1985) or high (about 300 pounds per car) will depend partially on our ability to solve the technical problems which result in increased costs and high technical risk. It will also depend on the aggressiveness of the metal fabricators and the auto manufacturer's financial ability to implement alternative weight saving strategies and to make a car which is familiar in size and performance while still meeting the legislated CAFE requirements.

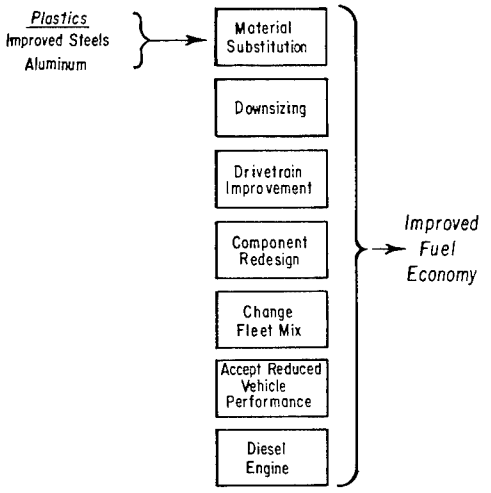
TABLE 1

POTENTIAL AUTOMOTIVE PLASTICS GROWTH

	1979 %	1979 Lbs	Weight Increment Lbs	1985 %	1985 Lbs	Important Potential Growth Areas
Interior	48	90	20	41	110	Seating, sound insulation
Exterior	31	60	50	41	110	Fenders, body panels, fuel tank, doors, windows, energy management systems
M/E/UTH[1]	21	40	10	18	50	Covers, oil pans
Total	100	190	80	100	270	

[1]Mechanical/Electrical/Under the Hood

Source: Arthur D. Little, Inc., estimates



PLASTICS MATERIALS SUBSTITUTION AMONG THE FUEL ECONOMY ALTERNATIVES

Table 2

TABLE 3

COMPARISON OF ALTERNATIVE STRATEGIES FOR MEETING CAFE

	Material Substitution	Downsizing	Component Redesign	Improving Powertrain
Effect on CAFE	Moderate	Major	Minor	Major
Investment	Minor	Major	Minor	Major
Variable Cost	Usually increases	Minor reduction	Minor reduction	Increases
Risks/ Uncertainty	Previous - low Future - high	Minor	Minor	Varies

TABLE 4

MATERIAL DISTRIBUTION IN 1978 GM INTERMEDIATES

Material	% of Vehicle Weight	Change from 1977
Steel	61.7	- 1.5
Iron	14.9	- 1.7
Plastics	5.3	+ 1.4
Aluminum	3.3	+ 1.7
Glass	3.3	+ 0.3
Rubber	2.7	- 0.1
Lubricants	1.2	-
Fabric	1.1	+ 0.2
Copper	0.8	+ 0.1
Lead	0.8	+ 0.1
Zinc	0.6	- 0.3
Paper	0.2	-
Nickel	0.1	-
Miscellaneous	4.0	- 0.2

Source: Hanson, E.K., SAE Paper 780132 (1978)

TABLE 5

ESTIMATED EFFECTS ON POWERTRAIN IMPROVEMENTS ON PASSENGER CAR FUEL ECONOMY

	% Improvement Over 1977 Fuel Economy Level
Engine	
Turbocharging	5
More efficient accessories and drives	5
Improved lubricants	2
Transmission	
4-speed automatic	7
Lock-up torque converter	5
Electronic controls (engine and transmission)	5
Tire	-
TOTAL	29

Source: Arthur D. Little, Inc. estimates

TABLE 6

A POSSIBLE SCENARIO FOR MEETING CAFE WITHOUT SUBSTANTIAL MATERIAL SUBSTITUTION

		MPG
1977 CAFE		18.0
800 pound weight reduction[1]	4.0	
Drivetrain improvements	5.2	
Tires/aerodynamic drag	1.5	
Total fuel economy savings without material substitution		10.7
Improved fuel consumption		28.7
1985 CAFE Target		28.5

[1]Average reduction in weight from 3700 to 2900 pounds

Source: Arthur D. Little, Inc. estimates

TABLE 7

ESTIMATED MATERIALS CONSUMPTION IN A TYPICAL U.S.-BUILT CAR
(pounds)

MATERIAL	1979	1978	1977	1976
High Strength Steel	155	133	127.5	120
Aluminum	129	112.5	98.5	85.5
Plastics	192	180	170.5	162.5
Glass	84.5	86.5	86	87.5
Copper	28	29	30.5	32
Zinc Die Castings	27	31	38	44
Rubber	143	146.5	150	153
Lead	24	25	25	25
Stainless Steel	26.5	26	27	28
Iron	492	512	540	562
Plain Carbon Steel	1813	1915	1995	2075
Fluids, Lubricants	183	198	200	190
Other Alloy Steel, Cloth, Cardboard, etc.	155	175	185	196
Totals	3452	3569.5	3673	3760.5

Source: Wards Automotive Handbook (1979)

TABLE 8

EXAMPLE OF STEEL COMPETITION FOR PLASTICS MATERIALS SUBSTITUTIONS

Part	Original Steel Sheet Material	Steel Substitution Candidate	% Weight Saved	Cost Saving	Plastic Candidates
Air cleaner	0.031" CR Sheet	0.014" Black Plate	55	Yes	Stamped or molded GR TP[1]
Valve cover	0.027" Low Carbon	0.006" Black Plate (Double Wall)	53	Yes	"
Bumper bar	0.120"	HSLA	30	No	Advanced composites
Body panels	0.031"-0.034" Carbon Steel	0.028" Silicon/Phosphorus Steel	12	No	R-RIM GR-Polyester
Bucket seat frames	0.030" Low Carbon	0.014" Black Plate	40	Minor Increase[2]	Stamped GR PP

[1]Glass fiber reinforced thermoplastic
[2]Depends on efficiency of previous design

Source: U.S. Steel and Arthur D. Little, Inc. estimates

TABLE 9

"INTERNAL" FACTORS LIMITING PLASTICS GROWTH

Physical Properties (stiffness, impact resistance, high CTE[1])
Variable Cost Increase
Low Production Rate
Design Know-how
Process Control
Quality Control Methods
Inadequate Product Performance Standards
Finishing Limitations
Technical Risk

[1]Coefficient of Thermal Expansion

TABLE 10

MATERIALS SUBSTITUTION TARGETS IN DETACHABLE BODY PANELS
(pounds)

	Intermediate	Compact
Hood	47	26
Fenders	40	30[1]
Doors	140[3]	80[2]
Deck lid	20	-
TOTAL POUNDS - STEEL	247	136
- PLASTIC[4]	148	82
WEIGHT SAVE POTENTIAL	99	54

[1]Assumes fenders remain plastics materials substitution candidate even for unitized construction
[2]Two doors and hatchback
[3]Four doors
[4]Assumes 40% weight saved

TABLE 11

PHYSICAL PROPERTIES COMPARISON OF CANDIDATE MATERIALS FOR EXTERIOR AUTOMOTIVE PANELS

	Specific Gravity	Tensile @ Yield (psi)	Flex Modulus[1] x 10^6 (psi)	Typical Thickness (in.)	Typical Lb/Sq.Ft.	Typical Weight Savings Potential (%)
Steel	7.8	30,000	30	0.032	1.3	-
HS Steel	7.8	50,000-80,000	30	0.028	1.2	8-10
Aluminum	2.8	28,000	10	0.040	0.6	40-50
SMC[2]	1.8	12,000-15,000	1-2	0.100-0.125	0.93-1.16	10-30
R-RIM[2]	1.1	-	0.3-0.48	0.125-0.150	0.7-0.86	35-50

[1]Room temperature
[2]25% glass reinforced

TABLE 12

THE PRODUCTIVITY PROBLEM

	Large Parts per Hour per Cavity	Example
Metal stamping (5 hits, 5 presses)	250	Fenders, gas tanks
Stamping, non-GR	175	Fender liners
Stamping, GR	120	Retainer panel
Injection molding	60	Instrument panel, kick panels
SMC	40	Header panels
Blow molding	40	Load floor
Reaction injection molding	30	Fascia, fenders
Structural foam molding	20	Instrument panel

Source: Industry and Arthur D. Little, Inc. estimates

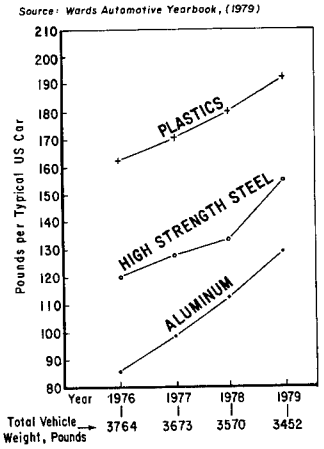
TABLE 13

INCENTIVES FOR WEIGHT AND COST SAVINGS ON 10-LB BODY PANEL

	Weight (lbs)	Variable Cost/Lb[1]	Part Cost	Cost/Lb Saved ($/Lb Saved)
Steel	10	$0.45	$4.50	$ -
HS Steel	9	0.50	4.50	no cost increase
Aluminum	5	2.00	10.00	1.10
SMC or BMC	7	1.00	7.00	0.83
R-RIM	5	1.30	6.50	0.40

[1]Total manufacturing cost of body panel excluding finishing (including raw material and tooling amortization at 300,000 parts/yr)

Source: Arthur D. Little, Inc. estimates



INCREASE IN AUTOMOTIVE MATERIALS SUBSTITUTION

Figure 1.

AUTOMOTIVE PLASTICS: NEW MARKETS FROM NEW PROCESSES

JAMES M. MARGOLIS

MARGOLIS MARKETING AND RESEARCH COMPANY

NEW YORK, NEW YORK

"Plastics: The Answer To Transportation in the 1980's"

The automotive industry is now in a materials revolution that is affecting every manufacturer of automotive materials and parts.

In order to understand the dramatic change in the use of materials in the automotive industry, we should review briefly the past 15 years for historical perspective. In order to sell materials and products to Detroit, a supplier was required to meet two conditions: 1. meet the specifications for the material or product, and 2. offer it at the lowest available price.

During the 1960's this selling procedure began to include another condition: the new factor was the in-place cost of the product. Automotive companies discovered that the in-place cost could be less with a product that cost more to purchase. This discovery can be considered the beginning of the materials revolution.

The best example was the flowed-in windshield seal which replaced lower cost solid cut-rubber seals. The installation cost for the flowed-in seal was less than the installation cost for the cut-rubber seal. The lower in-place cost resulted in a net savings, which made it worthwhile for automotive companies to pay a higher price for the product.

During the past 15 years, selling condition number one,"meet the (automotive company's) specifications," has also been changing. Both the customer, and the government, have mandated new performance requirements. Older specifications have been changed and new specifications have been created for new applications, such as emissions control devices.

During all these years it has become increasingly clear that plastics materials and products are best suited to meet the requirements for automotive applications, in many cases. Also, it has become clear that plastics products performance and costs are very dependent on processes.

New automotive plastics applications are becoming realities through new processes. The term "new processes" is a relative term. Fifteen years can pass during the development of an automotive part from the first prototype to commercial production. The term "new processes" means something different to different people. The people who developed post-molding transfer coating during the early 1970's do not consider it new, but it was introduced by the Fisher Body Division of General Motors Corporation in 1977. Most of us consider post-molding transfer coating new, and expect the process to help to create new automotive plastics applications.

Sputtering is a new chrome-coating method to the automotive industry, with a promising potential for new automotive plastics applications. The first sputter chrome application in automotives was the acrylonitrile/butadiene/styrene (ABS) Chevrolet Caprice lower grille opening panel, in 1976. Nevertheless, the process is not new at all to the electronics industry.

A new process, therefore, can include a wide range of processes. Injection molding certainly is not new. When you combine foam/reinforced plastics with higher strength and faster cycles, together with the large presses you need to make automotive body parts, you have a new process.

Selling to Detroit is no longer limited to meeting current specifications and selling at the lowest price. The automotive companies have learned that new plastics processes are vital to new automotive plastics applications. The industry-wide recognition of new processes to new markets is the basis for the materials revolution.

New processes that are most outstanding include reaction injection molding (RIM) and reinforced reaction injection molding (R/RIM), injection molding bulk molding compound (BMC), press-reinforced vaccum formed sheet, and pultrusion, as methods of fabrication. Decorative techniques include sputter chroming, in-mold coating, post-molding transfer coating, and continuous high speed foiling.

Reaction injection molding (RIM) and reinforced RIM are designed primarily for large parts. Conventional injection molding is ideally suited for mass production of smaller parts. The automotive industry is pioneering advancements in R/RIM, although RIM parts are used in appliance, furniture, business machine, construction, and marine products, and recreational equipment.

The newest development in RIM equipment is the Cincinnati-Milacron second generation RIM machine. Second generation RIM machines eliminate the "chemistry" steps for the molder. The glycol and isocyanate feed units are built into the machine. The equipment also has sophisticated electronic controls to monitor and adjust several parameters, including nozzle pressures, mold temperatures, and mix.

High pressure metering technology associated with reaction injection molding was originally developed by Bayer AG and Hennecke GmbH. RIM units are manufactured today by Cincinnati-Milacron, Hennecke, Mobay Chemical, Elastogen Maschinenbau which is represented in the United States by American E.M.B. Urethane Technology, Schloemann-Siemag, Afros-Cannon, Krauss-Maffei, Desma-Werke, and VTE.

Almost 15 years ago large parts were reaction injection molded from self-skinning rigid foams. Experience with high pressure impingement mixing equipment, with highly reactive components, resulted in an experimental car with FRP/RIM "Baydur" polyurethane foam core body shell. That was about 1967.

The first production car to use injection molded thermoplastic polyurethane front and rear ends was the 1974 Corvette. RIM fascia made from thermosetting polyurethanewere first installed on the 1975 model Corvette, Chevrolet Monza 2+2, Buick Skylark, and Oldsmobile Starfire. Several more models now carry RIM fascia. General Motors Guide Division "Guide-Flex" bumper systems are installed on the front and rear ends of the Chevrolet Monte Carlo, rear of the Pontiac Firebird, and the entire line of Pontiac LeMans. The Camaro bumper replaced extruded aluminum and the Monte Carlo RIM bumper replaced chrome plated steel.

The 1979 Ford Mustang, Mercury Capri, and Mercury Marquis have RIM polyurethane front ends, the 2-door Dodge Omni has RIM front and rear fascia, and the 2-door Plymouth Horizon has a RIM front end.

Reinforced reaction injection molding is intended for large structural parts such as seat frames and body panels. R/RIM competes with compression molding sheet molding compounds (SMC), filled acrylonitrile/butadiene/styrene (ABS), and steel, for semi-structural pats such as door panels, fenders, hoods, and trunk lids. Cab-over-engine (COE) hood-and-fender units now made from ABS, FRP, and steel, panel truck shells (panels), and trailer truck skins could be made from RIM polyurethane.

Higher modulus RIM polyurethane resins are expected to be used for large structural exterior automotive parts. Higher modulus is achieved by fiber reinforcement of the resin, or by chemically modifying the polymer, or both.

Bulk molding compounds (BMC) are injection molded into grille opening panels (GOP) and front end retainers. A key to this process is the medium intensity mixer which blends and intimately mixes the three components, compounded polyester resin, filler, and chopped glass, into a thick dough. The specially designed mixer is built by Farrell

Machinery/USM Corporation, and the total BMC injection molding process was developed by Bailey Division/USM.

The medium intensity mixer wets out and disperses the cut fiber glass and filler in the resin matrix, which is comprised of polyester, catalyst, and pigment. The mixed molding compound extrudes continuously from the mixer to a distribution system that diverts the material and conveys it to each injection molding machine in proportion to its requirements.

Press-reinforced vacuum formed sheet became commercially interesting when General Motors Truck and Coach Division ordered panels for its Rapid Transit Series (RTS-2). When acrylic sheet is press-reinforced with fiber glass mat, an automotive exterior panel can be produced with the outdoor weathering properties of acrylic sheet, and the structural properties of fiber glass reinforced plastics.

In this process "Swedcast" crosslinked acrylic sheet 0.080 inch thick is vacuum formed to shape the exterior bus panels. Immediately after forming, the panels are cooled in order to prevent further curing action by the curing system. The panels, still unreinforced, are placed in a press with aluminum matched metal dies. At the same time, a preform of glass fiber mat impregnated with polyester resin, approximately 0.100 inch thick, is also placed into the press, over the formed sheet. The glass fiber/polyester preform mat is pressed into the acrylic sheet at low temperature, about 125° to 200°F, and low pressure about 25 to 50 psi. The panels are vacuum formed and press-reinforced by Crown Division of the Allen Group, Orrville, Ohio.

After press-reinforcing, the panels are placed on racks and transferred to a finishing station where they are sandblasted and trimmed. Metal reinforcements are added, some of the panels have pultruded trim components, and the panels are readied for shipment to the General Motors Truck and Coach Division assembly plant. Variuos models of the RTS-2 buses use up to 14 different panels each. Altogether, Crown produces about 22 different types of press-reinforced panels. The RTS-2 buses are replacing buses that were put into service 20 years ago.

The pultrusion process can be used to form FRP curved bumper support beams, leaf springs, crankshafts, frames and frame crossmembers, and door intrusion beams.

The process basically consists of pulling fiber rovings or mat through a thermosetting resin bath, and finally through a heated metal die to form the pultruded shape, and to cure the composite. At the downstream end of the pultrusion line, the shaped profile is cut to length.

Prior to entering the heated metal die, the resin impregnated mat or roving is pulled through squeeze-out and shaping bushings where excess resin is removed. The composite can be pulled through an optional radio-frequency (RF) preheating chamber to raise the temperature close to the gel temperature of the resin.

Pultrusion equipment can be relatively inexpensive, the process has a low direct labor input, low scrap rate, and it usually does not require time consuming steps such as flash removal and sanding.

Pultrusion equipment is made by Goldsworthy Engineering, Gatto Manufacturing Development Corporation, and Pultrex, Ltd. Pultrusion grade glass fibers are produced by PPG Industries and Owens-Corning Fiberglas. Glastic and Morrison Molded Fiber Glass are among custom pultruders that have developed pultrusion methods for automotive applications. Replex International developed a truck bumper beam using Hercules preprегs.

Glastic Corporation pultrudes internal I-beams for new tractor trailer walls. The tractor trailer containers are a new concept in shipping perishable foods in high vacuum with constant humidity control. The I-beams provide a combination of high strength/low thermal conductivity for the internal structural webs of the hypobaric tractor trailer shipping container walls.

Pultruded reinforced plastics/composites (RP/C) can be made with polyester or epoxy resin, and glass, aramid, carbon (or graphite) fibers. Almost all pultruded products now are made with polyester/glass. Thermoplastics such as polysulfone and polyimide can be pultruded. Diamond Shamrock introduced pultrusion grade polyesters DION 8101, 8200, and 8300 with faster curing polyester resins now being developed. Since Koppers Company purchased the Diamond-Shamrock polyester plants, Koppers is now offering these polyester resins for pultrusion.

The selection of fibers, fiber rovings, mats, and veils are vital considerations in the development of structural components for automotive applications. Fibers are available in a wide variety of starnds, mats, woven rovings, woven cloths, and surfacing veils (which can be made from graphite fibers).

Goldsworthy pultrusion equipment includes sophisticated multiple fiber orientation tooling. One example of the use of this tooling is multiple fiber orientation tubing. A layer of surfacing and continuous strand mat is applied over the tubing, followed by two layers of longitudinal roving, a second layer of continuous strand mat, plus 45 degree roving and minus 45 degree roving, and a final outer layer of continuous strand and surfacing mat.

The weaving/winding equipment functions upstream in the pultrusion line, in sequence with the pultrusion, to apply various selected geometric layup patterns. This equipment is an alternative to purchasing pre-woven mats and crosswoven fabrics. According to the company, in-line fiber layup can reduce cost by utilizing more economical fiber reinforcements, improving pultrusion rates, and permitting simpler inventory.

At the present time about 6% of total pultrusion markets are automotive products. The process is new to the automotive industry on a commercial production basis. The process is well suited for the requirements for load bearing structural automotive products such as bumper assembly components, frame components, and door intrusion beams.

New automotive markets in the 1980's are also being created through decorative processes. One of these processes is sputter chroming. The first sputter chrome application in automotives was the Chevrolet Caprice lower grille opening panel, in 1976, made from acrylonitrile/butadiene/styrene (ABS).

Sputter chroming has several attractive characteristics. It provides excellent adhesion for elastomeric polyurethane bumper fascia, fast production rates, relatively low capital equipment costs, and it is a pollution-free vacuum metallizing process.

Sputter chroming has some disadvantages. It does not impart the high shiny luster which is characteristic of chrome plated steel. For this reason, the first production application was alower grille panel, which is not as visible as an upper grille panel, bumper, or trim. Sputter chrome coatings are not as abrasion resistant as chrome plated steel. If the lacquer wears off, exposing the chrome coating, the chrome can be stripped away.

Chrome sputtering is being evaluated for RIM bumper fascia. Soft plastics parts that are chrome plated by conventional electoplating methods tend to crack, due to the differences in thermal coefficients of expansion between the plastics and the chrome, and also due to the difference between the hardness of the materials, and the thickness of electroless plated chrome coatings.

An 0.0015 inch thick chrome plated surface on a flexible plastics such as polyurethane tends to crack when it is struck. Sputter chrome coatings are thinner than electroless chrome plated surfaces and do not tend to crack. Sputter chrome provides a more flexible surface which tends to yield with the fascia when it is struck.

In addition to bumper fascia, the sputter chrome process has potential applications for smaller automotive parts such as hub caps, headlamp housings, trim, bezels, door handles and door locks, lettering, and medallions.

General Motors has purchased sputter chrome equipment from Varian Associates and Airco/Temescal. Oxford Metallizing Company here in the Detroit area is a sputter chroming company on a custom basis.

New, improved platable resins permit electroless chrome plating to compete strongly for metallized plastics markets in the 1980's. Uniroyal introduced three plating grade resins in 1978: "Kralastic" MPA-2615, MPX-2606, and MPN. These resins were developed to meet tough thermal-cycling requirements of automotive parts. "Kralastic" MPX-2606 has been approved by American Motors for Concord taillight housings. Platable ABS is also used for radiator grille opening panels, mirror housings, and headlight and taillight housings.

Borg-Warner Chemicals introduced platable ABS "Cycolac" Z-58 and EPB with improved thermal cycle performance. "Capron" XPN-1030 platable nylon from Allied Chemical is suitable for applications not within the capabilities of some other resins, according to the company. The mineral-filled nylon "Capron" and Monsanto "Vydyne" RP-260 are candidates for chrome plated window cranks, door handles, mirror holders, and bezels.

Since sputter chroming is new for automotive applications, resin producers up to now have emphasized research to improve resins for chemical chrome plating systems. Acid etching is the critical step in chemical/solution chrome plating. Improved electroless chrome plating depends as much on the chemistry of the plating process as it does on the quality of the platable resins. New chemical etch systems are introduced in order to achieve a good bond between the chrome film and the plastics surface. A good etch process also promotes high luster on the chrome surface. Allied Chemical introduced a new etch system as an alternative to chromic acid etch systems. The system is compatible with several commercially available catalyst systems used in ABS lines, such as colloidal palladium/stannous activators and fluoboric acid accelerators.

Enthone, a subsidiary of ASARCO, introduced a new electroless copper process for chrome plating ABS, which the company uses with its "Enplate" Conditioner 474, Postconditioner, Activator 442, Post Activator PA-491, and "Enthobrite" bright acid copper electroplating solution.

Improved platabe polyphenylene oxide (PPO) resins and filled polypropylenes add to the electroless chrome plating potentials in automotive applications in the 1980's.

In-mold coating is another new decorative process. The purpose of in-mold coating is to eliminate porosity on the surface of compression molded sheet molding compounds (SMC). In this process, thermosetting polyurethane is introduced into the mold while the heated, formed SMC part is still in the press. The polyurethane forms a protective surface on the SMC part.

During compression molding, air bubbles can form which vent from the heated SMC and create surface porosity. The polyurethane coating

applied in the mold fills surface "caves," cracks, and to a less extent it smooths sink marks on the surface of the part. The process also greatly reduces finishing and priming.

In-mold coating is another method to produce automotive quality Class "A" surfaces, which is necessary for passenger car body parts. In-mold coating is not an alternative or substitute for compression molding sink-free plastics (SFP) such as the polyester resin used to mold the new Ford Econoline engine hood.

In-mold coating was developed by General Tire and Rubber Company and General Motors, in a joint research program. It could compete with R/RIM polyurethane and injection molding plastics such as structural reinforced foam polycarbonate to make door panels, trunk lids, roofs, engine hoods, and fenders.

In-mold coating was first used in automotive applications in the second half of 1978, for the Chevrolet roof panel and the Pontiac Phoenix front header panel.

The process permits single-piece parts with structural ribs and attachments to be molded with simpler designs and lighter weight construction, compared with steel.

Post-molding transfer molding involves forming a covering over or onto an injection molded substrate or any other suitable rigid part. The process utilizes a 4-station rotary thermoforming machine which carries the flexible covering material through the heating and forming stages of the operation. A separate rotary wheel carries the rigid molded part into position for coating.

The technique was introduced by Fisher Body Division of General Motors jointly with Brown Machine Company. The process is currently used to make sculptured trim panels including door panels, instrument panel components, and rear quarter upper trim panels. It is possible to apply foam materials on the substrate before forming. An example of this would be an integral armrest or an inner door panel.

The process also permits the use of one basic inexpensive substrate with the application of multicolored or multitextured surfaces.

ABS and polystyrene were post-mold transfer coated in 1974. More recently expanded vinyl and ABS/PVC sheet up to 40 mils thick have been transfer surface coated to make decorative, complex automotive parts such as the rear deck panels and instrument panels.

The vinyl or ABS/PVC sheet is palced on a 4-station R-244 forming machine with 20 inch draw and a maximum mold size of 82 inches by 44 inches. The two tables, one with the flexible sheet which is the cover and one with the ABS/PVC substrate molded part, counter-rotate and simultaneously advance toward each other.

The process invloves vacuum snap-back applications of the vinyl sheet to the substrate part, with molded-in vacuum channels which are coated with heat reactive modified epoxy adhesive.

When the tables have advanced until the heated flexible sheet is over the rigid substrate, the lower platen is raised, to bring the sheet and molded part into contact. The temperature is increased to 300° to 320°F. The covering is bonded to the surface of the molded part, and a vacuum (25 inches Hg) is generated to assure firm bonding, and rupture-free wrapping of the part. The total cycle time is 30 to 38 seconds.

Continuous high speed foiling is a fourth decorative process which is helping plastics in automotive applications. The decorative foil is usually wood grain or metallized. The foil is applied to film, either directly at the extrusion die before the hot film passes through chilling rollers, or further downstream after the extruded film has passed through the chilling rollers.

Continuous high speed foiling is a hot stamping process. It makes possible high speed transfer of decorative foils onto the entire surface of the formed parts made from polyethylene, polypropylene, high impact polystyrene, acrylic, polyphenylene oxide, and ABS.

The process is valuable for automotive applications in thicknesses between 15 and 30 mils, to provide decorative inserts for injection molded trim on instrument panels, armrests, and other interior trim.

Ford Motor Company, General Motors Corporation, and American Motors Corporation have captive insert molding decorating facilities. These companies also purchase hot stamped decorative inserts. Chrysler Corporation purchases decorative inserts from other companies.

Thermark, the company that pioneered in high speed foiling, produces "Thermark XT Foils" which are approved for automotive first surface exterior applications such as grilles, taillights, and side marker lights.

Dri-Point Foils and Kurz-Hastings supply complete systems including foils, equipment, and technical service. Both of these companies also supply post-extrusion roll-on equipment, which is designed to transfer decorative patterns such as woodgrains, leathers, and metallics.

In post-extrusion high speed foiling the decorative pattern is bonded to the extruded sheet at 250° to 450°F, depending on the substrate plastics. Either silicone rubber rollers or heated metal rollers are used to pressure apply the decorative foil to the substrate.

Automotive Applications and Materials

The "battleground" in the 1980's among various materials, especially plastics and metals, may very well be exterior body components. On a tonnage basis, large body parts each represent millions of pounds per year of resin sales.

John Deere 180 horsepower farm tractors are made with hood extenders molded from DuPont "Zytel" ST nylon. Mack Trucks have sheet molding compound (SMC) fiber glass reinforced polyester compression molded doors, made by Rockwell International Plastics Division.

High strength sheet molding compounds such as PPG Industries "HMC" and "XMC," Owens-Corning Fiberglas "SMC-C" and "SMC-D" as well as thick molding compounds (TMC) marketed in the United States by U. S. Steel Corporation/U. S. Polyester Company, and sink-free polyester (SFP) all contribute to advances in plastics automotive body parts.

ABS fenders, hoods, and cabs have been used since the 1960's on Mack, Diamond T, Kenworth, International Harvester, and other trucks. Fiber glass reinforced polyester (FRP) has also been used for more than 10 years to make these body parts, as well as to make the Corvette body (for more than 20 years).

The first use of ABS as an auto body part was for the Cord 810, in 1964, thermoformed in four sections from Uniroyal "Royalite" ABS sheet. In 1965 Marbon Chemical Division (now Borg-Warner Chemical) introduced the "Cycolac Research Vehicle" (CRV) made with two thermoformed ABS body halves.

Polypropylene fender liners have been used on Ford Mustang, Granada, and light trucks. Ford began stamping large non-structural polypropylene parts at its Maumee, Ohio stamping plant in 1977. Production rates range from 250 to 400 parts per hour.

General Electric "Valox" polybutylene terephthalate (PBT), a structural foam resin 30% glass fiber filled, was used for the 1978 Corvette moon roof.

High density polyethylene (HDPE) is blow molded into seat back/load floors by Ford Motor Company for 1979 Mustang, Mercury Capri 3-door hatchback, Mercury Zephyr, and Ford Fairmont models. Phillips Chemical "Marlex" HDPE is extruded into parisons which are blow molded into double-walled seat back/load floors with about 3.8 inches thickness, and weighing 3.2 kilograms less than the steel inits which are replaced.

Second generation high resilient (HR) polyurethane foam has been introduced as an alternative to conventional hot-cure flexible polyurethane foam, as seating material. These foams are standard material for automotive seating. The newer grades of HR polyurethane foams are being used as an alternative material for seating.

The 1978 Chevrolet Corvette introduced a nearly all-plastics seat construction, using in-mold coating. The seat is made of a fiber glass reinforced polyester (FRP) case, polyurethane foam cushion and covering, with no metal springs. The seat weighs 12 pounds compared to 24 pounds for the seat with steel springs which it repalces.

Ford Motor Company has introduced a new polyurethane foam/fabric headliner for most of its 1979 models, to obtain a cost saving in the assembly stage. The headliner is snap-clipped into position during assembly of the passenger compartment interior.

Larger one-piece instrument panel/crash pad units are being molded for cars and trucks. ARCO/Polymers subsidiary of AtlanticRichfield makes "Dylark" styrene copolymer which is injection molded into one-piece instrument panel/crash pad units. Borg-Warner Chemical "Cycolac" Z-48 ABS is injection molded into a one-piece instrument panel for the American Motors Concord passenger car.

Many recent advances in vinyl fabrics for passenger car upholstery have been improved vinyl compounds for more economical calendering and for longer wear physical properties. New ultraviolet absorbers, plasticizers, and flexibilizers such as ethylene/vinyl acetate (EVA), thermoplastic polyurethane (TPU), acrylic base modifiers, and porcmeric materials significantly reduce aging embrittlement of vinyl hardtop coverings. These additives also improve vinyl fabrics resistance to heat, chemicals, and wear.

Additives can increase vinyl fabric costs by as much as 40%, even when used in conjunction with phthalates, esters, adipates, azelates, and other conventional plasticizers. Woven fabric seat coverings are reappearing in new automotive models. Research on calendered vinyls or automotive upholstery should emphasize customer appeal, such as fabric printing, textured surfaces, and heat dissipation, in order to compete effectively with automotive woven fabrics.

Also in the interior compartment, a graphite/epoxy composite brake pedal assembly has been designed and constructed by the Automotive Control Systems Group at Bendix. The brake pedal blade assembly has greater stiffness and strength than the steel unit it could replace. Although the graphite/epoxy assembly is thicker than the steel unit, it is half the weight of the steel brake pedal assembly.

An epoxy/graphite steering column section has also been made, using Union Carbide Corporation "Thornel" carbon fibers.

Under-the-hood graphite/resin composites are also expected to be used in 1980's automotive applications. Ford Motor Company is introducing the first production run graphite/epoxy composite for automotive use, the air compressor mounting bracket. It is compression

molded by Armco Composites from continuous graphite fiber and chopped glass fiber reinforced polyester. The bracket weighs two pounds, compared with seven pounds for the malleable iron casting bracket which it is replacing.

Valve pushrods have also been made from graphite/resin composites. These rods will probably find use in racing cars.

Dupont elastomeric thermoplastic polyester "Hytrel" is extruded into vacuum harness tubing to control a variety of systems. The unplasticized polyester is also used to make transmission linkage bushings, seals, and grommets because it has resistance to under-the-hood temperatures, abrasion resistance against motor parts, and resistance to motor oil and gasoline, all essential characteristics for under-the-hood materials.

Thermoplastic polyester, acetal, and nylon are being used increasingly in under-the-hood applications where dielectric properties and thin wall construction are becoming more important. Some examples are high energy ignition system distribution caps, rotor covers, and retainer plates. Other under-the-hood plastics applications are emissions control devices, vacuum systems, switches, 3-in-1 unitized shrouds, radiator overflow tanks and radiator caps, windshield washer/wiper bottles and tubing, fuel pump housings, crankcase housings, fuel vapor separators, carburetor parts, and mechanical parts.

The electric windshield washer/wiper uses five different types of resins, nylon. acetal, polypropylene, polyethylene, and polyester, for 20 different parts. Nylon is used for the electric wiper motor gears, air pressure line tubing, stabilizer button between the wiper arm and actuating link to eliminate vibration and noise, hose connection to water reservoir bottle, and a nylon wiper blade arm tip attachment for "wet" wiper blades to permit the water nozzle to be snapped on to the wiper blade arm. Acetal is used for the pump housing, slide lever, washer button, washer wiper control assembly housing, valve, valve actuator, spacers, switch gears, motor housing, and glass fiber reinforced acetal bearing surface of the wiper pivot body.

The water reservoir bottle is polyethylene, the reservoir bottle cover is polypropylene, and fiber glass reinforced polyester is used to mold the diaphragm spacers, stop washers, and the cap in the coupler assembly of the hydraulic wiper motor.

Fiber glass reinforced polyester (FRP) is molded into distributor caps by Industrial Dielectrics, repalcing the conventional compression molded phenolic thermosetting resins. Higher voltage resistance is required in under-the-hood applications of new automotive models. During the 1970's higher temperature resistant plastics were introduced for higher performance engines and transmissions which were characteristic of passenger car models during the 1970's. Now, higher voltage resistant plastics are needed for the models of the 1980's to meet the advanced under-the-hood electronics.

Ford Motor Company EEC-II, Electronic Engine Control, second generation equipment, was optional for the 5.8-L V-8 engine in the 1979 50-state Mercury Marquis and California Ford LTD. The electronic control system, similar to electronic fuel injection systems, interacts carburetion (air/fuel ratio) with spark advance. In addition, the EEC-II correlates carburetion/spark timing with three-way catalytic (TWC) emissions control.

Higher voltage ignition controls, solid state high voltage distribution for distributorless ignition systems (DIS), and microprocessors to increase automotive computer applications, will affect plastics materials selections during the 1980's.

Any change in engine design can also have a significant affect on plastics materials selections and applications. For example, electronic fuel injection, and diesel engines, will greatly alter the pattern of plastics applications for carburetion. Significant engine modifications are expected to be introduced, in order to meet 1985 fuel economy standards by increasing fuel combustion efficiency of the powerplant.

Consistent with reinforced plastics/composites (RP/C) applications for exterior, passenger compartment, and under-the-hood parts, several RP/C materials are being evaluated for frame and chassis parts. Some of these parts are:

Leaf Springs
Driveshafts
Axle and Axle Housings
Suspension Arms
Transmission Housings
Transmission Supports
Frames and Frame Crossmembers
Frame Rail Reinforcements
Chassis Reinforcements
Brake System Components
Wheels

The dramatic possibilities for RP/C frame and chassis applications are due to advanced process equipment designs, as much as they are due to new high strength/weight ratio fibers and fiber hybrid/resin alloy compositions.

General Motors Inland Division is developing pultruded leaf springs. Other General Motors divisions and Ford Motor Company are also working with custom pultruders on crankshafts, door intrusion beams, and bumper support beams.

Graftek Division of Exxon Enterprises has fabricated carbon fiber composite driveshafts by wrapping the fibers in a resin binder arond an aluminum tube. Shakespeare Company has made one-piece driveshafts with a carbon+glass fiber hybrid system, using Union Carbide Corporation "Thirnel" carbon fibers. The composite driveshaft weighs 18 pounds compared with 33 pounds for a comparable steel unit.

Hercules, Inc. is designing a high speed filament winding technique for mass production of carbon/glass fiber reinforced resin composite driveshafts. Hercules has also formulated carbon/glass fiber reinforced polyester composites, and pultruded bumper beams for high volume production evaluation.

Celanese Corporation Structural Composite Division has designed a rear door panel using the company's "Celcon" carbon fibers in a thermosetting resin matrix. The door weighs 12.5 pounds, compared to 30 pounds for a steel door panel.

Automotive materials and processing companies can use aerospace industry technology for filament winding high strength load bearing composites for automotive applications. However, aerospace technology is used in relatively low volume production, and costs are not as critical as they are in the automotive industry. Therefore, aerospace technology, while useful in technology transfer to the automotive industry, has a limited value in automotive applications.

Experience obtained from new automotive materials processes and applications, on the other hand, can be expected to be transferred to other industries including aerospace, appliance, electronics, packaging, building, furniture, and hardware and houseware industries. Automotive performance evaluation is a crucible of materials and processing technology.

Compression molding sheet molding compounds (SMC), injection molding bulk molding compounds (BMC), pultruding, and filament winding, are the likely materials and processes to be used for high strength, load bearing composites for automotive frame and chassis parts.

Non-destructive test procedures are also being evaluated, in conjunction with the development of new automotive plastics applications. Useful non-destructive test evaluations have been performed on reinforced plastics/composites (RP/C) molded into wheels at Firestone Tire and Rubber Company Central Research Laboratories.

RP/C wheels can be 30 to 50% lighter than steel wheels. The weight reduction of a wheel saves more fuel than the same weight reduction of other automotive parts. The reason for this is that the mass moment of inertia (the effective weight of the wheel as it is turning while the car is in motion, and burning fuel) is directly proportional to the angular acceleration of the wheel. The RP/C wheel is not ready for road use yet, because its strength must be increased in order to withstand the impact that automotive wheels are often subjected to.

These are a few of the examples of the materials revolution in the automotive industry. The creation of new markets from new processes is an integrated effort joining resin manufacturers, plastics processors, and automotive companies. Other raw materials companies, especially fiber producers, and suppliers of plasticizers, for example, have a vital role also. And finally, machinery and equipment manufacturers are an essential link in the chain.

MASS PRODUCTION EQUIPMENT FOR CONTINUOUS FILAMENT COMPONENTS

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INTRODUCTION

Automotive weight reduction to meet government mandated mileage standards is now forcing the design of primary structural components away from the use of traditional metals into plastics. Structural components such as leaf springs, drive shafts, suspension members, stabilizer bars, bumpers, and beams require mechanical properties not achieveable in either short or long fiber molding compounds. Continuous filament fiberglass or continuous carbon (graphite) fiber reinforcements are dictated for these structural components by their function.

Continuous filament reinforced plastics cannot be fabricated by the primary processes currently prevalent in the automotive industry. Injection molding, extrusion, compression molding, and transfer molding have achieved importance in the automotive industry because they are automated, are not labor intensive, and can produce the large volumes required by the industry. But where structural requirements demand continuous fiber reinforcements these processes cannot be used.

New primary processes are required where the mechanical demands of the structure dictate continuous filamental reinforcement. And if such new processes are to be economically useful in the automotive industry, they must meet the criteria of being automated, not labor intensive, and have the ability to produce large volumes of product.

These important criteria are met by three new processes specifically developed for continuous filament reinforced thermoset plastic products: (1) Rotary Pulforming, (2) Continuous Tubular Winding, and (3) Pin Winding.

ROTARY PULFORMING

Rotary pulforming is defined as a process which produces a curved profile continuously by bringing together continuous filaments, impregnating the filaments, and curing (polymerizing) the shaped mass into a continuous unlimited length product.

The process is related to pultrusion particularly in resin curing methods employed, but differs from pultrusion significantly in being able to produce other than straight constant cross-section profiles. This feature is possible because the materials in rotary pulforming, instead of being drawn through a curing die orifice as in pultrusion, are drawn into a curved die cavity which is closed only at the point of cure by rotating the curved die against a stationary die segment or "shoe".

Consequently, the shape of the cured part is not only curved, but may be of varying cross-sectional shape. A mono-leaf automobile suspension spring, Figure 1, is a typical example of a product which may be produced by the rotary pulforming process.

For purposes of illustration, only constant radius, constant volume (but not necessarily constant cross-sectional shape) products and equipment will be described in this paper. In reality, however, the rotary pulforming process can produce varying volume products by introducing additional material at appropriate intervals.

ROTARY PULFORMING HISTORY

Historically, the first rotary pulformed composite parts were made in 1972 on prototype equipment shown in Figure 2. The product being made is a curved hat section, 1½" X 1½" X 3/4" flange, with oriented plies of both fiberglass and graphite cloths in an epoxy matrix. An ambitious product for its time, the hat section was initially designed as a rib structure for a space vehicle, cylindrical in shape, and 20 feet in diameter. A brief explanation of the operation sequence used in this program is as follows:

1. Webs of reinforcements (dry or impregnated) are unrolled from stock rolls of slit-to-width material, then drawn forward through staged, profile-establishing plates to the pressure impregnation zone (if dry materials are used).
2. The impregnated material then enters the radio frequency zone, passes through a form defining Teflon die, while being pre-heated through its section thickness to a temperature just short of gelation.
3. The heated material emerges from the RF cavity, through a final shaping bushing, into an externally heated steel die for final compaction, forming, and final cure. This final cure zone consists of two elements shown in Figure 3: (1) the stationary "male" half of the steel die and (2) the moving "female" half which also serves as a pulling device to advance the material continuously. This latter element is called a "forming sector".
4. The forming sectors, heated electrically, since they form the outside surface of the hat section, not only provide an accurate curing surface, but being pivoted on a 10 foot radius, they provide a true tangential pull, thereby preserving the hat section shape at all times even after exit from the curing zone. Two locked forming sectors are used to start. As the second sector clears the die, the first sector is unlocked, then advanced around the circle to be attached to the rear of the second sector. By repeating this sequence, any length product can be produced in the form of a flat spiral.

CURRENT PULFORMING EQUIPMENT

A current use for rotary pulforming equipment is in making automobile springs from composite materials. Shown schematically in Figure 4, a rotary pulformer continuously dispenses fiberglass roving from center pull packages, through a resin bath, through an RF preheating zone, then into the cavity of moving curved die. The product is cured continuously and cut automatically to the proper arc length. As in pultrusion, production speeds of 15 feet per minute are quite normal for typical spring sizes.

The original prototype equipment employed moving die sectors or quadrants for tooling economics. Dedicated production machines now employ complete circular moving dies, in which a number of spring part cavities are sunk depending on the arc length of the spring being manufactured.

The economic importance of rotary pulforming should be emphasized. The only other process, filament winding, capable of constructing an equivalent product is considerably slower having the distinct disadvantage of requiring molds to be rotated, plus the added operations of removing the molds from the winding machines for curing, also a secondary operation.

Conversely, in rotary pulforming, all the raw materials in the cross-section are entered into the equipment simultaneously; the polymerization (cure)

is continuous, hence the completed part emerges continuously without any secondary operations.

CONTINUOUS TUBULAR WINDING

A process borrowing technology from both pultrusion and filament winding, continuous tubular winding is used in the continuous fabrication of products requiring continuous fibers in an angular orientation, i.e. other than zero degrees to the product's longitudinal axis.

A typical product example is a composite automobile drive shaft which in addition to longitudinal filaments for stiffness, a relatively large percentage of the reinforcement must be placed at 45 degrees to the longitudinal axis to provide torque strength.

In order to economically use continuous filaments in angular orientations, the equipment criteria of automatic operation, low labor factor, and suitable production volume output were again the guiding equipment design factors. An equipment example of continuous tubular winding is shown in Figure 5.

Borrowing from filament winding to some extent, "over-winding" wheels were developed in which the reinforcing materials, usually conventional spools of fiberglass roving, are mounted on the face of the wheel and are revolved around the axis of the part being pultruded.

The materials are dispensed tangentially from the supply packages, and the filament angular orientation is obtained by controlling the ratio of two machine motions: (1) longitudinal through-put speed and (2) over-winding wheel rotational speed. Thus, the filament lay-down angle can be varied from near 90 degrees to any lesser angle by simply changing the motion ratio. Common over-winding angles are slightly less than 90 degrees for tubular hoop direction loads, and plus/minus 45 degrees for torsional loads as in a drive shaft.

An inescapable geometric fact is associated with continuous over-winding techniques. Because the process is continuous by definition, the product passes through the equipment only once. Therefore, each ply of reinforcements, made up of continuous helical circuits, in order to be contiguous (without gaps between the filament courses), must be applied in a band sufficiently wide to cover the part surface completely in one wheel revolution. The material band is determined by two factors: winding angle, and part circumference, and is mathematically equal to the part's circumference multiplied by the cosine of the winding angle. For example, a 4" diameter, 45 degree wind requires a band width of almost 9". When the number of roving spools orbiting around the part becomes impractical, rovings may be "beamed" into wider unit packages.

TYPICAL TUBULAR PULTRUSIONS

Tubular pultrusions are typically comprised of various plies of materials: continuous swirl mat folded convolutely, 90 degree hoop winds, zero degree longitudinal rovings, 45 degree winds both plus and minus for balance, and various surfacing materials folded convolutely or helically wrapped.

Tooling to apply and position the various plies is situated end-to-end, with impregnation stations interspersed as required. The reinforcement materials are always applied "in-the-round" over cylindrical tooling, then cured in the heated die as a round tube, or any other tubular section, e.g. square, hexagon, having a cross-sectional peripheral dimension identical to the circumference of the tooling at the forming/winding stations.

Theoretically, any tubular wall thickness may be built up using over-winding wheel techniques. Advantages of this technology are significant both in terms of raw material economics and the strength characteristics of the pultruded profile. Roving, the least expensive form of fiberglass, may be used in lieu of more costly cloths and mats; and because the roving filaments are placed accurately in the desired load paths, the laminate specific strength is optimized.

CONTINUOUS OVERWINDING SOLID PROFILES

The overwinding method of applying rovings in pultrusion is not limited to tubular profiles. Reinforcements made "in-the-round", in forming/winding stations, may be flattened into multi-plied sheets, or formed into any solid profile, e.g. an angle or channel before reaching the curing station. Obviously one 45 degree winding in the tubular form, when flattened, becomes two opposed 45 degree plies in a solid profile.

For structural components this feature is significant. Oriented plies can be obtained only one other way, by the use of bias woven cloth. Since cloth reinforcements are both expensive and difficult to process, overwinding techniques provide the economic answer for oriented ply products.

Employment of over-winding technology need not be limited to pultrusion. Introduction of discrete length metal mandrels into the material stream can be used to produce automotive drive shafts having metallic cores for ease in attaching universal joint hardware.

In still another machine application, by omitting the final cure station in the production line, oriented continuous fiber sheet molding compound may be produced in a tubular form, then flattened in line before the maturation cycle. This method eliminates the substantial waste generated at the mandrel ends when making this type of raw material by filament winding on a discrete length mandrel, then slitting off the winding to produce a sheet. In the overwinding wheel method of making oriented sheet molding compound the sheet width is determined by the tube diameter before flattening and, of course, the sheet length is unlimited since the process of overwinding is continuous.

PIN WINDING

The final process, pin (or strap) winding, considered in this paper, just as the two other processes discussed, employs continuous filaments for high structural strength, but produces discrete length parts rather than continuous length products.

First used in the aircraft industry, for making helicopter rotor blade spars, the process places structural filaments around the periphery of a tool and in the process encapsulates the attach points in the product with the load bearing filamental reinforcements. Figure 6 illustrates equipment used for making blade spars. Spools of pre-impregnated fiberglass are dispensed from a carousel which reciprocates around end pins in a horizontally slotted tool of the desired shape. In the photograph, the slotted tool has been removed and vertical end posts substituted for machine resting. In actual fabrication, the horizontally slotted tool is not a straight line cavity, therefore the table on which the tool is mounted is programmed to move vertically as the carousel filament feed eye proceeds along the cavity keeping the filament placement position always directly in the cavity. In a helicopter rotor blade, the hub bushing, or attach point, to the helicopter transmission, is placed in the tool before pin winding starts, thus the entire structural load is carried to the hub bushing (pin) by the continuously wound fibers.

As a relatively new process, pin winding is being considered in the automotive industry for those parts requiring integral end attach points, i.e. steering arm support rods, and torque rods of various types. While in the case of small parts, the same winding pattern can be achieved by rotating the part end-over-end while holding the material feed eye static as in conventional filament winding, this advantage is quickly discounted as the parts increase in length. Pin winding, therefore, is seen as a process essential for making large parts, as well as valuable for smaller parts. Irregularly shaped products such as door frames, and conceiveably complete structural frame members, can be made by the pin winding process.

CONCLUSION

The use of plastic materials in automotive cosmetic and secondary structural applications is accepted design and practice. The weight savings, hence energy savings, through these applications is well documented. With new processes such as Rotary Pulforming, Continuous Tubular Winding, and Pin Winding, the auto designer can now provide primary structural components constructed of continuous fiber reinforced composites in his constant quest for improved performance and economy through weight reduction.

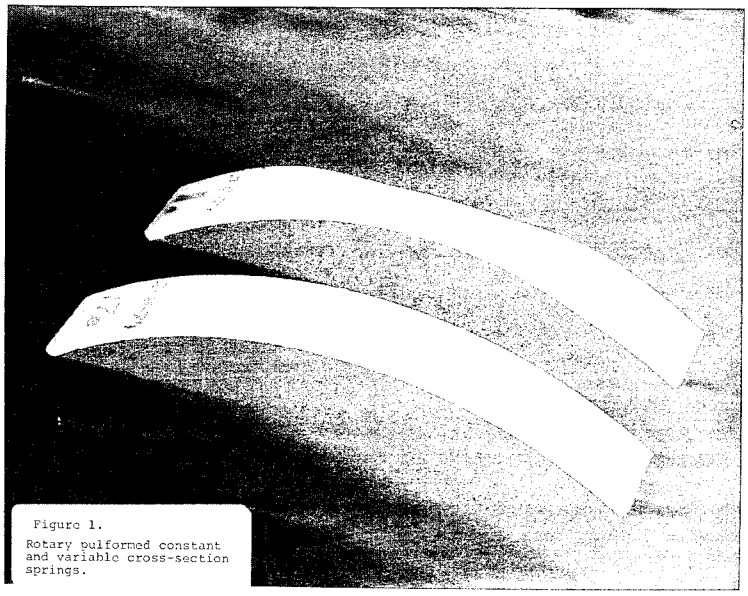

Figure 1.
Rotary pulformed constant and variable cross-section springs.

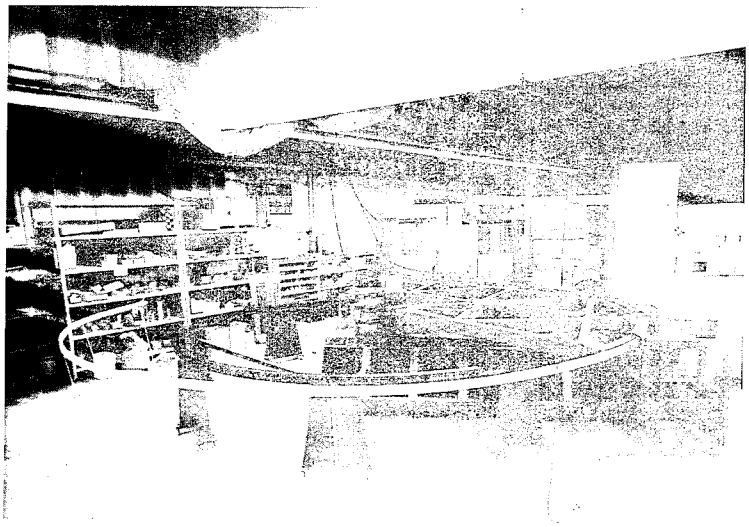

Figure 2.
Rotary pulformer prototype machine.

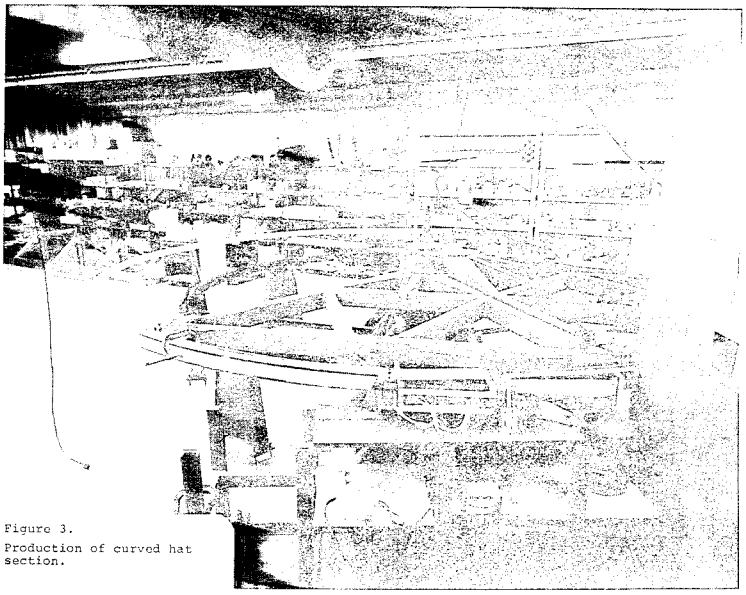

Figure 3.
Production of curved hat section.

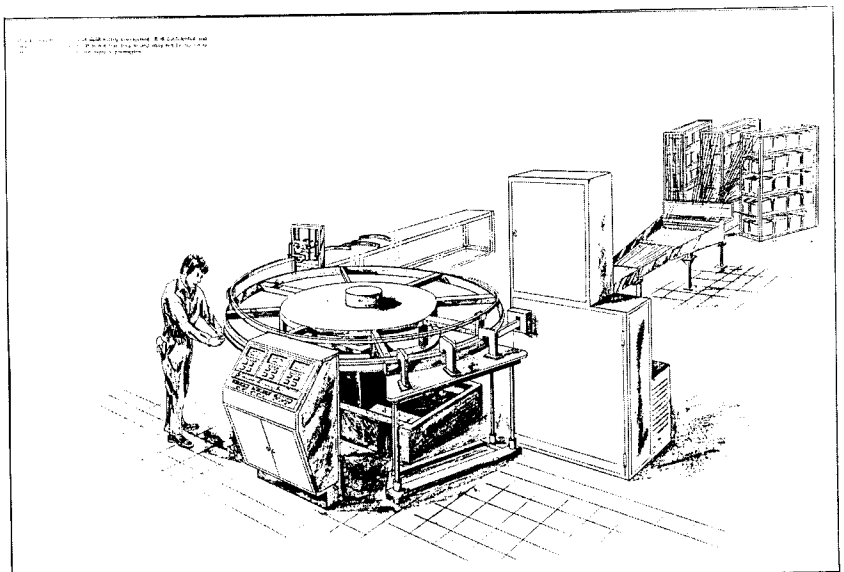

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Figure 4.
Artist's concept of production rotary pulformer.

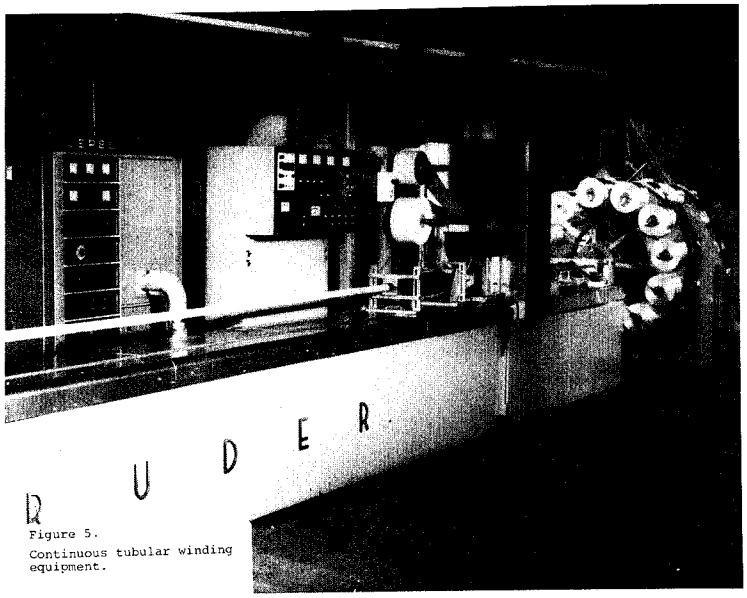

Figure 5.
Continuous tubular winding equipment.

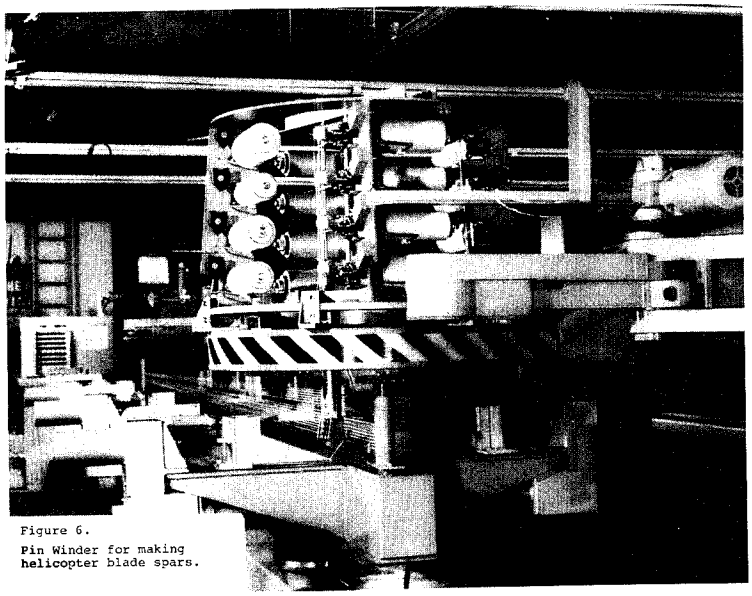

Figure 6.
Pin Winder for making helicopter blade spars.

SANDWICH IN AUTO BODIES—FANTASY OR REALITY?

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INTRODUCTION

Sandwich structures have been used in a great many applications in the past twenty years. They range from a few rather costly parts in aircraft, beginning just after the end of World War II, continued into a period of rapidly increasing usage in the 1960's, on up to the present time, when we see such structures appearing quite commonly in commercial and residential buildings, all sorts of moving vehicles, sports equipment, and so many others that a listing of all of them has become impractical. Indeed, one of the significant areas of application for sandwich structures which has become quite noticeable by it's absence, is that of production trucks and automobiles. Some typical applications in other industries are shown in Fig. 1, 2 & 3. Each of these examples, from the commercial aircraft of Fig. 1 to the Navy ship interiors of Fig. 3, has been turned out in large volume and is regarded as a quite normal production method for such items. It is the intent of this paper to probe the situation outlined above, and to attempt to assess the probability and timing of possible future applications of sandwich structures in production auto bodies.

PAST AUTO APPLICATIONS

Before making an attempt to forecast future usage, it might be well to examine in more detail the past instances in which sandwich structures have been used on projects of an experimental or special purpose nature. An excellent example is the Ford J-car. This vehicle, designed nearly twenty years ago, employed a structure in which the entire basic frame and body shell was made of an aluminum core, aluminum skin sandwich. The result was an improvement in torsional stiffness and a reduction in structural weight overall, when compared to alternate approaches then available. These improvements were quite substantial, and were generally credited with providing a major contribution to the considerable success that this project achieved. The cost to produce the structures was rather high, though, and no groundswell of general acceptance was noted by even the most partisan observer. Even when achieved at high cost, however, winners tend to be remembered, and the existence of sandwich structure as a possibility for automobile bodies was duly noted by many designers in the early 1960's.

A different concept of sandwich proved of interest in the late 1960's. This is the idea of utilizing the structure to fail in a predetermined manner and absorb energy at a specified load when failing. Structures using this novel approach gained considerable respect when the Lunar Landing Module first touched down on the moon with landing gear shock struts using crushable honeycomb instead of the more usual oil-air devices. Although these units were not really sandwich, but merely cartridges contained within a cylinder and compressed by a piston, the material was the very same as that employed extensively as a sandwich core in many currently used aircraft structures. The next step in auto bodies was to use this material as a panel in which it was desirable to provide an emergency capability to absorb energy in a thickness direction. Following this train of thought, several of the safety vehicle projects undertaken within the past ten years have employed "crush panels" to limit the loads imposed upon a human skull or kneecap under conditions of catastrophic deceleration. The first round of designs tended to neglect the potential of the core material for adding to the basic bending or column strength of the structure, and merely included a slab of it within a structure already completely capable of carrying the primary loads involved. However, it is obvious that the primary loads are rather high, and it seems a pity not to use the energy absorbing material to help carry them while it is waiting around for an impact to attenuate. The side door and instrument panel design of the Calspan-Chrysler RSV are a good case in point. Although the honeycomb used was quite successful in enabling the vehicle to protect occupants from impacts of upwards of 40 mph in both front and side, it was not used at all in it's potential as a door beam or a frame stiffening member, which the judicious choice of skins and the addition of an adhesive bond line would have provided. To word it another way, this design of an impact-resistant door assembly is about two pounds heavier than it would be if the bond lines were included and the then-redundant door beam discarded. With the recently mandated emphasis on reducing the weight of all production vehicles, it is certain that careful consideration of this sort of choice will someday soon become commonplace in every design group, whether experimental or production.

The applications described above have also been applied to some of the newer racing cars. An outstanding example is the Cicale Champion 2-Liter CanAm racer shown in Fig. 4. It uses an aluminum honeycomb sandwich 3 inches thick and nearly 4 feet long as a crush pad on the outside of the fuel tank area on each side of the Formula-2 chassis, as shown in Fig. 5. This surface also forms the inside of the air duct which runs along either side of the body from front to back, allowing the car to be operated as a ground effect vehicle. The honeycomb core, even though it is only a 1 pcf density, 5052 material, still provides sufficient beam strength when bonded to two .062 inch-thick aluminum alloy skins, that a substantial degree and amount of protection is given to both the fuel tanks and the driver. This protection has been demonstrated twice, the hard way. On one occasion, the car sustained a guard-rail collision at about 155 mph, and on the other it slammed into a concrete wall (sideways) at approximately 145 mph. In both incidents the fuel cells behind the panels remained undamaged and without leaks, and, although major repairs had to be made to chassis and body components, no debris whatever was scattered on the track. Also, in both incidents the driver suffered no injury whatever.

THE CHOICES AVAILABLE

In order to understand just how the successful applications now in the record might be translated to possible production, let us examine the available materials and surrounding circumstances which might affect such a translation.

The materials available for sandwich skins substantially improved from those available only ten years ago. It is now common to design with S-Glass, Graphite fiber, Kevlar and Boron filament, in addition to the more common E-Glass, Aluminum alloy and steel with which most sandwich designers are familiar. The improvements available are of the order of 100% on an equal thickness basis, and up to 900% on an equal weight basis. Naturally these improvements cannot be gained by a simple

substitution, a short cut which has led to many disappointments in past attempts to use the new materials, but there are now enough working examples to lend real credibility to such claims.

There are also several new core materials available. They include Aramid paper honeycomb and bias-weave glass fabric reinforced honeycomb, as well as some of the newer formulations of foamed plastics, such as the rigid PVC foams. However, there is a high probability that most of the structural jobs to be performed in the field of Automobile bodies can be handled by the older (and much lower priced) core materials such as Aluminum and Paper Honeycombs, end-grain Balsa wood or Polyurethane Foam. All of these are available from several suppliers at a cost ranging down to as little as $5 per cubic foot, or two or three tenths of a cent per cubic inch. They are all surprisingly close in relative strength at equal weight, as shown in Fig. 6. The real difference shows up in the suitability of each for specific applications. For example, the core for use in a side-impact crushable door beam must crush in direct contact with a human body, which limits the maximum compressive strength to perhaps 25 psi. This figure excludes Balsa, since the material is not available in low enough densities. Another peculiarity of most cores is that the modest-cost cores are found in only a portion of the available spectrum of densities. For example, Aluminum honeycombs are available at rather surprisingly low cost in the density range of 0.8 pcf up to about 4.0 pcf, while at densities of over 8.0 pcf the price is many times higher. Balsa cores, however, are about the same cost for most of the available range of density, except that a premium is charged for selecting any tightly specified uniform density. Each core material family has it's own set of limitations, and these limitations must be understood by anyone expecting to design with the material.

Adhesives and resins have also improved substantially in the past twenty years. The strengths have topped out at around 5000 psi or higher, but improvements in toughness, reductions in cure time requirements and broader tolerance of processing variables have made the whole idea of using a bonded structure in an auto body a lot more acceptable.

THE FUTURE

It appears that there are two obvious types of structure which will soon be included in a production body. The first will no doubt be a direct descendant of the energy-absorption, or "crush", applications typified by the RSV door or instrument panel honeycomb padding, but will also include the advances demonstrated by the Cicale Champion side impact protection panels. The dramatic enhancement to impact safety offered to occupants by this relatively low-cost structural modification will probably show up in a lot of race cars in the next year or two, and in at least one or two production vehicles within four to six years.

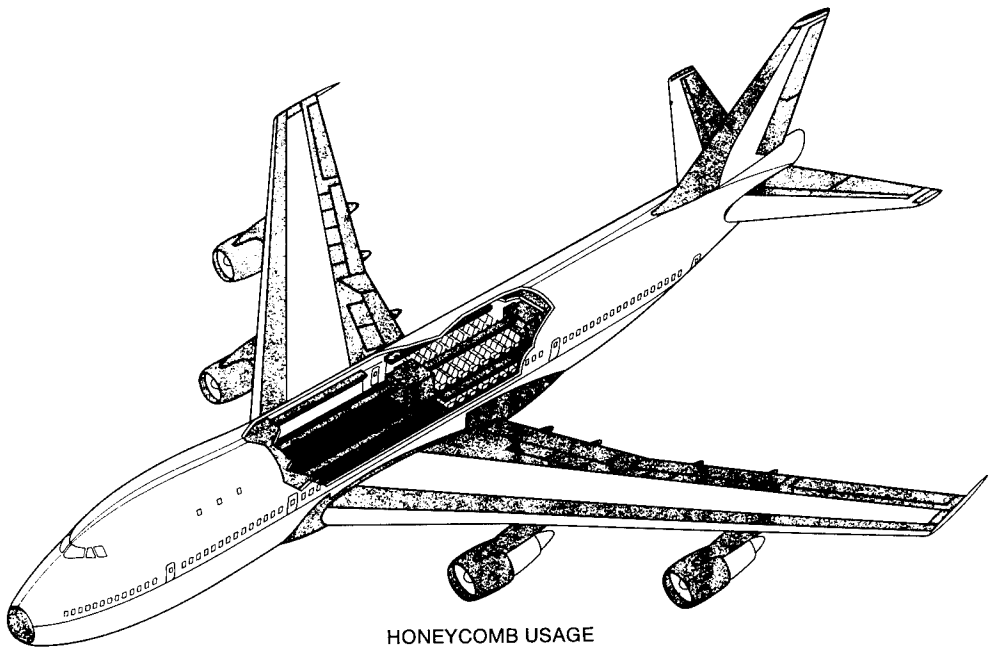
The second likely candidate part is a Station Wagon roof panel. The inherent large size of these parts makes them an annual target for any weight saving effort, and some specific parts, such as the one on the current Pontiac Grand Le Mans, already have nearly all the basic ingredients. The part referred to has a steel outer skin, a Foam core about 5/8 inch thick, and an inner skin of soft fabric already bonded to the core. Because of the soft materials and the missing bond to the outer skin, no sandwich structure exists. However, with a change to a rigid foam or honeycomb of the proper density, and a switch from fuzzy cotton to a little less fuzzy Kevlar fabric of the same weight, along with the addition of a bond line between the core and the outer shell, the same structural performance could probably be achieved with less than half the weight of steel now in the part. This change will probably show up just as soon as the struggle for weight saving heats up to the next level, say in about two years for the designers, or about five years in the showroom.

CONCLUSION

In summary, we can expect to see the first sandwich parts in auto bodies in from four to seven years. They will be either in the form of the lightest weight version of a required structure, or simply a result of internal effort to save weight in present structure. In any case, additional motivation will be needed on the part of the manufacturers before such a change is made. The costs will be either slightly or substantially higher than that of presently used equivalent parts, and a little more time will pass before we see the results. In the view of history, though, we're getting rather close!

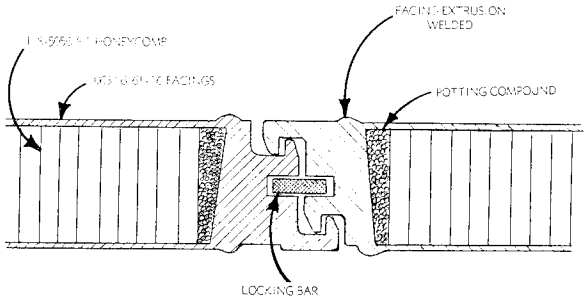
ACKNOWLEDGEMENTS

The author wishes to acknowledge the assistance of Cicale Champion Racing and the Hexcel Corporation for information and illustrations used in preparation of this paper.



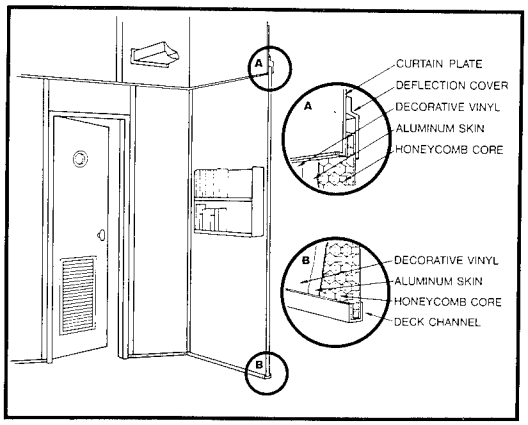
HONEYCOMB USAGE
Boeing 747
All shaded areas make use of honeycomb

Fig. 1



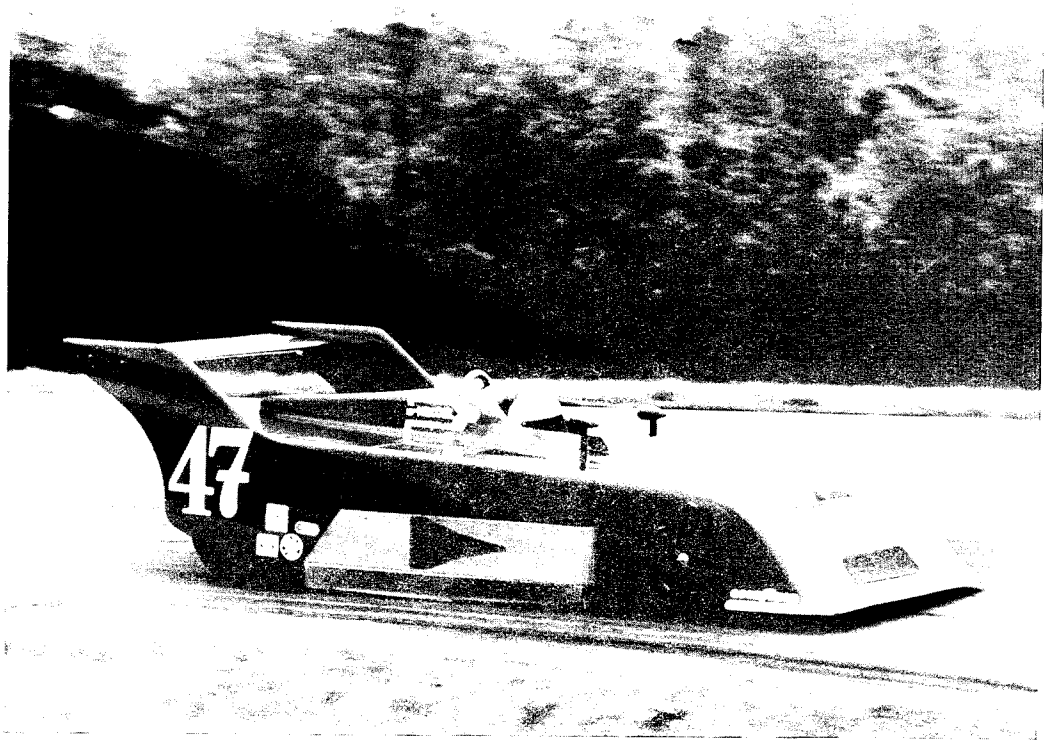
Structure of Relocatable Airfield Surfacing

Fig. 2



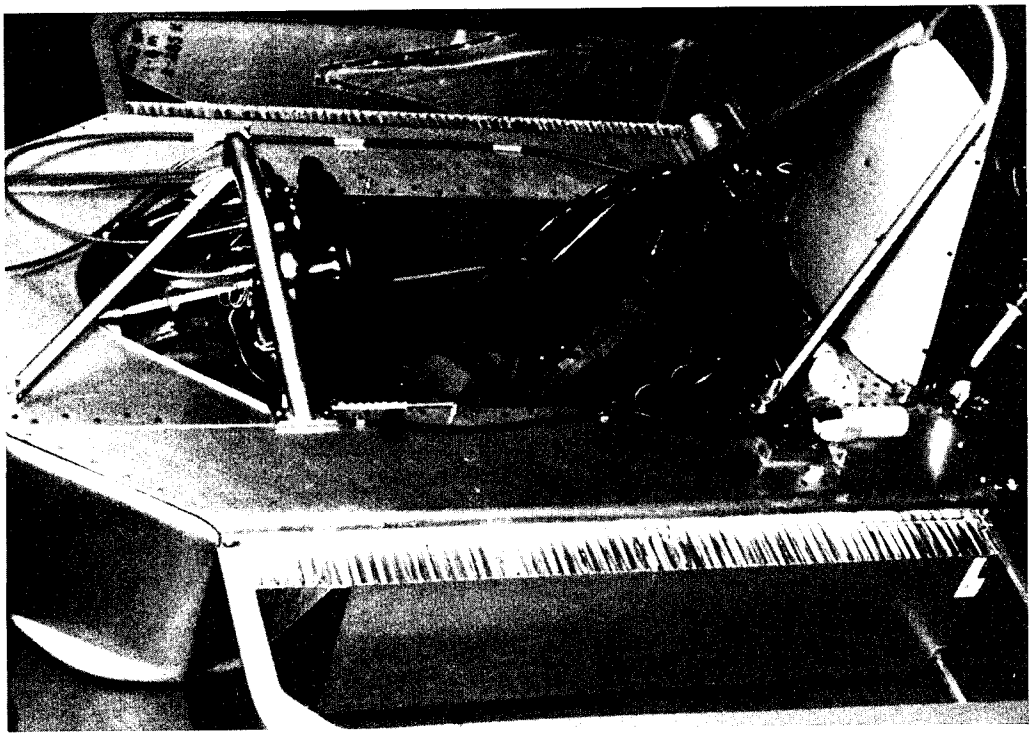
Typical Navy Ship Interior on LHA and DD963

Fig. 3



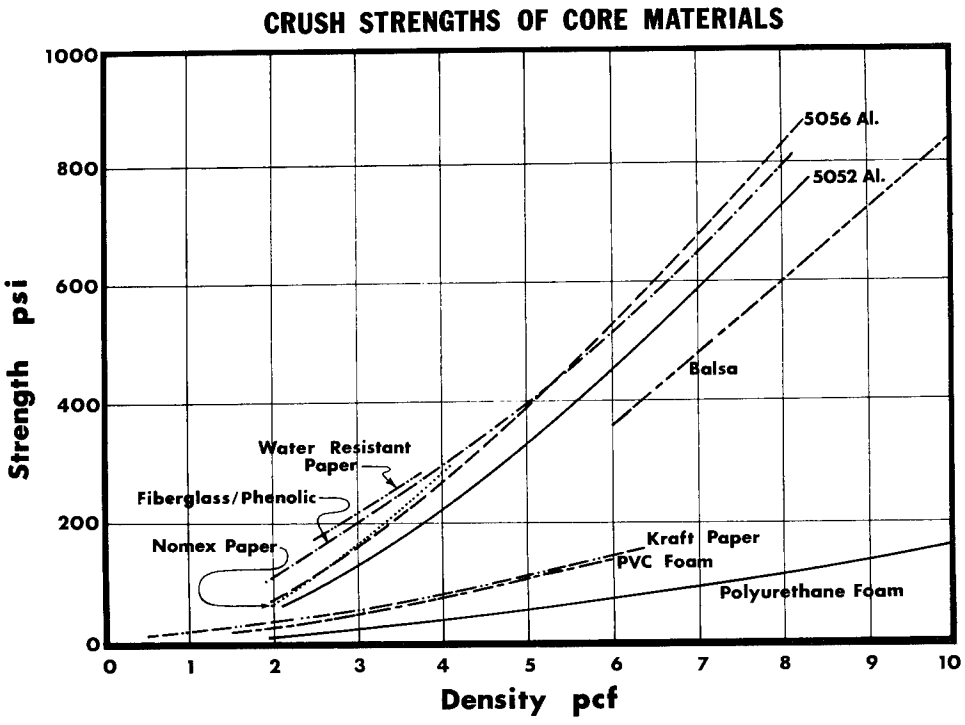
CICALE CHAMPION CANAM RACER

Fig. 4



Side Impact Panels on Cicale Champion Design

Fig. 5



Comparative Crush Properties of Several Core Materials

Fig. 6

CORVETTE APPLICATION OF REINFORCED PLASTIC— A LOOK INTO THE FUTURE

D. R. McLellan

General Motors Corp., Chevrolet Motor Div.

Our quest for lightweight vehicles stems from the need for energy efficiency in transportation vehicles. In many ways the Corvette offers an opportunity to explore and develop new lightweight material applications at, by automotive standards, relatively small production volume.

Currently, reinforced plastics constitute approximately 9% of the curb mass of the Corvette. Looking to the future the total amount of reinforced plastic is not expected to increase, rather it will be distributed more sparingly in current applications and will find application in a number of new areas.

The search for new applications must begin with:

1. An understanding of the performance requirements of the application including vehicle dynamics and crashworthiness.
2. Suitable material properties that will make the application of reinforced plastics not only possible but advantageous.

Ultimate success in these applications will require the integration of design and manufacturing concepts such as filament winding, pultrusion, tape laying, etc.

The search for effective production applications of reinforced plastics has already led us to structural bumper parts in the 1980 Corvette, the exploration of a fiberglass leaf spring for the 1981 Corvette and the identification of such parts as radiator support, propshaft and side door intrusion beam as potential candidates for effective material substitution.

GRAPHITE FIBER AND GRAPHITE-GLASS HYBRID COMPOSITES FOR AUTOMOTIVE APPLICATIONS

J. J. Harwood, P. Beardmore, and W. J. Burlant

Materials Sciences Laboratory

Ford Motor Company

Energy conservation and mandated fuel economy standards have markedly intensified and accelerated the development and production of lighter weight, more fuel efficient vehicles. For a given vehicle performance and powertrain efficiency, significant increases in fuel economy can be achieved by decreases in vehicle weight (Fig. 1). Thus, one obvious emphasis is on development and substitution of higher performance, lower weight materials for vehicle application. For the near term (i.e. to about 1985) the automotive industry is banking on developments in high strength steels, aluminum and plastics along with downsizing and increases in powertrain efficiencies to satisfy both legislated fuel economy requirements and consumer wants. Fig. 2 shows one projection for the extent of materials substitution planned to achieve an average vehicle inertial weight of about 3000 lbs by 1985 - about 1000 lb. weight reduction over current models.

However, if we look beyond 1985, it is clear that the weight-reduction potential inherent in other classes of materials offers the opportunity to perhaps achieve further improvements in fuel economy. Our analyses, based upon projections in technological and manufacturing developments, indicate that polymer-fiber composites offer potential as a next-generation class of materials for future vehicle applications. Within this class, graphite fiber systems hold out the potential of dramatic weight saving opportunities - up to 70% weight reduction on a material basis (and a projected possibility of ultimately achieving 35 to 50% reduction in vehicle weight through maximum utilization). This then was one stimulus which led us into what has proven to be an exciting exploration of a new class of materials for advanced vehicle applications.

This paper summarizes our assessment of the role of graphite and graphite-glass hybrid composites for vehicle applications.

GRAPHITE FIBER REINFORCED COMPOSITES

In 1977, Ford announced a program to build a prototype concept car with body, chassis and powertrain components to be made of graphite fiber composites to the maximum extent possible. The all new 1979 Ford was selected as the base for constructing a duplicate 6 passenger car with graphite fiber reinforced components. This project was undertaken to demonstrate the potential of graphite fiber composite technology for making possible a light weight 6 passenger car with good fuel economy, retaining the performance and interior space and comfort of larger vehicles. Specifically, the project was intended to identify:

(1) Concept Feasibility - to demonstrate the possibility of constructing a 6-passenger standard vehicle with the performance and characteristics of a large vehicle, but yet exhibiting the fuel economy of a compact vehicle.

(2) Design and Materials Feasibility - to assimilate the knowledge available and expand our capabilities for design and construction of automotive components and assemblies from graphite fiber composites; to establish in house capability and a cadre of experts to utilize the advanced design methodologies, computer aided design and associated software programs for the design of structural parts in compositie materials; and to explore the potential for major body and frame parts integration.

(3) Major issues - to identify near-term automotive applications based upon known technology, and to identify critical issues related to production feasibility for future vehicles.

This completed experimental vehicle weighed in at 2504 lbs., some 1246 lbs. less than a 1979 production Ford LTD equipped with a 351, 5.0 liter CID engine. The experimental vehicle is powered by a 2.3 liter, four cyclinder engine - our standard powerplant for Ford Pinto and Mercury Bobcat Subcompact cars. With the 2.3 liter engine, a C-3 automatic transmission and 3.45 axle ratio, the fuel economy is projected at 24.7 mpg, approximately 6 mpg (33%) more than the base production car. The projected 0-60 acceleration time is 14.7 seconds, somewhat greater than the baseline vehicle. Virtually all of the body, frame and chassis parts - about 160 parts - are made of graphite fiber reinforced composites. Only the power-train, trim and some chassis components were not converted. Most of these however (e.g. engine, brakes, transmission) were downsized or downgaged for secondary weight reductions.

Some 600 lbs. of graphite composites was used containing about 400 lbs. of graphite fiber. The primary weight saving -- by direct materials substitution -- was 706 lbs; the remaining 540 lbs. reduction was the result of secondary weight reductions. A summary of the weight savings achieved in key components is given in Table I. For the hood, front end, deck lid, bumpers and door, part weight savings ranged from 61-69%, gratifyingly close to our design expectations. For the wheels and miscellaneous brackets, a 45-50% weight reduction was achieved. Because of over-design of the frame (initially conceived for a 3750 lb. vehicle) and fabrication problems with this complex part, it was only 27% lighter than its steel counterpart. If the frame had been designed for the 2500 lb. vehicle weight, we probably would have achieved about a 48% weight reduction.

Some of the key components of the experimental vehicle from the chassis and body areas are highlighted below in Figs. 3 to 12.

Chassis

- The all GrFRP frame (Fig. 3) exceeded the torsion and bending stiffness of the production steel frame.

- The rear suspension arms (Fig. 4) successfully passed all laboratory tests. Aluminum inserts were used at the pivot-points, and the overall weight savings was 42%.

Body

- The body-in-white structure (Fig. 5) was converted to GrFRP with a 253 lb. weight saving. Perhaps more significantly, 83 major steel stampings were integrated into only 10 GrFRP components.

- The hood (Fig. 6) was a 2 piece design, replicating steel and was based on our Granada GrFRP hood experience which passed torsion, bending, slam and dimpling tests. A 32 lb. (66%) weight save was achieved.

- The deck lid design (Fig. 7) based on the hood design, and resulted in a 29 lb. (67%) weight save. Both the hood and decklid were stiffer than the steel counter parts and therefore could be reduced further in weight.

- The four GrFRP doors (Fig. 8) gave a total weight saving of about 85 lbs. The design was based on our earlier successful GrFRP Granada door installations which passed door sag and dimpling tests. Window frames (thin sections) proved to be difficult areas and much higher modulus graphite tape was required to achieve the desired window frame stiffnesses. A pultruded graphite/fiberglass door guard beam was used in the four doors.

- The 8 GrFRP hinges (Fig. 9) gave an overall weight saving of 9 lbs. All laboratory test requirements for steel hinges were successfully passed. Based upon the success of this experience, fiber glass composite hinges are now being developed.

During this year, the vehicle is scheduled for a series of experimental and development tests. So far, with practically no vehicle development tuning after assembly, the graphite experimental car exhibited an initial ride quality equivalent to production vehicles in the same stage of development.

Future Directions

The graphite fiber experimental car program demonstrated that composite materials technology and design feasibility are sufficiently far along to support the view that vehicle applications justify continued research and development.

One immediate fall out of the program was the decision to proceed with extended vehicle evaluation of a graphite fiber reinforced composite part. About 1000 units of a GrFRP air conditioner compressor bracket for 2.3 engines will be installed on some 1980 production cars (Fig. 10). This we believe is an industry first and will give us some manufacturing know-how and experience in actual on-the-road performance. The part is 1/3 the weight of the malleable iron casting it replaces.

The experience gained in this car program underscored the two key issues which will determine large scale future applications: materials cost and manufacturing feasibility. The fiber industry indicates that the price of graphite fibers will come down dramatically as capacity and markets increase. A price of $6 per pound of fiber in the mid to late 1980's appears to be a reasonable projection. However, on a materials basis, all graphite composites will not approach the more favorable economics of automotive materials such as steel or aluminum. The automotive industry, together with the composites and resin industry, must develop hybrid composites containing graphite, glass and other fibers, to improve the economics of such systems parts. Equally important is the need for low cost manufacturing processes for producing both preforms and components compatible with automotive industry practice. Hand lay up techniques obviously are not economically feasible. High speed manufacturing processes, perhaps involving new resins and processing techniques are required.

The automotive industry needs to have in hand well characterized and tested materials classes, more understanding of performance characteristics in service and failure modes, design methodologies which are compatible with new materials and manufacturing processes, bonding and joining methods, methods of nondestructive evaluation and quality control. Other long range issues relate to the release of graphite fibers in the atmosphere during burning or fragmentation, crash-worthiness and durability of fiber composites and the question of recyclability of graphite composites. All of these issues must be settled before we can move towards large scale production considerations.

In our view, the graphite fiber composite experimental car marks the end of a phase in graphite fiber composite technology - a phase in which conceptual feasibility was the predominant focus. We now face the hard tasks of bringing to reality the potential demontrated to date. Hybridization, formability, and low cost high rate manufacturing processes emerge as the targets for the next round of materials manufacturing R & D programs.

GLASS-GRAPHITE STRUCTURAL PLASTIC HYBRIDS

The incorporation of glass fiber along with the graphite permits significant material cost reduction at a modest weight penalty, compared with the all-graphite systems. However little information existed about the maximum potential weight reduction likely with structural plastic hybrids, and an estimation material and fabrication costs and penalties for a structural plastics vehicle components. The following summarizes the results of such an analysis, sequentially describing the composite systems considered, the design assumptions, fabrication processes and finally the analytic procedure.

Composite Systems

Viable structural systems for production use need to be designed with minimum Gr fiber (because of fiber cost) consistent with the required properties. Thus, hybrid composites (mixed fibers) are the primary composite candidates for structural applications. The Gr fibers are positioned for optimum efficiency (e.g. at the surface), while the remaining fibers would be the less expensive glass fibers. While the GrFRP experimental vehicle utilized epoxy resins as the matrix material for commercial application, unsaturated polyesters (and the closely related vinyl esters) would be matrix systems because of the lower cost and acceptable properties. The specific systems with potential for automotive use which have been incorporated in the analysis are:

- A graphite-glass hybrid with a polyester (or vinyl ester) matrix--this hybrid would be used in the critical structural applications where strength, stiffness and fatigue resistance are paramount. The graphite might be woven cloth, primarily located near the surface for maximum effectiveness. The glass fiber would be used in two forms; as continuous E-glass fiber and chopped fiber. The use of both continuous and chopped forms affords pseudo-isotropic properties in the composite.

- Glass fiber composites consisting of either S-glass or E-glass in continuous form, along with chopped E-glass as filler. Two values are given for the fatigue resistance of glass composites--the generally accepted value of approximately 30-35% of the ultimate tensile strength, designated C (for conservative). However, it may be that the fatigue resistance of glass composites can be increased to as high as 60% of the ultimate tensile strength; these values also are included in the analysis to permit assessment of the weight reduction such a change would afford (designated O for optimistic). The conservative values are the better basis for comparison at the present time.

- Chopped fiber composite of the SMC/HMC type, now either in use for non-critical structural parts or close to commercial use.

Compositions of these materials are shown in Table II while mechanical properties and costs are given in Table III. The cost of the glass/graphite hybrid is projected to be $2/lb, based on long term projected graphite fiber costs ($6/lb) and current prices for glass and polyester resin.

Design and Fabrication Assumption

(a) Design Elements

The application of structural plastics in a new vehicle allows extra freedom of design because of molding flexibility and much part integration--two features that significantly reduce the cost penalties normally associated with high performance composites. Further, based on information collected from the GrFRP experimental vehicle, it is assumed that significant secondary weight savings can be effected in a new vehicle application. Elimination of joints by part integration increases the effective stiffness of the parts. The thicker composite sections, relative to steel, will result in an increase in effective stiffness (over the relatively low material stiffness) by the ratio of the thicknesses of the composite component to that of the steel component. Since the composite vehicle is much lighter, the required vehicle stiffness is reduced by the ratio of the vehicle weights so that the effective stiffness of the composite parts is much greater than the material modulus suggests. For the vehicle analysis described below, it is important to note that the effective stiffness is greater than 80% of the steel.

(b) Fabrication Processes

Costs for fabricating composite components can be approximated based on the material information described above, and incorporating the following processing assumptions.

- A continuous filament SMC or XMC high volume facility is employed capable of supplying the hybrid fiber configuration needed for the preform.

- Labor, press costs and secondary operations are estimated to be about that for current compression molding automotive operations.

- Polyester-based resins, or epoxy modified polyesters with press cycle times of 3 minutes are employed as the matrix.

- Conventional compression molding of the preform is the preferred process.

Annual production volumes, based on the system described in this paper are about 50-60,000 parts from a single press and tool. For low volume applications, tooling and press costs may favor plastics; for higher volumes--upwards of a hundred thousand--the multiple tooling presses needed often swing the economics toward a metal component.

The advantages of part integration compared to part substitution, include reduced manufacturing costs, need for fewer tools and reduced labor content for the finished assembly. Potential part integration economies are suggested from the experiences noted in the GrFRP experimental vehicle:

Part	Body Side Outer *	Body Side Inner *	Floor	Frame
No. of steel parts	16	12	8	30
No. of composite parts	1	1	1	7

* 2 per vehicle

Variable costs for such large parts show that the cost penalities normally associated with composite usage are significantly reduced for this class of applications. Optimum usage of structural plastics obviously would be in an all composite vehicle, where even more complete part integration may be utilized. One of the issues which obviously must be addressed will be repair techniques and costs.

Vehicle Component Analysis

The analysis assumes that the steel structures of a typical 3000 lb vehicle are replaced with "equivalent" composites of the same dimensions, of thickness calculated to meet the performance requirements. The analysis logic consists of forced ranking each component for the importance of 5 different functional requirements (durability, crash, noise vibration and harshness, towing/jacking, and oil canning); ranking is based on engineering judgement. The most critical function of the design interior determines the percentage weight reduction. If stiffness or rigidity are the critical parameters the weight reduction opportunity is significantly reduced. The maximum weight reduction and associated materials cost penalty can then be calculated. The logic and component design requirements have been reduced to a computer program where input of the materials properties allow overall projections for different assumptions.

The analysis concluded that: -

- Major vehicle weight savings should be achievable with comprehensive use of hybrid composites. Where maximum part stiffness is needed, a maximum potential weight savings of 26% should be attainable, at a material cost penalty of the order or less than sheet Al. The weight reduction compares to approximately 33% for the all GrFRP vehicle.

- The potential weight savings using hybrid composites is greater than that attainable using high strength steels or Al.

CONCLUSIONS

From both a weight reduction and cost effectiveness viewpoint, structural plastics (hybrid composites) represent an attractive materials system for the longer term. Compared to steel, these materials offer the opportunity, perhaps at acceptable cost penalty, to maintain vehicle size at significant reduced weight:

In particular: -

- Structural hybrid composites for the long term offer significant weight reduction opportunities—up to 24% compared to their steel counterpart on a vehicle basis. For specific parts, weight savings can be as high as 60-70%.

- Technological developments are within reach to suggest large scale manufacturing feasibility for hybrid composites. Manufacturing composite preforms and fabrication of components appear to be the key issues and require the main developmental emphasis.

- Cost-weight analyses, together with the technological developments, lead us to view hybrid composites as potential production systems in the late 1980's/1990 vehicle era. Potential vehicle use within this decade should provide major incentives for both the automotive and chemical/plastics industries to develop the manufacturing systems required for this major market opportunity.

BIOGRAPHY

Julius J. Harwood is Director-Materials Sciences, Engineering and Research Staff, Ford Motor Company, Dearborn, Michigan. Prior to April, 1975 when he assumed his present position, he was Director-Physical Sciences (1974-1975), Manager-Research Planning (1972-1972), Assistant Director-Materials Sciences (1969-1972), and Manager of the Metallurgy Department (1960-1969) with the Ford Research Laboratories. Before joining Ford in 1960, he was associated with the Office of Naval Research as Head of its Metallurgy Branch (1946-1960). Prior to leaving ONR for Ford, he was on special assignment to the Advanced Research Projects Agency (DOD) to help formulate and establish the ARPA Interdisciplinary Materials Sciences University Laboratory Program.

Mr. Harwood is well known and active in professional activities. He is a Fellow of the American Society for Metals and a Fellow of the Metallurgical Society of AIME. He served as President of the Metallurgical Society for 1973-1974 and is a past Chairman of the Institute of Metals Division of the Society. He was President of the American Institute of Mining, Metallurgical, and Petroleum Engineers in 1976, and a member of the Board of Directors of AIME from 1974-1977. He is a past chairman of Gordon Research Conference on Corrosion and a past chairman of the Corrosion Research Council of the Engineering Foundation. He serves on the Editorial Advisory Board of the Journal of Materials Science and Engineering and of the Series "Treatises on Materials Science and Technology" and on the Governing Board of Acta Metallurgica. He has published over 60 articles in the fields of corrosion, high temperature materials, materials resources, new materials development and the management and planning of industrial research. He is the editor of five books on these topics.

Mr. Harwood is a member and was 1976 chairman of the Board of Control of Michigan Technological University. He serves as an Adjunct Professor of the Faculty of Wayne State University and is a chairman of the Board of Visitors to the Engineering College of R.P.I. In the past he has been on Engineering Advisory Committees to the University of Pittsburgh, Carnegie Tech, Vanderbilt, M.I.T. and Pennsylvania.

He is active in various civic, religious, educational and philanthropic organizations in the Detroit area. In 1966 he was a recipient of the Ford Motor Company's Good Citizenship Award for Outstanding Community Service and in 1968 was named Ford Citizen of the Year for his activities.

Mr. Harwood has served on numerous government committees and participated in numerous government studies including COSMAT and the National Commission on Materials Policy. He is a member of the Materials Advisory Committee to the Office of Technology Assessment of the U. S. Congress. He also serves on the Solid State Advisory Committee of the NAS. He is a consultant to the National Science Foundation, a member of the New York Academy of Sciences, Michigan Academy of Sciences, AAAS and RESA-Sigma Xi.

Mr. Harwood was elected a member of the National Academy of Engineering-1977. He is Chairman of the National Materials Advisory Board, one of the major arms of the National Research Council of the National Academies of Science and Engineering.

TABLE I

GrFRP Components Weight Summary

	Wt. in Steel (lb.)	Wt. in Graphite (lb.)	Weight Savings (lb.)
Body-In-White	461.0	208.0	253.0
Frame	282.8	207.2	75.6
Front end	96.0	29.3	66.7
Hood	49.0	16.7	32.3
Deck lid	42.8	13.9	28.9
Bumpers	123.1	44.4	78.8
Wheels	92.0	49.3	42.7
Doors	155.6	61.1	94.5
Miscellaneous (Bracketry, Seat, Frame, etc.)	69.3	35.8	33.5

	Vehicle Weight
Ford LTD 1979	3740
Lightweight Concept Vehicle	2504

TABLE II

COMPOSITION OF MATERIALS

Material	% Continuous Gr	% Continuous GI	% Chopped E Glass	% Polyester Resin
Gr-GI Hybrid	25	38.75 (E)	6.25	30
S Glass Composite	-	57.5 (S)	12.5	30
E Glass Composite	-	57.5 (E)	12.5	30
HMC	-	-	70	30

TABLE III

MATERIAL PROPERTIES

Material	E (psi)	FRAC. (psi)	FAT. (psi)	Cost ($ per lb.)
Gr-GI Hybrid	6.6×10^6	80,000	48,000	2.00*
S-Glass Composite	3.5×10^6	80,000	40,000 (O) 24,000 (C)	1.55
E-Glass Composite	3.1×10^6	50,000	25,000 (O) 15,000 (C)	0.55
HMC	2×10^6	30,000	7,500	0.55

* Based on Gr fiber at $6 per lb.

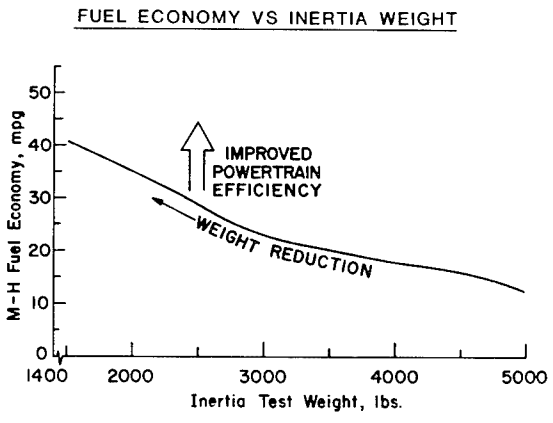


FIG. 1

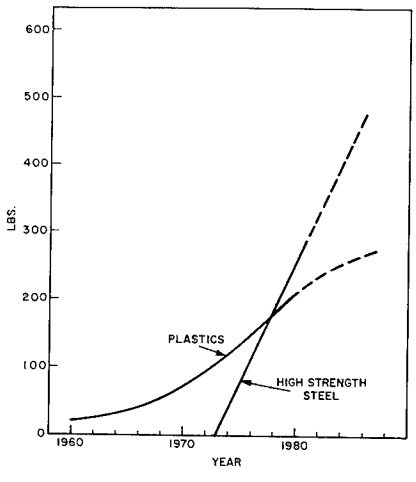


FIG. 2

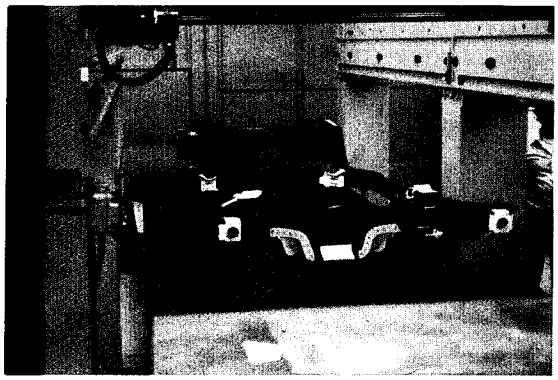
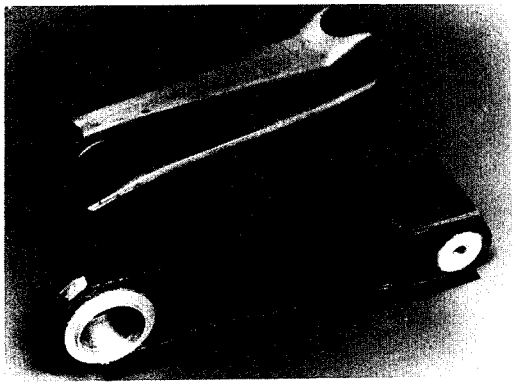


FIG. 3



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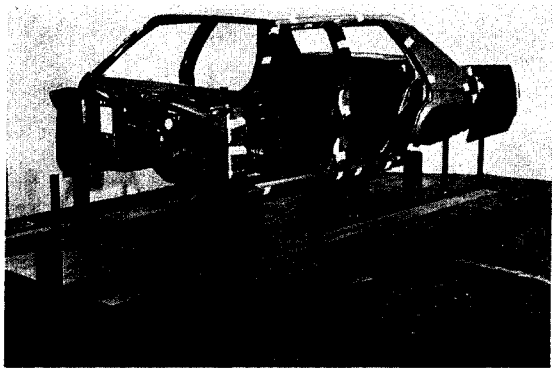

FIG. 5

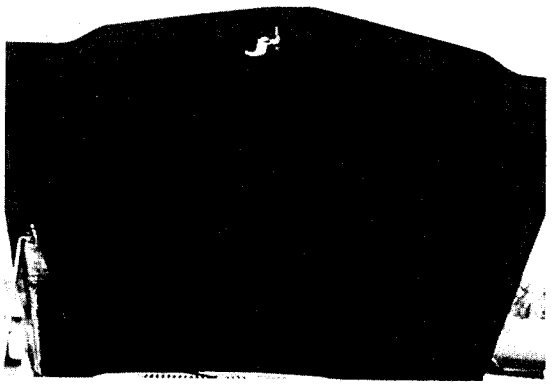

FIG. 6

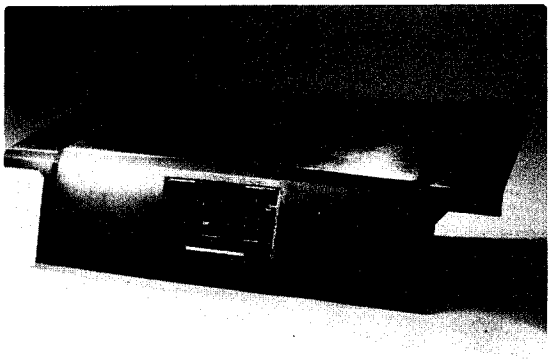

FIG. 7

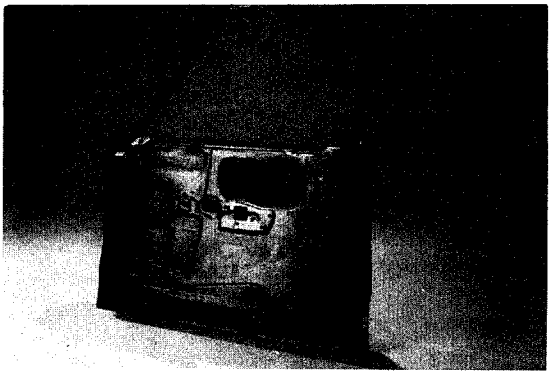

FIG. 8

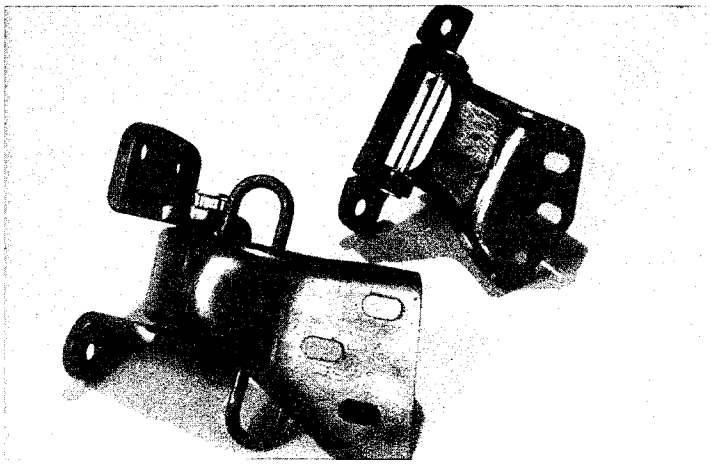

FIG. 9

FIG. 10

A LIGHT-WEIGHT, ENERGY-ABSORBING BUMPER SYSTEM UTILIZING CONTINUOUS GLASS FIBER REINFORCED THERMOPLASTICS

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INTRODUCTION

Because of specific functional requirements imposed by NHTSA, further emphasized by imposition of stricter damagability standards (Part 581), several approaches to energy management bumper systems have evolved, each with specific advantages and disadvantages in the area of cost and weight. Essentially, however, these break down into three major categories: hard facebar systems featuring bright plated metal, with or without added reinforcing structural back-up, mounted on hydraulic shock absorbers; hard/soft or "hybrid" systems featuring an elastomer-coated steel facebar mounted on shock absorbers with a soft elastomeric grill fascia; and the all soft systems featuring an energy absorber face in front of the structural member in lieu of shocks, and covered with a RIM fascia and bumper cover.

The objective of this study was to investigate the all soft system because of its potential for maximum weight reduction combined with styling latitude, and to concentrate our effort on the heaviest single part in the system, the bumper back-up plate assembly.

BACKGROUND

Currently, materials of choice for weight savings in production bumper back-up beams in the all soft system are HSLA steels and aluminum. The specific selection of one over the other is contingent upon cost/weight effectivity in a particular vehicle class. An example would be a car line offered in both 4-cylinder and in 6-cylinder engine models where the weight penalty of the heavier engine necessitates the use of aluminum to stay in a specific weight classification in spite of a cost penalty of nearly 60%.(1) Long range projections, however, magnify both the weight penalty of steel and the cost penalty of aluminum. Increasing fuel prices, along with the likelihood of a "gas guzzler" tax for manufacturers not meeting the mandated CAFE schedules, emphasize the need for weight reduction, while a projected shortfall in the world supply of aluminum and its attendent price increases will preclude its use in many applications.

Evaluations of non-metallic composite structures for bumper back up beams are underway with the major auto companies and the supplier industry as a solution to the problems cited above. The primary thrust of these efforts has been the investigation of high-strength, high-modulus glass fiber reinforced thermoset plastics often identified as HMC® and XMC®. Indeed, this type of material system has been selected by Chevrolet for the 1980 model Corvette bumper back-up, the first U.S. produced non-metallic bumper system in a production vehicle.(2) Similar material systems were also used in the successful development program of an FRP beam for the 1979 Ford Mustang, although not incorporated into the production vehicle build because of time constraints. (1)

MATERIAL SELECTION

Because of the apparent initial successes with the high-strength thermoset systems, consideration was given to exploring glass reinforced thermoplastics, where the advantages of higher productivity molding processes and lower specific gravity of the materials could offer significant cost/weight savings. In addition, the use of a resilient matrix resin was expected to overcome the failure mode encountered in many of the thermoset systems, namely shear failure attributable to relatively brittle resin systems.

The molding material selected for this program was PPG Industries' Azdel® sheet, an essentially continuous glass fiber reinforced thermoplastic laminate used for high-speed compression molding. In order to meet the performance requirements of this program, glass fiber content was increased to the 50% level (from 40% in commercial grade Azdel sheet), and minor modification was made to the glass fiber mat geometry. The resin system was polypropylene homopolymer with carbon black content at less than 0.1%. A brief comparison of material properties is shown in Figure 1.

DESIGN CONSIDERATIONS

As a base program, a 3300 lb. weight class vehicle was selected for target application and the system was to meet the Part 581 no damage requirements of NHTSA. The system to be tested was a soft, fixed bumper, of which the main elements were an elastic fascia mounted over a foam absorber and backed up by a fixed, non-stroking beam, as illustrated in Figure 2. The beam was designed as a straight section in plan view, except for a 30° angle at each end. The cross-section was an open C-channel, closed off by an aluminum back plate to form a box section. The face of the beam was tapered in thickness from 0.40" on center to 0.25" on the ends. Sidewalls were 0.25" thickness. The foam and fascia were chosen as simple lightweight components, and were merely taped to the face of the beam for convenience of testing. Design parameters, based on the test vehicle selected (a 1977 Ford Mustang) are shown in Figure 3.

MOLDING PROCESS

The Azdel® sheet molding process is similar, in many respects, to SMC molding, but for one major reversal: the mold is at room temperature and the material is at an elevated temperature of approximately 400°F after preheat in an infrared oven. Mold designs are essentially the same, with one cored for cooling water to remove heat from the thermoplastic material, while the other is cored for hot oil or steam to effect the cure of the thermoset system. Material charge patterns are also similar. Significant differences do occur in the molding cycle time, however, with typical dwell time under pressure running 10-20 seconds, depending on the part thickness. The result is a net productivity per cavity of about 3:1 over the thermoset system.

FABRICATION

The beam assemblies illustrated in Figure 1 were fabricated initially using hollow aluminum rivets. Mounting to the vehicle was accomplished by bolting through the aluminum backing plate into spacer brackets, which were attached to the frame rails to take up the space created by removal of the shock absorbers.

Weight of the molded C-section beams was 9.25 lbs. each. The aluminum backing plates (.152") weighed 4.25 lbs. for a base weight total of 13.5 lbs. Because of shear failure of the hollow aluminum rivets in the first beam, steel nuts and bolts were added to the remaining beams, resulting in a fastener weight total of 1.5 lbs., bringing the total assembly weight to 15.0 lbs.

VEHICLE IMPACT TESTING

An FMVSS pendulum impact test was used for evaluation of the bumper system to develop performance data at various speeds and foam thicknesses. Pendulum impacts were conducted at center line (high and low), over the rails and on the corners (30°). Speeds were increased from 3.0 mph to 4.0 mph, 5.0 mph and 5.2 mph, except for corner impacts, which were run at 2.5 mph and 3.2 mph. In each test, measurements of foam compression, beam deflection and peak force were recorded.

Results of impact testing on the beam assembly described above indicate performance levels well within the acceptable limits of FMVSS requirements. Peak force at 5.2 mph on the center line impact was 16,700 lbs. with foam compression of 2.4 inches and beam deflection of only 0.4 inch. Figure 4 summarizes test results on this beam assembly.

Modifications of the assembly referenced above were also tested, with varying degrees of success. Most promising of these was elimination of the aluminum backing plate through substitution of a plate fabricated from one of the molded C-channels. (See Figure 5.) As such, the back-up plate was grossly over-designed at the nominal part thickness of the original C-channel, but did serve to demonstrate the potential for further weight reduction through design of an 'all-Azdel' beam. This assembly weighed only 14 lbs. and met 5.0 mph impacts before cracking at 5.2 mph, although beam deflection still did not exceed 0.4 inch.

In addition, the crack occurred at one of the bolt holes which was subjected to greater stress concentration because fewer fasteners were used. (The other beams had the hollow aluminum rivets of the original fabrication scheme in addition to the bolts.)

CONCLUSIONS

This preliminary study demonstrated the feasibility of utilizing 50% continuous glass fiber reinforced polypropylene for molded, light-weight bumper back-up beams. The performance and weight saving potential can be optimized by development of an 'all-Azdel' beam assembled with ultrasonic or vibration welding techniques. (Hot plate or "fusion" bonding is also a consideration.) Elimination of mechanical fasteners would reduce system weight by 1.5 lbs. and eliminate stress concentrations at the fastener holes. (All the failures encountered started at fastener holes and were not indicative of material strength per se.) Further weight reduction of 1.9 lbs. is projected by proper design of the molded back-up plate, and reduction of the over-designed C-channel thickness is projected to eliminate an additional 1.0 lb. Thus, it is projected that the total beam weight can be as low as 10.6 to 11.6 lbs. Phase II of this program, optimization of the weight savings and performance of such a structure, is currently underway and will be concluded in 4th quarter 1979.

ROBERT D. CAMPBELL

Mr. Campbell received his B. A. in Marketing from Michigan State University in 1959 prior to joining Owens-Corning Fiberglas Corporation as a Sales Representative in 1960. In 1970, he joined Windecker Industries, Inc. as Manager, Proprietary Products Division. Mr. Campbell joined PPG Industries, Inc. in 1972 as a Sales Representative for their joint venture with Union Carbide Corporation, G.R.T.L. Company, assuming the title of Sales Manager in 1975. He is currently Manager, Azdel® Market Development, Fiber Glass Division, PPG Industries, Inc.

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(1) HIGH STRENGTH REINFORCED PLASTIC BUMPERS FOR PASSENGER CAR APPLICATIONS
N.A. Hull and D.H. Bergstrom
34th Annual Technical Conference, 1979
Reinforced Plastics/Composites Institute
The Society of the Plastics Industry, Inc.

(2) DEVELOPMENT OF AN FRP BUMPER STRUCTURE
J. Delmastro, D. Landwehr and J. Schejbal
National Technical Conference (NATEC), 1979
Society of Plastics Engineers, Inc.

® PPG Industries, Inc.

CRITICAL MATERIAL PROPERTY COMPARISONS

	ASTM TEST	AZDEL® SHEET 40% Glass	AZDEL® SHEET 50% Glass
Tensile Strength	D638-72	11 KSI	19.2 KSI
Tensile Modulus	-	700 KSI	1000 KSI*
Flexural Strength	D790-71	22 KSI	28.8 KSI
Flexural Modulus	D790-71	800 KSI	1228 KSI
Shear Strength	D-732	8 KSI	9 KSI
Specific Gravity	-	1.19	1.34

*Extrapolated

Figure 1.

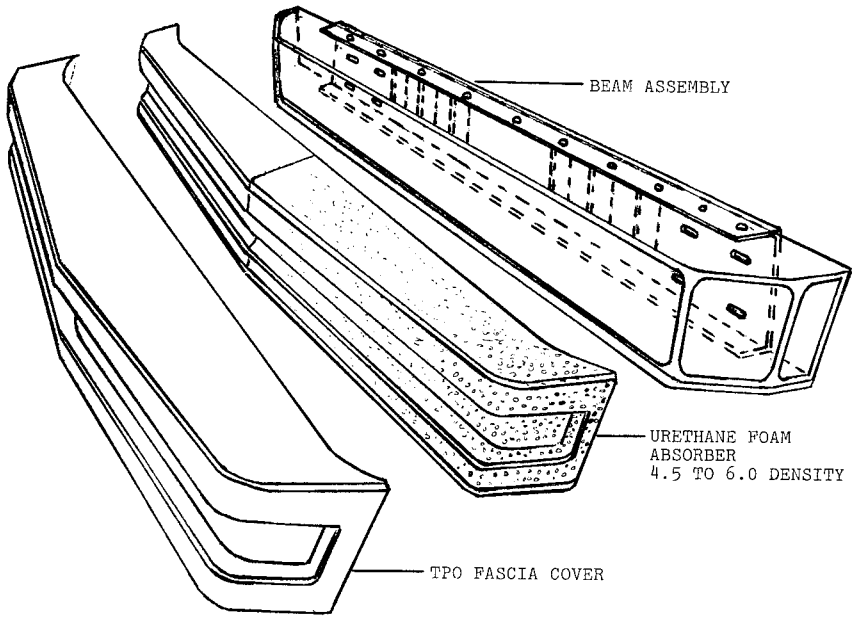

Figure 2.

BUMPER SYSTEM DESIGN PARAMETERS

Vehicle Weight Class:	3,300 lbs.
Vehicle Rail Strength:	8,000 lbs.
Max. Load on Beam C/L:	16,000 lbs./rail
Span Between Rails:	36 inches
Overall Beam Length:	57 inches

Figure 3.

PENDULUM IMPACT TEST SUMMARY

IMPACT	VELOCITY	FOAM DEPTH	FOAM COMPRESSION	BEAM DEFLECTION	PEAK FORCE
#1 On C/L	3.0 mph	3.0"	1.5"	.15"	7,100 lbs.
#2 On C/L	4.0 mph	3.0"	2.0"	.25"	10,000 lbs.
#3 On C/L	5.0 mph	3.0"	2.3"	.40"	16,400 lbs.
#4 Over Rail	4.0 mph	3.0"	1.2"	0	10,800 lbs.
#5 Over Rail	5.0 mph	3.0"	2.2"	0	15,700 lbs.
#6 On C/L	4.0 mph	3.0"	2.2"	.30"	10,300 lbs.
#7 On C/L	5.0 mph	3.0"	2.3"	.40"	15,400 lbs.
#8 On C/L	5.2 mph	3.0"	2.4"	.40"	16,700 lbs.
#9 On Corner	2.5 mph	3.0"	1.0"	0	4,400 lbs.
#10 On Corner	3.2 mph	3.0"	2.5"	0	8,000 lbs.

Figure 4.

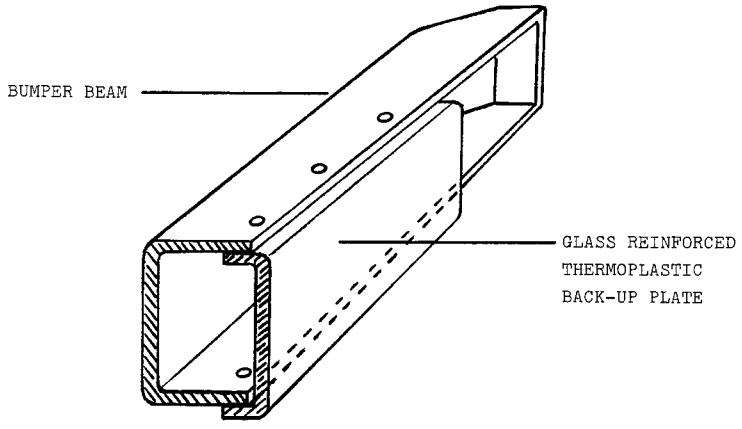

Figure 5.

ALL PLASTIC BUMPER DESIGN USING HIGH IMPACT THERMOPLASTICS

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PLASTICS BUSINESS DIVISION
AUTOMOTIVE POLYMERS CENTER
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INTRODUCTION

As the automobile companies strive to make vehicles lighter to satisfy governmental and consumer demand for greater fuel efficiency, other materials, in addition to steel and aluminum, are being analyzed as bumper candidates in an effort to satisfy this demand. In addition, any bumper manufactured after September 1, 1979, must meet the Federal Motor Vehicle Standard which limits damage (Part 581). The combination of the above requirements, along with the constant drive to reduce cost in any system, make a bumper a very challenging design area.

In the fall of 1978, the General Electric Plastics Business Division undertook the task of developing an all plastic bumper using a high impact polycarbonate (LEXAN EM). The requirements for this bumper were that it must:

1) Meet or exceed the requirements of FMVSS, Part 581.

2) Be lighter than current aluminum bumper systems

3) Be equivalent in cost, if not less expensive, than current aluminum systems.

Due to the fact that polycarbonate is injection molded, a further advantage may be realized. This is the fact that injection molding permits design of a tapered beam as well as increased styling flexibility by allowing the integration of parts, i.e. the end caps and air dam, into the bumper beam.

The damage resistance of any parts combined with the main bumper beam will be correspondingly high.

DESIGN & FABRICATION

The design and testing of this polycarbonate bumper was done in three phases. The first phase involved the actual design analysis and feasibility study, as well as initial testing, of polycarbonate as a bumper. The second and third phases involved further beam and bracket design refinements and testing.

In the initial phase of this bumper study, a tapered beam was designed for a 910 kg vehicle, a Ford Fiesta chosen as a typical vehicle of this size. This beam was to consist of a polycarbonate C-section front face bar, incorporating air dam, rub strips, and end caps, bonded to a rear reinforcement, also a polycarbonate C-section (See Figure 1). Two aluminum brackets, for attachment of the bumper to the carry-over EA's (Energy Absorbers), were also to be bonded to the beam. The initial design analysis for this system is given in the appendix.

To prove out the feasibility of this design, wooden vacuum forming tools were fabricated. Bumper fabrication in this manner does not allow for a controlled taper, but does permit quick, inexpensive tooling and parts. The requirements for this design are a center line thickness of 6.35mm on the face, tapering out to 3.2mm over the frame rails.

The first bumper (bumper A) was fabricated from 9.5mm sheet stock, which upon forming produced a maximum thickness on center of 4.8mm (1.5mm less than design). The brackets were of two-piece fabricated aluminum construction 4mm thick. They were designed to attach directly to the pin supports of the carry-over EA's and provide an extra 75mm clearance to body, which was maintained in all bumper designs for a safety margin (See Figure 2). The adhesive used was a two-part urethane, Goodyear Pliogrip 6011.

Phase II bumper development involved removal of the air dam and bumper guards, fabrication of one-piece aluminum brackets, and overlapping of the rear reinforcement and aluminum brackets (See Figures 3, 4 & 5). Phase III bumper development studied the potential of a fixed bracket design, bracket gauge reduction, and involved bumper tolerance testing (high and low impacts). In both Phase II and III, the wall thickness of both the face bar and rear reinforcement was increased to 6.35$\pm$ 0.5mm on center.

TESTING

The Phase I bumper, when tested at the horizontal and vertical center line, exhibited a 66mm deflection at 8.1 kph with a vehicle mass of 816 kg and a pendulum mass of 960 kg. A small crack (about 50mm long) developed at the base of a high point in the rub strip due to a localized stress concentration. This led to the revision of the rub strip to a uniform height for Phase II testing. Upon corner impact at 4.2 kph, the spot welds on the two-piece corner bracket failed, causing high deflections, but not seriously damaging the bumper. In both types of impacts, corner and center line, the EA units failed to stroke. The only time stroking was observed was on an impact over the frame rail.

Removal of the air dam for Phase II allowed concentration on actual beam behavior. The overlapping of the reinforcement and aluminum bracket smoothed out the section modulus transition in that area of the beam. The vehicles were of equal mass for this testing, 914 kg each, the pendulum being brought to this mass by A and B plane removal. Center line impacting at 8.0 kph produced a deflection of 59.7mm on center. One EA did stroke 8.9mm, which was the only time EA stroking was observed during any phase of center line testing. Corner impacting at 4.8 kph produced a deflection of 38.6mm and EA stroking of 11.7.

In Phase III, on bumpers which had brackets down-gauged from 4.0mm to 2.3mm, the brackets deformed in impacts over the vehicle's frame rails. The vehicle was kept at its normal test mass of 914 kg, but the pendulum mass was increased to 960 kg with the replacement of the A and B planes for tolerance testing. In worst case tolerance testing, a low center line impact exhibited a 77.7mm deflection at the bumper bottom, and a 54.4mm deflection at the top at 8.1 kph. The fixed support bracket in an 8.4 kph center line impact had a deflection of only 36.1mm. The same bumper, upon a 5.1 kph corner impact, deflected 17.8mm.

CONCLUSIONS

The following conclusions may be drawn from the results of this program:

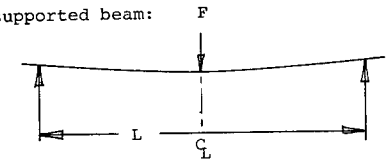
- A high impact polycarbonate system capable of meeting the 1980 FMVSS no damage law is technically feasible. Further development on specific vehicles is recommended.
- Initial weight estimates show a 0.77 kg savings over aluminum for a 910 kg vehicle (See Appendix).
- EA's for polycarbonate bumper system require modification to permit stroking on a center line pendulum impact and reduce the stress level in the beam. Potential for replacement with an alternate device (foam, rubber blocks, etc.) is present.
- Fixed supports as are currently used on most U.S. automobiles are recommended over pin supports to aid in deflection reduction.

Initial estimates project a cost savings as well as weight savings for vehicles ranging from 900 kg to 1400 kg.

APPENDIX

DESIGN ANALYSIS

For a simply supported beam:



$$y = \frac{FL^3}{48EI}$$

Where: $L = 100.3cm$
$E = 213 \times 10^3\ N/cm^2$
$I = 325cm^4$

$F_{dyn.} = 2.2$ (F-car) Dynamic Loading Assumption

$F_{car} = 914\ kg = 8.96 \times 10^3 N$

$F_{dyn.} = 2.2\ (8.96 \times 10^3 N) = 19.7 \times 10^3 N$

$$y = \frac{19.7 \times 10^3\ (100.3)^3}{48\ (213 \times 10^3)\ 325} = 5.98cm = 59.8mm$$

BUMPER ASSEMBLY
WEIGHT ANALYSIS

ITEM	CURRENT ALUMINUM	PROPOSED LEXAN	PROPOSED LEXAN (0)/U CURRENT
Face Bar	3.85 kg	1.72 kg	2.13# kg
Reinforcement	0.0 kg	1.09 kg	(1.09) kg
Adhesive	0.0 kg	0.32 kg	(0.32) kg
End Caps	0.41 kg	0.0 kg Integral	0.41 kg
Rub Strip	0.18 kg	0.0 kg Integral	0.18 kg
Brackets & Lamps	1.00 kg	1.54 kg	(0.54) kg
TOTAL	5.44 kg	4.67 kg	0.77 kg

FIGURE 1. PHASE I BUMPER DESIGN

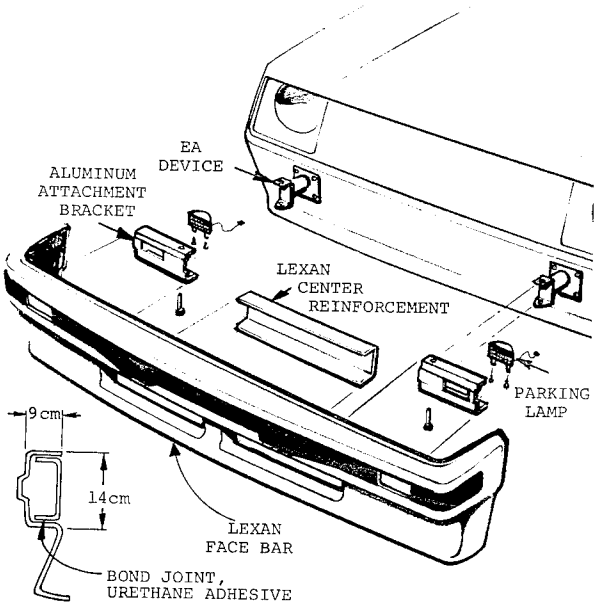
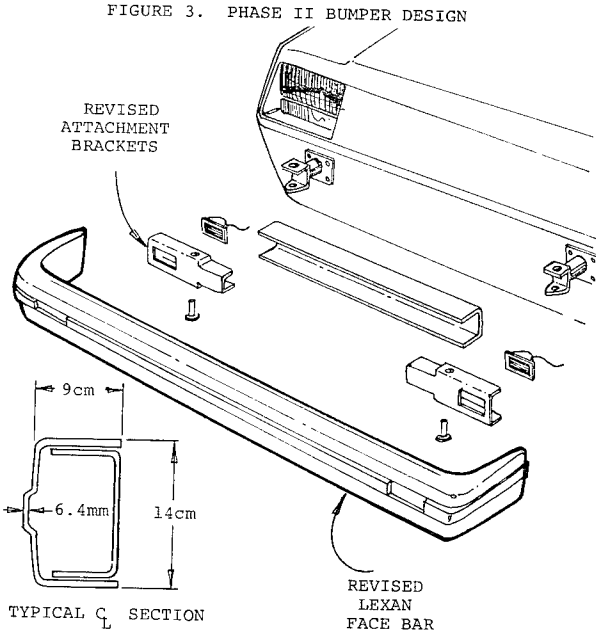


FIGURE 3. PHASE II BUMPER DESIGN



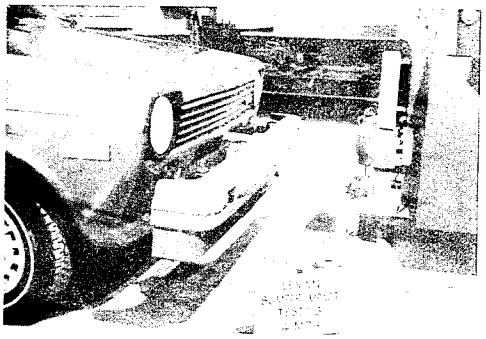


FIGURE 2. PHASE I BUMPER IN TEST POSITION.

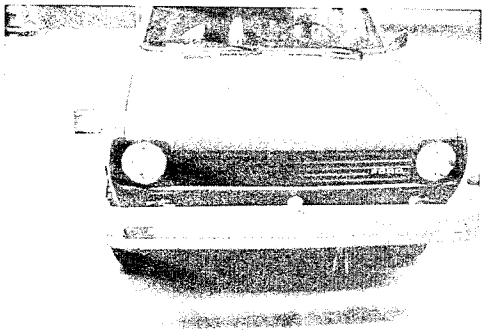


FIGURE 4. PHASE II BUMPER IN TEST POSITION.

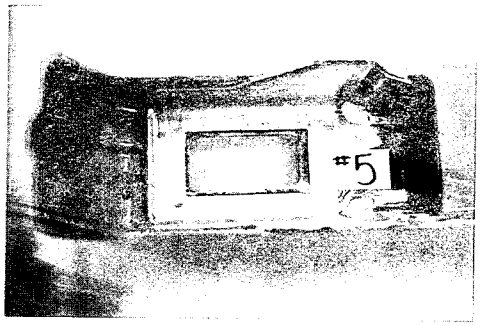


FIGURE 5. OVERLAPPING BRACKET DESIGN
OF PHASE II AND PHASE III BUMPERS.

TESTING AND DESIGN OF FOAM FOR SOFT BUMPER SYSTEMS

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INTRODUCTION

Recent emphasis on reducing low speed impact damage to automobiles has resulted in increased usage of elastomeric materials for exterior body parts and for energy absorbing bumper systems. This paper deals with the testing and application of relatively low density polyurethane foam as the energy absorbing system for automotive bumpers.[1] Details of the pendulum and data acquisition system used to obtain design properties at impact speeds and to run simulated pendulum and barrier impacts on full-scale parts is described.

Certain types of low density polyurethane foams[2,3] exhibit load/deformation characteristics approaching those of the ideal square wave response (maximum area under the load/deflection curve). The stress/strain and specific energy/strain curves characterizing these foams are used to design a bumper for a typical application. Although the properties of the energy absorbing (EA) foam vary with temperature, the impact forces developed over the range of use temperatures may vary only slightly if a proper design scheme is followed.

The steps necessary in finalizing the design for a representative application are reviewed.

LABORATORY EQUIPMENT

Standard material properties tests do not give the type of information necessary to design energy absorbing bumpers for 5 mph impacts. A laboratory test procedure and apparatus were developed to evaluate various foam formulations and to provide the data needed to design foam bumper systems. The apparatus consists of a swinging mass pendulum with adjustable mass and velocity, force and deflection transducers, and a data acquisition system.

The important parameters for each test are input mass and velocity and the output force and deflection. The input mass is determined by direct weighing. The velocity is measured just prior to impact by using a magnetic pickup and a digital oscilloscope to record the time it takes to travel a fixed distance. The slope of the deflection vs. time output curve is an additional check on velocity.

The load cells used to measure the output force are of strain gage type. They were specially designed to minimize the effect of side or off-center loading and to have a very high spring rate for proper dynamic response.

The displacement during impact is measured using a standard linear variable differential transformer (LVDT). A special stroking rod was designed to withstand the repeated impacts. Refinements were required to ensure that the device accurately follows the pendulum mass throughout the entire stroke. The LVDT was attached to this device.

Both the force and deflection transducers are analog devices. To get the data into a processable form, it is converted to digital form with a special high-speed analog to digital (A to D) converter.

The actual impact time is normally less than one-tenth of a second. In order to accurately describe the impact response, we can collect data as fast as 60×10^{-6} seconds per data pair. A data pair consists of a reading of the force and deflection at a given point in time. We continue to monitor the dynamic response of the energy absorber through maximum strain and the return stroke of the pendulum.

The data collection, A to D conversion, and some data processing take place in a mini-computer. We have incorporated smoothing routines to reduce noise in the output data. Figure 1 shows actual output curves. The maximum force and deflection values are also computed in this computer.

The collected data is stored on punched paper or magnetic tape. It is then transferred to a larger computer where all the desired parameters can be calculated. The output is obtained in numerical and/or graphical form.

The parameters studied are force/time, displacement/time, force/displacement, stress/strain, specific energy/strain, energy/strain, energy/volume, efficiency/strain, specific energy/stress, and stress/energy/volume.

IMPACT PROPERTIES OF FOAM

The two most important design relationships for foam are stress/strain and specific energy/strain as shown in Figure 2. Specific Energy (SE) is defined as the energy absorbed (area under the force/deformation curve) per cubic inch of foam. A characteristic of this foam, which makes it well-suited for energy absorption applications, is the shape of the stress/strain curve. The initial rapid rise in stress, followed by a leveling off, approaches that of the ideal square wave curve.

The term "efficiency" is used to compare the load/deflection curve of the foam to a square wave. Efficiency is the ratio of the energy absorbed by the foam, at a given load and deflection, to the energy under a square wave curve at the same load and deflection. Typically, the efficiency of a steel spring is 0.5. The efficiency of EA foam reaches a peak of about 0.8 in the range of 25% strain.

The stress and SE properties increase linearly as foam density increases, at least within the range of 4 to 8 pcf.

Figure 3 illustrates how the stresses vary with density at specific strains. SE also varies linearly with density. Normally, design strains in the range of 25 to 60% are used for most applications. For a given foam density, the stress increases proportionately less with strain, in the 20 to 40% range, than does the SE. Therefore, depending on the design strains selected, some manipulation of the balance between energy absorbed and forces developed is possible.

The properties of these foams depend upon test speed and temperature.[4] For automotive bumpers, the maximum impact speed is specified at 5 mph; however, after initial contact, the speed decreases to zero at a rate that is dependent upon the properties of the material. For this reason, it is important that the properties be determined under conditions simulating end use; i.e., a pendulum as opposed to a constant velocity deformation. Compression set measured 30 minutes after impact is typically around 2 to 3%.

With respect to temperature, automotive bumpers are expected to function at temperatures ranging from -20°F to +125°F. The properties, therefore, must be determined at these extremes as well as at normal operating temperatures. Typical SE/strain properties at -20, 65 and 125°F are shown in Figure 4. It is evident that temperature has a significant effect on the foam properties. Considering that the SE requirements remain essentially the same, regardless of temperature, it can be seen that the strains will vary with temperature. The stresses (or forces) corresponding to these different strains, as shown in Figure 5, can be of similar magnitude depending on the strain

selected for room temperature impact. This means the material will deform less at low temperatures and more at high temperatures but the forces will be similar.

ENERGY REQUIREMENTS

DOT's current specifications require both pendulum and barrier tests at 5 mph, and corner pendulum tests at 3 mph. In the 5 mph tests, the energy at impact for both tests is based on the weight of the vehicle; however, the energy to be absorbed by the bumper system in each case is different. The "compliance" of the vehicle is involved in both the barrier and pendulum impacts. Energy transfer is also involved in the pendulum impacts. The total energy to be absorbed at impact is given by:

$$E_K = \frac{Wv^2}{2g} = \frac{Wv^2}{2.495}$$

where

E_K = Kinetic Energy at impact (in-lbs)
W = Vehicle or pendulum weight (lbs)
v = Vehicle or pendulum velocity (mph)

In the barrier test where the vehicle impacts a rigid object, all of the energy must be absorbed by systems within the car. These systems include the bumper, the suspension, engine mounts, body mounts, etc. For the barrier impacts, the bumper system typically is required to absorb about 75% of the impact energy. The remaining 25% (compliance) is absorbed by other systems in the vehicle.

For the pendulum impacts, the pendulum weight is equal to that of the vehicle. The vehicle is at rest, in neutral, and the brakes are off. Some of the energy is absorbed by the compliant parts of the vehicle and the bumper; however, the pendulum is not completely stopped and the vehicle is put into motion, so not all of the energy is absorbed. Typically the energy absorbed by the bumper in a 5 mph pendulum test is half that of a 5 mph barrier test or about 37.5%. The rest of the energy is 1) absorbed by the compliant parts of the vehicle, 2) remains in the pendulum, and 3) is transferred to motion of the vehicle.

There are a variety of approaches and factors to consider in the design of a bumper. From the standpoint of design, the approaches include full face, voided face and spaced blocks as shown in Figure 6. The best design approach will depend on many factors such as curvature or sweep, styling, and cross-section of the bumper, frame rail load limits, car weight, deflection limits, and desired pressure distribution. It is not practical to go into all the details of selecting the proper design here. Therefore, the discussion is limited to a typical design for a bumper with relatively low-sweep or no-sweep. Generally, a full face design will use relatively low density foam because of the large frontal area involved in the barrier impact. Although the low density should be the most beneficial to pedestrians,[5] it may not be satisfactory for the extreme (high and low) pendulum impacts because of the relatively small pendulum contact areas involved. We feel that the voided face design provides a reasonable compromise between the barrier and pendulum impacts with due consideration to pedestrians. The spaced block approach may improve the barrier and pendulum impact compromise where large sweeps are involved, but the benefit to pedestrians is minimized.

To illustrate how the design curves are used to design a bumper, the stress and energy calculations are made for a typical example as follows:

Requirements

Vehicle Weight = W = 3000 lbs
Maximum Frame Rail Loads = F_R = 12,000 lbs/rail

Bumper Size:

Height = h = 6"
Width = w = 60"
Depth = d = 8" max. (includes back-up beam)

Effective Pendulum Size:

h' = 2.5"-5.0" for extreme to midheight hits
w' = 24"

To illustrate the differences between the full face and voided face designs, the calculations for each are included.

Stress Calculations

Term	Full Face	Voided Face
σ_B*	66.7 psi	88.9 psi
σ_{MOP}†	100.0 psi	142.9 psi
σ_{EOP}‡	200.0 psi	200.0 psi

*Maximum Barrier Stress = $2F_R/hw$

†Maximum Midheight Outboard Pendulum Stress = $F_R/h'w'$

‡Maximum Extreme Outboard Pendulum Stress = $F_R/h'w'$

The required density for the barrier impact can be selected from stress/density curves (Figure 5). Some flexibility in design exists at this point in choosing the strain. A 25 to 35% strain for the barrier impact is a reasonable range and establishes the maximum densities. The desired density for the voided face is about 6.6 pcf and for the full face about 5.6 pcf using 30% strain for this example.

Energy Calculations

$$\text{Kinetic Energy} = E = \frac{3000 \times 5^2}{2.49} = 30{,}062 \text{ in-lbs}$$

Energy to be absorbed by the bumper in the barrier tests

$$E_B = 30{,}062 \times 0.75 = 22{,}547 \text{ in-lbs}$$

Energy to be absorbed by the bumper in the pendulum tests

$$E_P = 30{,}062 \times 0.375 = 11{,}274 \text{ in-lbs}$$

Term	Full Face	Voided Face
D_B*	62.6 in-lbs/in^2	83.4 in-lbs/in^2
d_B**	4.2 inch	4.1 inch
W_B†	4.9 lbs	4.7 lbs

*Energy Density for Barrier Impact = E_B/hw

**Bumper Depth for Barrier Impact = D_B/SE‡

†Bumper weight = $hwd/1728 \times pcf$

‡SE is determined from SE/density curves at the previously selected strain for the barrier impact

Similar calculations are made for the extreme and midheight pendulum impacts and the deflections determined to insure that no "A" plane contact exists. For the example, both designs meet allowable maximum loads and deflections, so either one is usable. There are, however, certain advantages for the voided face design. These include slightly less weight, lower pendulum loads and less deflection of the pendulum. Deflection of the pendulum is important from the standpoint of "A" plane contact (3" clearance), bumper sweep and contour, and for fascia or trim allowances. The above calculations assume a flat bumper face (no sweep). As a pendulum impacts a foam bumper with sweep, initial contact occurs only at one end of the pendulum and progressively picks up contact area. This results in a less efficient load/deflection curve depending on the severity of the sweep and consequently more deflection. Therefore, the voided design provides more clearance, not only for possible sweep but other possible allowances.

FINALIZING DESIGN

The above calculations can only be considered approximate, particularly for the pendulum impacts. It is necessary, therefore, to finalize the design with simulated impacts. After a design has been calculated, foam bumper sections of the appropriate density and configuration are prepared from molded blocks. Techniques for machining the foam to any configuration have been developed. The two types of bumper sections that are made are the center and outboard halves of the bumper.

Simulated pendulum and barrier impacts are made with these sections. Initially, only the foam response is studied. The foam is rigidly attached to a fixed barrier. The appropriate pendulum mass is determined to allow the proper compliance. Pendulum impacts are made at high, low, and midheights with a standard DOT impact ridge mounted on the pendulum mass. In the barrier simulations a flat impact face is mounted in place of the DOT head, and the pendulum mass is adjusted.

Additional simulated tests are run to optimize the foam density and geometry. Next, a foam and beam prototype is made and tested. After passing all these tests, the bumper system is ready for the final test--on the actual vehicle.

CONCLUSIONS

A swinging mass pendulum and data acquisition system provide an effective means of obtaining reliable design information for EA foam bumpers. This has been confirmed by subsequent car to barrier and pendulum to car impacts.

EA foam is an efficient energy absorbing material well suited for the 5 mph bumper application and useful over the anticipated range of use temperatures.

EA foam bumpers can be designed using the techniques described to provide lightweight, compact packages. Design approaches can be varied to suit the particular styling requirements.

Simulated full scale testing with shaped blocks is an effective means of demonstrating the design and making final modifications.

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4. "Urethane Energy Absorbers for Automobile Bumper," P. A. Weller, Rubber Chemistry and Technology, September 1973, pp. 843-861.

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FORCE & DISPLACEMENT VS TIME

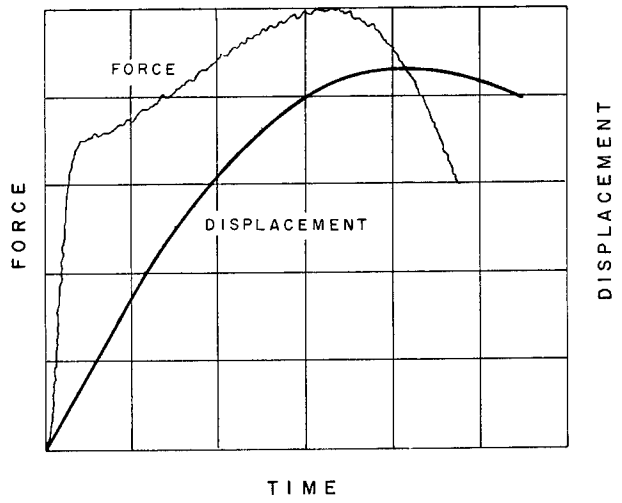

FIGURE 1

STRESS & SPECIFIC ENERGY VS STRAIN

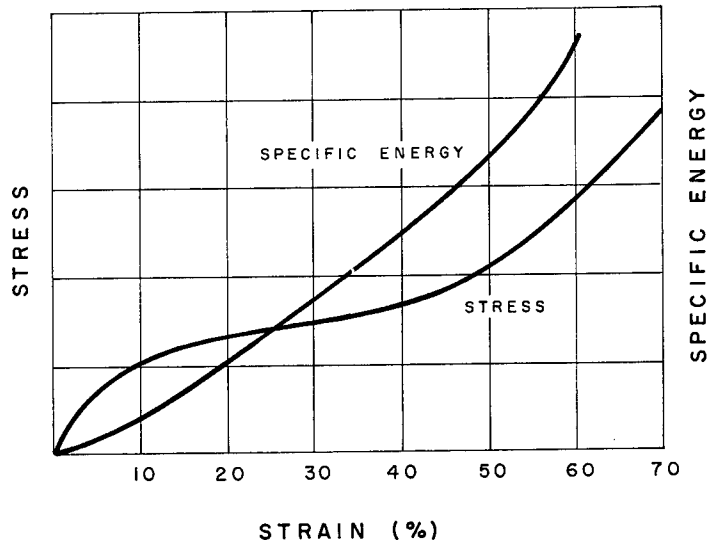

FIGURE 2

EMS DESIGN CURVE

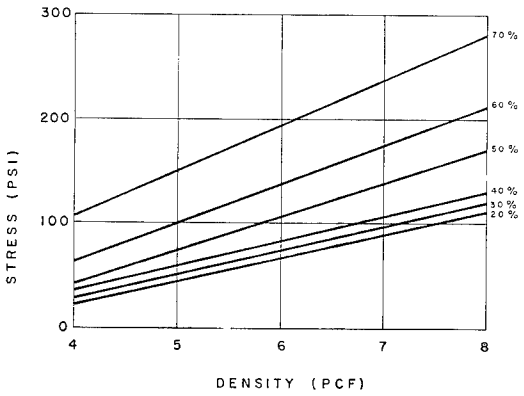

FIGURE 3

STRESS VS STRAIN

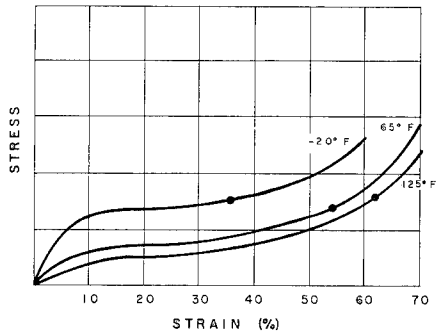

FIGURE 5

SPECIFIC ENERGY VS STRAIN

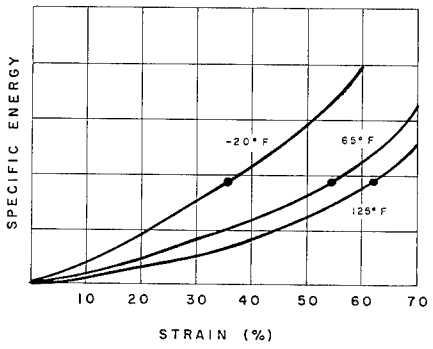

FIGURE 4

TYPICAL FOAM GEOMETRIES

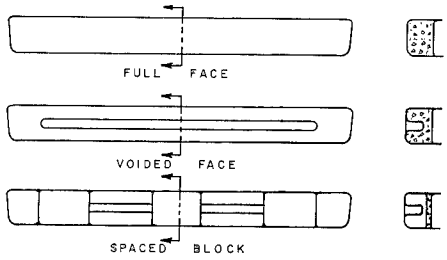

FIGURE 6

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