

METALWORKING PROCESSES  
AND  
EQUIPMENT

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**METALWORKING PROCESSES AND EQUIPMENT**

Prepared by the

**AD HOC COMMITTEE ON METALWORKING PROCESSES AND EQUIPMENT**

**MATERIALS ADVISORY BOARD**

**Division of Engineering - National Research Council**

Publication MAB 206-M (7)

National Academy of Sciences - National Academy of Engineering

Washington, D. C.

September, 1968

**This report is one of a series in a study undertaken by the Materials Advisory Board for the National Academy of Sciences in partial execution of work under Contract No. DA-49-083-OSA-3131 with the Department of Defense.**

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## PREFACE

Traditionally, the metallurgical community has concentrated primarily on developing improved alloys, responsive in some way to user demands, and in the course of such development, hopefully has at least probed the deformation and working characteristics of the more promising prospects, often using these characteristics as criteria or guides for the continuing alloy development. Because of increasingly severe demands for higher strength and higher temperature resistance in alloys for defense and space applications, inevitably--almost by definition--there has been a trend in these high performance, critical alloys toward increased deformation resistance, creating the unfortunate dilemma of forced choice between "weaker" alloys or "more fabricable" alloys. Too often the former has won. Regrettably, albeit realistically, these decisions necessarily were based on conventional, already-available metalworking processes and equipment, with the result that potentially greatly improved alloys were sadly relegated to the shelf as being "unworkable" and inferior (in terms of strength) products substituted therefor.

So it came to pass that, about five years ago, the military services decided to emphasize a converse approach: given the continuing prospect of increasingly difficult-to-work metals—ultra high strength steels, beryllium, superalloys, refractory metals, etc.--what new concepts could be developed or explored, what fresh scientific principles could be applied, what existing but dormant knowledge could be exploited, to create novel and substantially improved metal forming techniques and equipment? Could, more reasonably, the technique be made responsive to the alloy instead of always forcing the alloy to be subject to an existing, perhaps unreasonable technique? It was with these thoughts in mind that the Metalworking Processes and Equipment Program was brought into being. It was considered that the rate of effort, particularly scientific and analytical effort, being applied to process development was not commensurate with that for alloy development; and although progress was certainly being achieved over the decades in deformation techniques and equipment, there had not been, in general, the dramatic and novel advances in this field that had occurred

in materials development. As a further incentive to initiating this pursuit and project, it was evident that there was extant an impressive research program, and indeed body of knowledge, in universities and research laboratories throughout the world, contributing substantially to our understanding of metal deformation mechanisms and processes, as well as many relatively new and sophisticated research tools to apply to such studies. It was not equally clear that this fund of knowledge and capability were being adequately exposed, coordinated or applied, or that there existed a proper forum for integrating the several disciplines necessary for a comprehensive treatment of the subject.

The Materials Advisory Board Committee, whose activities and conclusions are recorded herein, was established to explore the questions and fill in the gaps described above. It did succeed in making visible the many relevant islands of information which existed; it did provide a forum for presentation of many views from many disciplines; it did provide a mechanism for coordinating and integrating many on-going activities; it did effect novel approaches to time-worn problems; it did clarify and define numerous technical issues which had been sensed rather hazily before; it did focus attention on the importance of this topic; and it did stimulate considerable national activity which converged on salient aspects of the problem. Perhaps most importantly, during the years of its existence it provided the necessary and continuing guidance for the generation and execution of a well-conceived, significant, broad-spectrum research and development program with telling results, short range and long range.

This report is more of a coherent, extensive summarization of the committee's activities, with specific conclusions and recommendations rather than a detailed technical recital. The more detailed technical discussions are contained in a series of special reports, progress reports, symposia proceedings, etc., referenced and briefed herein. It is hoped--in fact, with considerable optimism--that these publications, combined with the more personal technical activation

generated by and within the committee during the past five years, will continue to stimulate progress and innovation in this important field, contributing to the development of truly advanced and sophisticated metalworking processes and equipment, already in the realm of anticipation.

N. E. Promisel

Washington, D. C.  
July 1, 1968

## SUMMARY

The products of metalworking\* are so much in evidence everywhere that advancement of the art and technology might be taken for granted. Five years ago, the technical branches of the military services undertook to coordinate their funding support activities to reduce the risk of this assumption and to ensure that planning for military needs requiring advances in metalworking could be met in proper time.

The Materials Advisory Board Committee on Metalworking Processes and Equipment was organized to support this planning. Its membership represented practical and fundamental viewpoints, both mechanics and metallurgy disciplines, and the contrasts among the administrative, production and development attitudes. It provided a wide-ranging, sustained dialogue on the subject area from which emerged a clearer definition of the boundaries between knowledge and ignorance, a clarification of issues and approaches to the solutions of salient problems.

An integral part of the organization was a group representing those in the armed services directly responsible for funding projects. They numbered about as many as the committee itself and they were party to the dialogue, especially when the government interest needed more specific definition. It is presumed that (as with the committee members) their fundamental and engineering grasp of the subject was improved substantially and that their judgment was sharpened accordingly. No reading of the literature could have had comparable impact.

Although the live audience was relatively small and the reports were given limited distribution, the work of the committee became widely known in the technical community. Symposia on metalworking and related subjects are more common today. Members of the committee have been drawn into the organization and programs of most of these.

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\* Herein and hereafter the term "metalworking" is limited to deformation processing and excludes metal removal.

The most tangible product of the committee's activities was a series of carefully selected recommendations for support of research and development. More than 30 of these were outlined. A majority of these have been incorporated into funded programs. In perspective, they demonstrate how a comprehensive program can and must embrace both long and short range and also applied and basic objectives.

It is not possible in this brief summary to give the essence of the committee's recommendations; however, seven examples will be briefly cited to indicate the type and range of topics considered.

1. Recommendations to explore the feasibility of designing forging dies by computer similar to a current program for computer design of tool motions for shaping by machining.
2. Recommendations for improving present capabilities to predict formability limits.
3. Recommendations for extending the applicability of superplasticity to difficult forming operations.
4. Recommendations for an experimental program to evaluate a new type of rolling mill to reduce cost and improve quality of titanium alloy sheet.
5. Recommendations for advancing techniques for calculating temperature profiles during hot working.
6. Recommendations to extend incremental forming to the shape of rib stiffened aircraft wing sections.
7. Recommendations for applying current knowledge of lubrication to special friction problems encountered in metalworking.

The future holds promise of some highly sophisticated and new metalworking processes of which glimpses can be seen even now. They seem a bit incredible because they involve design considerations that are beyond present capability. This is where art must give way to technology. The basic issues have been defined and the shape of the beginning has been characterized by the committee.

## FINAL REPORT

by the  
Materials Advisory Board  
Committee on Metalworking Processes and Equipment

### I. INTRODUCTION

The Materials Advisory Board Committee on Metalworking Processes and Equipment was constituted in September, 1963, based on a request from the Bureau of Naval Weapons to the Department of Defense for the purpose of providing technical guidance to the appropriate government agencies supporting research and development in that area. Its function has been to recommend rather specific programs, which, according to best judgment, are likely to lead to improved manufacturing capabilities with regard to materials presently considered difficult to fabricate and to provide technical support for advanced approaches to manufacturing of the future.

Metalworking processes exploit the plastic deformation capabilities of metals for two major purposes. The obvious one is shape generation. The initial consolidated state is usually of simple geometry and large bulk. A series of evolutions follow, to some intermediate, and ultimately to a final manufactured product which is specific in shape and dimension. Perhaps it is not as obvious, but it is equally important that plastic deformation also assists in developing the mechanical properties necessary for later stages of processing and for final service.

Always lurking in the background is the threat of loss of integrity (i.e., the formation of flaws that lead to fracture). Deformation patterns and extent may be limited by available machine force but more often they are limited by the incidence of flaw formation. Sensitivity to cracking is a highly variable condition, combining inherent attributes of the metal and the circumstances of the deformation operations. Therefore, the value of a new approach to metalworking has to be viewed in terms of dimensional control, resulting properties, and maintenance of integrity.

The problems of metalworking in the manufacturing of military hardware differ only in degree from those associated with consumer products. With military hardware, specification of dimension can be more stringent and performance requirements are certainly more demanding. This usually leads to the use of special alloys. The very attributes that make these special alloys superior in performance can make them difficult to manufacture. The present utilization of these materials has certain cost magnifying attributes:

- (1) A high initial cost in consolidated form.
- (2) Low recoveries in conversion from ingot to a semi-finished or finished part.
- (3) Largely irrecoverable scrap values.
- (4) A purchasing pattern of small orders.
- (5) A changing roster of alloys and composition tolerances.

These features of military materials conspire to make the cost of inefficiency very high. Inefficiency in a series of metalworking operations implies:

- (1) The inability to minimize or eliminate subsequent machining operations to meet final dimensions.
- (2) A high incidence of cracking or flaw formation of various kinds.
- (3) Poor reproducibility of service properties.
- (4) Too many stages in the progress of shape evolution.
- (5) Low output.

Industrial metalworking is largely an art. Engineering plays a role, although minor, and science impinges rarely. In the past, this was probably inescapable because of the embryonic state of technology and the apparent complexity of the problems. Perpetuation of this state of affairs is not really justifiable today. There is engineering and scientific potential not being used. A great gulf exists between plant practice and developments forthcoming from the research centers of the world. Shop people in general do not make use of the technical literature and cannot interpret its substance in terms of their own problems. On the other hand, research and development activities are frequently not pertinent to real needs.

There is potential today for extensive interaction between technology and practice. There are new phenomena in the laboratory world of metalworking which, under ordinary circumstances, would find their way into the industrial world only after many years. There are analytical procedures which properly applied can circumvent the erratic success pattern of planning based on prior art. There are long standing problems which can now be defined in terms that admit of intelligent study.

In recommending the use of R and D funds, there are various, legitimate viewpoints. At one extreme there are the short range problems which are relatively simple and have a high probability of successful solution. At the other extreme are the long range issues which, if neglected, cast the future as little different from the present.

When one examines the ingredients of balanced progress, a kind of pattern emerges; partly as refinements of established procedures and processes; partly as the conversion to established practice that has been coming through some form of technical adolescence; and, partly the shrewd gamble that a concept or unexpected observation contains the seed of genuine innovation. It is in the nature of balance that all of these parts coexist and be regarded as equally necessary. It will be seen that the recommendations of this committee, acting as it did in a relatively uninhibited manner, reflect this kind of spectrum.

Metalworking is an entwinement of shape changes, materials, temperatures, machines, die configurations and lubricants. To attempt to systematize all aspects of all processes for all materials is a task of stupefying complexity--and one likely to become sterile even before completion. In approaching its assignment, the committee decided that there was more profit to be gained by using its judgment to single out the individual issues of particular significance. In singling out main issues and defining them adequately, the nature of objectives also takes shape and discussion is unfettered by preoccupation with a specific material or specific process. Later, when clear conclusions could be reached, it was possible to translate these into the terms of specific problems and, what is more important, into the terms of several specific problems not previously associated.

Over the four-year life of the committee, the random pattern of selection of topics for discussion acquired the appearance of systematic coverage of the metalworking subject. The issue behind one topic showed up to be behind other topics. The recurrence of some of these served to emphasize their importance.

Selection of topics was based on meeting certain criteria. At the outset it had to be clearly germane to some aspect of metal deformation technology or art. The topic should direct recommendations to some tangible objective--such as reducing the incidence of cracking or controlling the pattern of plastic displacement. Finally, there should be some reasonable expectation of arriving at recommendations of either a positive or negative nature.

Topics were examined primarily from the viewpoint of "what is not known". There was no attempt at an exhaustive inventory of present knowledge; among informed people, active in this area, this is redundant. The committee made a practice of inviting specifically knowledgeable guests to its meetings to provide factual technical input, special viewpoints, and to engage them in a kind of objective discussion from which the salient issues emerged.

The discussion of a topic or subject area was terminated by a group decision on whether a constructive recommendation could be made. In the affirmative cases, the recommendations were rendered to a form where the purpose, scope, and sometimes the approach were spelled out in simple terms. A brief background of the reasoning leading to each recommendation was included as an introduction. A large part of this final report is an editorialized rendition of these recommendations and their supporting statements.

## II. COMMITTEE RECOMMENDATIONS

The mission of this committee has been to provide advice on research and development in the field of metalworking. The products of its efforts have been a series of recommendations appearing in a sequence of interim reports. The recommendations have been presented in two parts--a preamble placing the subject in a context of relevance, importance, and technical ramifications; and a description of an appropriate research program or development task. This final report now brings these together to give the whole project a sense of coherency and scope. It also serves to emphasize how some specific limitation in understanding or concept shows up to be the retarding factor of progress on a variety of problems. This is the consequence of approaching related subjects at different points in time.

In the areas of "lubrication" and "rendering to practice", attention to details and the need for special competence dictated the organization of two panels. Their recommendations have been added to those of the main committee.

The recommendations have been taken out of the chronological order of appearance in interim reports, edited and regrouped according to subject relationship.

## A. PLASTICITY AND FRACTURE

### 1. The Function of Continuum Mechanics in the Analysis and Design of Metalworking Processes (June, 1965)\*

The term "continuum mechanics" includes both the analytical and analytical/experimental techniques which permit calculation of overall forces and deformations and those which provide complete point by point solutions to stress, strain, velocity and displacement in plastic flow. The latter methods are complex and the solutions are laborious. The problems to which the complete continuum mechanics approach is applied should therefore be those which cannot be adequately handled by the overall gross approach.

The present analytical and numerical capability is restricted to certain conditions and idealizations. Except for the simplest of axisymmetric problems, complete solutions have been found for plane conditions only. Friction is usually taken in the limits of either perfect sticking or zero coefficient, otherwise the coefficient of friction must be specified, implying reasonable certainty of knowledge. The actual behavior of a material undergoing plastic deformation must approach the perfect plastic or the ideal nonlinear viscous which characterizes true hot working.

Information which may be sought by analytical and numerical techniques falls into three categories:

- (1) Prediction of the magnitude of forces involved in a given metalworking operation.
- (2) Prediction of the probability of cracking in a given operation.
- (3) Prediction of structure and property change as a result of a given shape change.

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\* Dates following titles indicate date of the progress report in which the subject is discussed.

With the assumption of homogeneous deformation, the analysis of force demand as a function of material flow resistance and tool geometry has been conducted for every process of general interest. With large reductions (20%), the calculated forces are in reasonable agreement with measurement. This, however, does not mean that under these circumstances the assumption of homogeneous plastic strain is valid. In the case of lighter reductions, agreement between calculations and measurement is no longer obtained, indicating clearly that inhomogeneity of plastic strain has become substantial. Even in these cases approximate compensating factors are known and can produce adequate calculation accuracy without resorting to the detailed analysis of slip-line field or allied theory. The uncertainty of input data makes further refinement of calculation procedure unlikely to be profitable.

Our ability to predict the properties of a metal which has been subjected to a series of deformation operations is poor. Even crude computations involve the repetitious use of large amounts of experimental data. The simplest problem of calculating ultimate properties in hot working requires intimate knowledge of stress-strain behavior as a function of strain rate, temperature and stress system. Complexing this with the usual metallurgical variables in any real material makes the magnitude of the effort exorbitant except to establish a fundamental principle. In a practical situation, it may be cheaper and faster to run the process on a pilot scale and test the product.

The stress distribution in an idealized deforming body of simple two-dimensional configuration can be described in detail at the instant of cracking by slip-line field theory. Recognizing both the advantages and the limitations of analysis, it seems appropriate to design experiments which would be analytically tractable. This approach would serve a double purpose, testing the validity of slip-line field and related analysis against real operations and illuminating the critical conditions for fracture.

To avoid duplication of current research activities, it is recommended that the proposed experiments consider the various cracking events common in

primary working operations such as open die forging, extrusion and slab rolling.

#### Recommended Task

The objective is to identify the critical conditions for cracking fracture in primary metalworking by the design of experiments amenable to analysis. The design will involve considerations of materials choice, strain rate, temperature and tool/workpiece configurations.

Controlled experiments to produce and identify the conditions of hot cracking should be combined with calculations of stress distributions by slip-line field theory and other techniques of plastic flow analysis toward the following goals:

- (1) Demonstration that a maximum stress or critical combination of stresses either does or does not exist at the observed points of cracking.
- (2) Correlation between fracture criteria and the incidence of cracking in various selected tool/workpiece configurations.
- (3) Exploration of the dependence of stress or combined stress and strain criteria for cracking upon temperature, strain rate and prior deformation history of the material.

## 2. The Application of Crystal Mechanics to Deformation Processing

(June, 1965)

Crystal mechanics is concerned with the mechanisms by which crystalline materials deform plastically. There is an experimental side concerned with observations ranging from slip and twinning displacements to the complexities of defect structures revealed by thin-film transmission electron microscopy. There is also an analytical side which treats the forces related to the movement of dislocations and dislocation assemblies and their interaction with other defect structures. In the search for simplification, much of this work is based on behavior of single crystals.

Deformation of single crystals provides basic information on the mechanisms, modes and crystallography of the unit processes. In recent years, thin-film transmission electron microscopy has been developed as a technique for providing specific information about vacancies, dislocations, stacking faults, and interactions with each other and with structural features such as grain boundaries and finely dispersed phases. Although there has been some criticism that thin-film and single-crystal studies are not representative of bulk behavior, the techniques are unquestionably a powerful tool for linking theory with experiment. Both single-crystal and thin-film studies provide their most useful information in the early stages of deformation. Structures developing after large plastic strains are more difficult to interpret.

Basic data from single crystal studies are most pertinent to the deformation processing of highly anisotropic metals. The study of beryllium is particularly relevant. Single crystals offer a way to study "inherent brittleness", free of complication by unknown grain boundary impurities, indicating whether or not a material is hopelessly brittle. However, the capability of producing a ductile material in polycrystalline form cannot be predicted from such studies. The impediment to slip propagation provided by grain boundaries is an obvious complication. Since in most metals and alloys useful in military hardware fine grain size is desirable, the role of grain boundaries, both chemical and physical, is a major one and in far greater need for understanding than is the behavior of single crystals.

Von Mises (1928) showed mathematically that at least five independent slip systems must be operative in each grain of a polycrystalline aggregate to preserve continuity of strain from grain to grain. This fundamental relationship provides basic limitation to the attainment of extensive plasticity in metals whose crystal structure allows only a limited number of slip systems. In crystal structures with limited slip systems, shear displacements of other origin are necessary. Twinning is the usual source of these shear movements.

In rolling polycrystalline hexagonal close packed metals, the basal slip plane tends to become aligned parallel to the surface of the sheet. Under such circumstances, the limited number of slip systems may be compensated by local twinning. This provides reorientation of part of the crystal so that new basal planes become favorably oriented. Zinc and cadmium twin under compressive stresses, whereas beryllium and magnesium do not. The room temperature workability of the latter two metals is therefore poor.

Preferred orientations or textures are responsible for other effects on mechanical properties. When texturing occurs in sheet, the compressive yield stress in the thickness direction may be higher or lower than the planar yield stress. This has important implications in a wide variety of structural and deformation processing applications, and is frequently of concern in pressure vessels, notched bars, strip rolling, sheet bending, shear spinning and deep drawing.

#### Recommendation

Crystal mechanics, as herein described, interacts with deformation processing by demonstrating fundamental limitations. The weight of effort and support in this area has been very large over the past years. In serving the Government Metalworking Processes and Equipment Program it is the function of the committee to concern itself with phenomena of immediate and direct importance to deformation processing systems. Since it does not appear that the present character of crystal mechanics is applicable, it is recommended that no additional effort be undertaken in this area.

### 3. Mechanisms of Ductile Failure (April, 1967)

The general features of the events leading to failure of a metal object undergoing plastic deformation have been reasonably known for several years. Microvoids are observed to develop during the plastic strain history long before the plastic process is terminated by visible separations (cracks). While integrity is still apparent, and plastic deformation proceeds, these seeds of failure grow in size and frequency, elongate, link up and finally develop an instability that produces failure. The process is, therefore, protracted and concurrent with a large part of the plastic strain history. The term "progressive damage" is meaningful, for if the achievement of intended shape change is reached before apparent failure, the service properties may be impaired. The impairment, however, is recognized only if better service performance is achieved by another shaping route less conducive to the initiation and extension of the failure process.

It is known now, in a general way, that nonmetallic and intermetallic inclusions are favored sites for the genesis of failure nuclei. The process is envisioned as either one of brittle fracture of the nonductile dispersant, or interfacial separation of the inclusion from the plastic metal envelope. Beyond this, very little can be said that is more than generalization in terms of defining relative fracture propensity of various inclusion species and quantitative significance of size, shape and population.

A beginning has been made by treating an idealized model for the growth and ultimate instability of a void population in a plastic medium undergoing deformation. The value of a theoretical model must be judged in terms of its ability to characterize reality, at least in a qualitatively correct fashion. The model and analyses for ductility as presently constituted must be regarded as a prototype forerunner of more advanced analysis. The conditions for solution are sufficiently special so that validating experiments with conventional materials are likely to be inappropriate. It seems necessary to design special experiments, more closely simulative of the model, to test the validity of the model and to justify more sophisticated work.

There are good indications that the genesis of failure voids involves a combination of susceptible sites and tensile stress\* conditioning. From this it becomes evident that early nucleation of voids can be circumvented in metalworking operations by proper choices of tool design, friction conditions and pass sequence, which are conducive to a compressive stress condition in the work zone. Where this is not presently possible, the superposition of an externally applied hydrostatic pressure may prove an ultimate solution. Even if the latter is commercially feasible only in a few circumstances, the use of hydrostatic pressure in metalworking will provide an important reference basis for estimating the magnitude of cumulative damage under present norms.

This work, too, is in its early stages. There are qualitative guideposts yet to be established before large-scale exploitation can be intelligently planned. The local state of strain accumulation, for example, has yet to be included or implicated as part of the failure criterion. While the application of slip field analysis and its revelations of stress distribution in the work zone has been particularly fruitful, a minimum strain energy approach purports to be able to reach similar conclusions on failure initiation. This latter viewpoint has probably not been adequately subjected to experimental verification. In neither case is any physical property of the material other than virgin flow stress involved in analysis.

For the present and near future, progress toward a fundamental understanding of the failure process which limits ductility will be governed by the evolution of fragments which tie together only loosely. Application to practice can be treated only qualitatively. At this point, the committee can draw attention, primarily, to the rather few people engaged with the fundamental aspects of this subject compared, for example, to the scale of activity in brittle fracture which even now persists.

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\* It is not clear whether the hydrostatic tension or the maximum principal tensile component dominates.

#### 4. The Application of Plasticity Theory to Forging Die Design

(September, 1966)

In discussing all manner of metalworking operations, the point has been repeatedly raised that present methods for predicting change of shape are purely empirical when the tools apply only limited restraint to the workpiece. In the most elementary cases of forging rectangular bars with flat-faced tools, it is possible to predict the ratio of longitudinal extension to lateral spread only by semi-empirical means. The design of rolls for round bars, extrusion dies for non-symmetrical shapes and blocker dies for closed die forging are only more complex aspects of the same basic problem. The importance of the problem cannot be underestimated. Implicit therein is the ability to plan a minimum number of steps and minimum number of die sets to evolve from one shape to another. Also implicit is the future development of automated incremental forging processes.

Experience is the major guide factor at present. This represents the most expensive and time consuming trial and error method. Presumably a more sophisticated use of modeling experiments could reduce the magnitude of effort; but, in the long run, one seeks an analytical method even if the results are only reasonably approximate.

While plasticity theory has made great strides in treating the problem of stress and velocity distribution in the plastic zone, it is simply not capable of treating the subject of local displacements and strains as characteristic of real forging type problems. Apparently this is a theoretical problem of great magnitude. Advances in theoretical mechanics are invariably based on fundamental theorems. In the matter of local displacement and strain distributions, no such theorems exist. It is recognized that achievement in this direction will not be accomplished by just any seemingly competent teams or individuals. There are only a few people in this country, or perhaps any country, whose stature and accomplishment in the field of theoretical mechanics justify some expectation of success. Such individuals are, of course, happily and constructively occupied in other areas of mechanics.

If this aspect of plasticity is to emerge from its empirical position, it will be necessary to excite sufficient interest in the right people to induce them to tackle the problem. This can only be done by revealing the great ramifications of the technology of metalworking and by providing adequate financial support for a sufficient number of years.

This activity and its associated investment must be regarded as a long range venture. The results will not have immediate application but will set the stage for the solution of more specific problems of great diversity. Accordingly, the following recommendation is submitted for implementation.

#### Recommendation

Undertake a fundamental study of the principles governing the details of the displacement and strain distribution of a plastically deforming body, restrained only in part by the tools. It is suggested that the basic model be characterized by the squeezing of a rectangular bar between flat-faced tools with frictional restraint lying between the limits of easy slipping and complete sticking.

## 5. The Use of Model Experiments in Forging Die Design

(September, 1966)

There is a long history of laboratory experiments with plasticine and similar soft plastic materials to simulate, in a geometric sense, the operations of both open and closed die forging, extrusions, and shape rolling. The advantages are obvious. Dies can be carved from wood or clear organic solids easily and cheaply. The plastic materials themselves are cheap. Therefore, in principle, a great deal of experimentation can be done quickly before decisions on design of the prototype operations have to be made. To what extent and in what way similarity has been achieved is clearly unresolved. The question then is what valuable information can be derived from such experimentation.

In general, the information sought falls into three categories:

- (1) Forces required which relate to machine capacity, tool wear and tool fracture.
- (2) Plastic displacements which relate to filling efficiency, wastage through flash, and potential for laps and folds.
- (3) Plastic strain distributions which relate to control of metallurgical structure and mechanical properties in service.

In order for a model material and modeling experiment to simulate the forces in a real hot working operation, a large number of conditions must be fulfilled. These fall into the categories of material behavior, inertia effects, temperature gradients, boundary conditions and tool properties.

The modeling experiment can be designed in two different ways. One can use a very soft plastic material with relatively soft die materials at either full or sub-scale. Alternatively, one can use the real materials for both dies and work-piece, operating on a sub-scale. The latter is obviously more expensive.

Moreover, it is not possible to scale down the temperature gradients and transients of a hot working operation. Nevertheless, in either case, it is necessary to meet a number of criteria of similitude and in neither case can these, in fact, be met because of contradictions which arise.

Even if some similitude requirements could be relaxed for the case of using soft plastic modeling materials, a wide variety of these would be required to represent a spectrum of flow stress, strain-rate, and temperature characteristics. The expectation of identifying or developing such materials was considered to be not very optimistic. It was generally concluded that model experiments to provide information on forces in real operations are not very feasible.

On the matter of simulating plastic displacement, we are considerably less fettered. There is a reasonably large body of experience indicating that shape changes produced in plasticine, gelatine, or waxes are very similar to those encountered in prototype hot working operations. Moreover, by various devices, it is possible to incorporate markers which can be used to estimate local strains.

Despite the work which has been done in this area, there is as yet no general acceptance of the method. This is partly because the degree of correlation between modeling deformations and prototype real operations has not been established in sufficient detail and in sufficiently diverse variety of typical shape changes; and partly because there has been no standardization of procedures or materials.

In particular, discussion brought out that plasticine, which is highly favored by some, is a non-standardized material of varying characteristics as commercially procured. There are large differences in strain rate and temperature sensitivity of flow stress from batch to batch and from color to color. Since this kind of work requires a precisely characterized and reproducible material, it is necessary to realize that the normal commercial product is not suitable.

The future of modeling experiments as a means of providing useful information on forging die design concepts is predicated on eliminating interdependent

uncertainties. While there is a manifest need for establishing detailed correlation between displacements and strains in model experiments and geometrically similar prototype operations, this work may be delayed in part until the rheological characteristics of modeling materials can be brought under control.

In light of the above discussion, the following recommendations are made. The development of improved model materials is placed first and might be viewed as a prerequisite for the second recommendation; but since the first recommendation is likely to signify a rather short term project, and the second a much more time consuming task, it would not be unreasonable to consider initiating them concurrently.

Limited inquiries as to the potential of identifying a series of polymeric materials representative of a wide spectrum of rheological characteristics yielded rather negative responses. It may be that a pessimistic conclusion about polymers was hasty. The committee will be receptive to specific information not available to it at the time of this report.

#### Recommendation (1)

Undertake to identify the factors which influence the temperature and strain rate sensitivity of the flow stress of the material commonly called plasticine. Define the processing conditions by which plasticines can be produced with uniform reproducible rheological characteristics, preferably in more than one color variation. Develop a series of plasticines for use in modeling experiments which represent a spectrum of rheological characteristics.

#### Recommendation (2)

Evaluate the ability of modeling experiments to replicate the displacements and strain distributions of typical forging operations. This must involve comparison with real engineering materials experiencing similar shape changes. The evaluation should explore the relative advantages of various modeling materials of which plasticine, gelatine and waxes are exemplary. The program of correlation between model and prototype should incorporate the significance of variations in frictional conditions, rate of the die approach, and temperature.

## B. DUCTILITY AND FLOW STRESS

### 1. Laboratory Measurement of Mechanical Properties (March, 1965)

The force demand and plastic strain capacity of a given material in a given metalworking operation are dependent on such conditions of operation as strain rate, temperature, tool-work geometry, and tool-work interfacial friction. With meaningful measures of the flow stress over large plastic ranges and the plastic strain capacity as a function of these parameters, the cut-and-try approach to process development can be substantially reduced. For example the roll separating forces can, in most instances, be calculated with an uncertainty of less than  $\pm 10\%$  given appropriate measures of the flow stress and friction coefficient. Less directly, flow stress data combined with roll force data on a limited number of test passes can be used to calculate mill demands on other pass reductions. At the very least, laboratory mechanical property measurements can circumscribe the conditions of strain rate, temperature, and total plastic strain which are conducive to cracking.

In some instances, the use of a properly instrumented metal working machine can provide sufficient material property data, but only in a very narrow sense. More often it is simply impractical to obtain information in this manner. It has been recognized for many years that suitable methods of laboratory measurement of mechanical properties under equivalent metalworking conditions of temperature and strain rate are important adjuncts to technology.

There have been at least three laboratory schemes capable of serving these purposes to some measure. The tension test is useful only over the range of uniform elongation and cannot give useful data over large plastic strain ranges. The torsion test introduces complications of localization of strain at the surface and strain gradients through the section leaving interpretation sometimes controversial. The compression test, as provided by the cam plastometer, is closely simulative of rolling and forging. The flow stresses derived have frictional conditions implicit which is an asset provided that they simulate actual operations.

Since present analyses of forming processes involve unavoidable simplifications, the utmost sophistication in determining flow stress data for metal processing calculations is not required. In this respect, existing work with tension, torsion, and compression testing at present strain rate capacities does show adequately comparable data. In terms of range of strain, strain rate, temperatures, variation in critical specimen dimensions, process simulation, surface friction simulation and interpretation of data, the cam plastometer seems to warrant broader use and general acceptance. However, such test facilities are quite rare. The root problem is the capital cost associated with present designs of test machines. It is generally agreed that good engineering design can rectify this matter.

All present mechanical property test systems have strain rate upper limits of about  $10^2$  / second or less. Yet, important metalworking operations involve strain rates in the range of  $10^3$  / second. The extrapolation of test results from slower strain rates in hot working, for example, may only be adequate in some circumstances. From this viewpoint of controlling wrought product structures, extrapolation is inadvisable. There is general agreement on the lack of suitable test system for strain rates in excess of  $10^2$  / second.

#### Recommendation (1)

Redesign the cam plastometer as a good engineering machine of reasonable cost and capable of rapid generation of compressive stress-strain data. It is anticipated that the accomplishment of this objective would greatly increase its general acceptance and make it an indispensable tool to the metalworking industry.

#### Recommendation (2)

Develop a suitable test system for the measurement of flow stress-strain behavior, and the crack-free plastic strain capacity and which would also permit the synthesis of structural changes associated with hot working in the strain rate of  $10^2 - 10^4$  / second.

## 2. Sheet Formability Limits (April, 1967)

For some time to come, the practicalities of living with ductility limits will tend to compartmentalize the subject according to classes of operation. The forming of sheet is one of these. Although sheet forming embraces many operations--stretching, deep drawing, bending, joggling, dimpling, beading (and others)--they can be related in terms of a ratio of the two principal stresses in the plane of the sheet. There has been a great deal of work in this subject area for many years, nationally and internationally, on both common industrial materials and on the wide diversity of specialized materials. A study of accomplishment in this area provides some idea of the extent to which technical control can be exercised in default of adequate theoretical understanding of the mechanisms of ductile failure.

In discussing sheet forming, it must be recognized that the term "formability limit" embraces more than ductile failure. Obviously, a part fails if splits, tears, cracks or any form of separation is identified; but, a part may also be unsuitable by virtue of local buckling or wrinkling, local thickening or thinning (necking). Therefore, other material properties such as elastic modulus, yield strength, strain hardening coefficient and plastic anisotropy are involved.

Technical control can be characterized in several ways which complement each other:

- (1) Given a material and a part shape, anticipate for process design purposes, the limits on critical dimensions such as thickness radii, relative displacements or ratios of these.
- (2) Given a material, relate its known ductility limits in one set of planar stress circumstances to other combinations of planar stress.
- (3) Given a material performing satisfactorily, initially define a simple set of qualifications to exercise quality control on succeeding batches.

- (4) Given a die set designed on best estimates, but failing parts, define a diagnostic procedure which can direct minor modifications such as lubricant application or relaxation of restraints.

Two approaches to these kinds of technical control were examined and discussed. They followed essentially independent lines and were motivated differently; yet they complemented each other in many ways.

By the first approach, twelve sheet forming operations, common to the aircraft industry, were analyzed in detail for failure limits. For each operation, a failure envelope was constructed on coordinates, representing critical dimensions or ratios of critical dimensions. Part of the failure envelope was related to buckling and could be computed directly from elastic modulus and yield behavior using simple elastic stability theory. The rupture or splitting part of the failure envelope was derived from a simple tensile test, using an appropriate gage length. Implicit in this method is the assumption that a relationship exists between the stress ratio in plane stress deformation and gage length of a uniaxial tensile test for equivalent strain at failure. This is a highly intuitive approach that seems justified in retrospect only by the measure of success encountered.

Seventeen aerospace materials were tested in bending, joggling, dimpling, rubber stretch (for flanged parts), linear stretch (wrapping or brake formed sections), sheet stretch cup drawing (with residual flange), and beading. More than 20,000 prototype parts were formed and pass or failure (and failure type) logged in terms of workpiece geometry and process parameters. In more complex processes such as joggling, factors such as radii and lubrication were kept constant in conformance with best work practices of the day. This latter simplification must be kept in mind.

The results were then correlated with a readily measured material property. Standard gridded tensile specimens were used, permitting the determination of elongation over gage lengths ranging from 2 to 0.02 inches. It was found that

localized strain (measured over short gage lengths) correlated well with joggling, beading and bending, whereas larger gage lengths were more typical of rubber stretch, lineal stretch and sheet stretch.

The methodology of the approach may be explained by the rubber stretch as an example. For each workpiece material, a number of parts were formed representing variations in part geometry. The splitting part of formability envelope was demonstrated to correlate to one ratio of part dimensions. Of the tensile elongations for various gage lengths plotted against the experimentally determined critical magnitudes of the dimension ratio, correlation with various materials was best established using a gage length of 2 inches. The master curve of strain in 2 inches against limiting part dimension ratio becomes the basis for predicting the behavior of another, i. e., its measured tensile strain in 2 inches is used to designate the dimension ratio limit of the rubber stretch part.

Of the total of more than 20,000 prototype parts formed with and without failure, at least 83% fall correctly in the failed or unfailed regions of their respective formability envelopes. This represents a major advance in procedure for initial process design.

The applicability of ductility limits in simple tension to so many different forming operations probably reflects the fact that the range of planar stress ratios ( $\sigma_2/\sigma_1$ ) for all of those lies between 0 and 0.5, i. e., between simple tension and plane strain. The region of  $\sigma_2/\sigma_1$  between 0.5 and 1 embracing biaxial stretching, which plays a large part in the deep drawing operations, is not represented, nor are the negative magnitudes of the stress ratio (combined tension and compression).

One other gap in coverage lies in the choice of materials. The sheet alloys chosen were all of the difficult forming variations common to the aircraft industry. None of the high formability, ferrous and nonferrous sheet materials used by the automotive and appliance industries were represented. This is not a distinction in application but rather one of plastic strain capacities and yield strengths.

The formability of deep drawing quality steels, aluminums and brasses has been the subject of industrial research for many years. The conditions for a satisfactory evaluation scheme in these circumstances are rather more stringent. Materials are regularly being used near the limit of their ductile capacity and economies demand that rejection rates be less than some figure of the order of 3%. The margin for error is obviously much smaller.

For years controversy has persisted internationally in the deep-drawing technical community over the relative merits of strain hardening exponent, anisotropy ratio and combinations of tensile properties, as well as simulative tests such as hydraulic bulge, Fukui, Swift cup forming.

Despite great progress on the question of the most suitable laboratory criteria for formability, none of these approaches comprehensively evaluates the extremes of conditions encountered in the diversity of industrial sheet forming operations.

It is clear by now that sheet metal forming involves a substantial range of dominant plane stress ratios and that ductility is dependent on stress-ratio. Each of the various formability tests have evaluated ductility only in some narrow ranges of stress ratios. The situation has become a modern day version of the parable of the blind men and the elephant.

This is not to say that close control of formability quality cannot be maintained. In fact, close control is achieved many times but by highly empirical correlations with laboratory tests which are valid only by virtue of substantial experience and too often totally invalid in some other regime of sheet forming.

Recognition of a correlation between ductility limit and plane stress ratio is the basis for a rather recent and new approach to the subject of stretch formability of high ductility materials. It has been discovered that a reasonable correlation exists between the maximum tensile strain and the plane-stress ratio ( $\sigma_2/\sigma_1$ ) at the point of failure, irrespective of the geometry of the punch. For

the present, this consistent correlation is restricted to stress ratios between 0.5 and 1 but it embraces many commercial ferrous and nonferrous materials, common to the automotive and appliance industries, i. e. , steel, aluminum, copper and brass.

At this point, the correlation between  $\epsilon_{\max}$  and  $\sigma_2/\sigma_1$  cannot be used directly to predict maximum allowable strain in a generalized part, primarily because it does not yet seem possible to calculate, in advance, the dominant stress ratio likely to be encountered in a given part-forming operation. It does, however, represent an important beginning to a broad characterization of formability. It also points up the need to recognize the various means at an operator's disposal to make local changes in the stress ratio. Some of these are: radii of curvature, punch roughness, lubrication, and lateral constraints.

Probably of more interest to the long-range view are questions relative to the applicability of such a correlation to materials of lower ductility capacity and of hexagonal structure such as Ti and Mg (and perhaps Be). Still further, one might wonder what clue this presents with regard to the nature of the failure process in ductile materials. The form of the correlation seems simple enough that in analytical form it might be totally characterized by constants obtained from a few selected uniaxial and biaxial tension tests.

The most recent advances in technical control of formability fall short, at present, in the extent to which they are generally known and applied and in the breadth and diversity of applications to materials and operations. Their margin of success has implications for fundamental mechanisms of failure which have yet to be appreciated.

#### Recommendation (1)

The studies of failure envelopes for typical aircraft part forming operations are contained only in four bulky contract reports. In this form they are indigestible to any but the most dedicated. Moreover, their circulation has been very limited.

There has been almost no discussion of their merits by the technical community. They have been used in process design by several aircraft companies over the past five years with no general or specific knowledge of success or progressive refinement. A literary effort is clearly in order at this time, taking the form of incorporating the latest assessment of applicability, recapitulating the whole approach in a more presentable manner and objectively analyzing the potential for refinement of precision. Finally, the results of such a task should be made available to as wide an audience as possible.

#### Recommendation (2)

The main weakness of these failure envelopes is the use of tensile elongation in arbitrary gage lengths as the direct measure of formability in a biaxial stress system. The direction for future improvement seems clear enough. Ductilities must be used which are characteristic of the stress ratio at the critical position for failure. Yet, to acquire ductility data for all materials over the whole biaxial stress range from  $-1$  to  $+1$  is a task of prohibitive magnitude. It is necessary at this point to acquire sufficient data to deduce a general relationship for  $\epsilon_{\max}$  vs  $\sigma_2/\sigma_1$  whose proportionality constants can be evaluated from limited selected tests. The proposed research task would involve a careful selection of materials representative of ductility levels, anisotropy variations, and a range of gages. The scope of testing would include ductility measurement in terms of maximum strain or equivalent strain as a function of stress ratios between  $-1$  and  $+1$ . The objective would be to define the minimum number of tests to characterize a material over the whole stress ratio range and to identify the features of this characterization. When this has been accomplished, a subsequent research task would logically undertake to establish more refined failure envelopes for practical operations and test their accuracy.

#### Recommendation (3)

An analytical approach to the failure envelope of non-symmetrical shapes might be prohibitively difficult at this time. However, it should be possible to

reduce an arbitrary shape to an assembly of simple and typical shapes. This sort of approach is basically in the nature of projecting past experience into future designs. Conceivably from a classification of simple shapes, and measurement of their critical stress ratios, a system of feasibility of a given material or of minimum requirements for a suitable material could be established. Pursuance of a task of this nature should be conditional on not duplicating existing or planned activity (such as by the International Deep Drawing Research Group).

Recommendation (4)

While the possibility of generating voids in shape processing is an important new concept, verification is lacking as to whether the implication of cumulative damage is of significance to manufacturing and service properties. More specifically, it is important to know whether void formation has any measurable influence on ductility and fatigue strength. To this end it is suggested that a difficult-to-form alloy containing significant quantities of strengthening phases (such as Rene' 41) be processed by two-routes--one conducive to void formation and one designed to minimize this--and that the bar or plate produced be subject to ductility and fatigue evaluation under circumstances appropriate to its utilization.

### 3. Superplasticity (March, 1965)\*

This subject is clearly in the early stages of technical and scientific inquiry. Even the definition of the term is not always taken in the same way.

The condition of superplasticity has come to be identified with low (even vanishing) strength and an unusual capacity for stable, neck-free (i. e., uniform) plastic extension. This latter aspect has intriguing potential in metalworking processing. Much of past work has been preoccupied almost entirely with the low strength aspect.

Unusual capacity for uniform plastic extension has been observed in the near-eutectoid compositions in the Al-Cu, Al-Si, Pb-Sn, Mg-Al, and Mg-Cu systems, in certain alloys from the Cu-Zn system and in certain titanium alloys. Some form of structural instability seems to be a common denominator in all such observations.

Recent work with eutectoid Al-Zn alloys demonstrates that necking resistance is a consequence of an extremely high strain-rate hardening capacity in the "superplastic" state. Values of the strain-rate hardening exponent reached about 0.7, which is an order of magnitude greater than usual values for hot metals and comparable to values found in various polymeric materials.

#### Recommendation

In view of the embryonic state of this subject, the step of first priority should be a comprehensive exploration of "anomalous" capacity for low strength and uniform extension in common and special engineering materials. In each instance, the critical temperature and strain-rate range and the phase or structural instability associated should be identified.

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\* See subsequent recommendations on Page 60.

#### 4. Mechanical Property Changes by Plastic Strain Cycling

(April, 1967)

When cold-rolled copper strip is subjected to a few (1-10) reverse plastic flexures over its whole length, as by drawing over a small diameter mandrel, the yield stress in subsequent tensile testing is observed to decrease and the elongation to increase. The decrease in yield stress by plastic strain cycling has been further examined on several occasions and it is now clearly a phenomenon associated with heavily cold-worked materials. The feature of change in ductility is still rather obscure. However, this too is confined to heavily cold-worked metals.

The reduction in yield stress, either in subsequent compression or tension after plastic bending, has been used in the contact-bend-stretch (CBS) mill with notable success. Some experiments have demonstrated that hard-drawn copper tubes show considerable reduction in draw force in a subsequent draft.

The increased elongation feature has not been exploited in any practical manner. In the light of present problems of forming unusual materials with limited ductility--materials which are often used in the cold-rolled condition--any phenomena which might give a measure of advantage is worth some exploration.

##### Recommendation

A modest research program can be envisioned to serve this purpose. Work can be confined to sheet using a suitable roller-leveller to produce plastic strain cycling. Candidate materials would be selected from Mo, Cu, Ti alloys and Be. Experiments would be directed to measuring formability in brake forming and hydraulic bulge forming as a function of the number of plastic strain cycles, unidirectional and cross flexing, and prior level of cold work. Supplementary experiments should be performed to demonstrate whether the same level of formability change can be gained by stress relief annealing only.

There is fragmentary evidence that plastic strain cycling can modify the preferred orientations in sheet. Since this is clearly a major problem with Be sheet, the issue should be explored since almost any texture change from that presently encountered would be an improvement. However, this aspect should be the minor part of the whole program.

#### 5. Metalworking Information Transfer (February, 1968)

Technical information transfer to engineers and scientists is being actively promoted and expanded on a national scale. There is no lack of current general-purpose systems for information accumulation, digestion and dispersal. In exploring this subject, the committee recognized quickly that there is really no need for more vehicles for information transfer. Discussions were directed toward questions on packaging of information peculiarly suited to the metalworking industry.

For information to be effectively used, the target must be carefully considered. The fundamentals of metalworking involve very sophisticated mechanics, metallurgy, and a number of other disciplines, but a large part of the population in this industry has had rather unsophisticated training. The literature in book form tends to be well above the grasp of the bulk of the potential readership and the literature in trade journal form tends to perpetuate the existing "blacksmith" approach. If some real innovations in information transfer are to be made, they can be in bringing the existing sophistication of science on the subject to those who could use it if it were available in digestible and usable form.

Specialized information packaging of this type (not in metalworking) is being produced currently in Great Britain and in Germany and is being well received. These packages, distributed as "data sheets", are concise summaries of the techniques and data needed to carry out a very specific operation--usually the design of a general purpose item. They are similar to specific chapters in a comprehensive handbook, but without the bulkiness and formidable aspect of most handbooks.

"Data sheets" have, or should have, a common set of features:

- (1) They should be directed to a specific problem type, typical in an industry.
- (2) Methods of solution should be worked out in careful detail with numerical examples.

- (3) Selected and relevant data on important materials should be presented in graphic or tabular form.
- (4) The package should be small enough with attractive printing and presentation so that the timid are encouraged to have a try. A pamphlet or loose-leaf form makes the "data sheets" easy to store and retrieve.

Within the context of metalworking, there are obviously a number of appropriate subject areas. Hot rolling is a case in point. There are sophisticated treatments of this subject by mechanics. There are also semi-empirical methods of load and horsepower calculation which are much simpler to use and often quite adequate. All of these, however, lack any large body of factual data on the flow stress of materials in the hot working range of temperature and in the strain rate ranges typical of hot working operations from press forging to hammer forging (these being extremes of strain rates in hot working in general).

Other appropriate subject areas could be: formability limits; lubricant usage; heating rates; and oxidation kinetics. This is not intended to be a comprehensive list but only exemplary. Industrial organizations have this kind of information in their files but it is often isolated and not generally available. This means much of the industry survives without it or duplicates the efforts to acquire it privately. In this pattern, large industries become more sophisticated and the gap widens between them and the small industries.

The committee supported the proposition of a pilot project which integrated an early recommendation that was implemented. Some time ago, the committee urged that the development of a cam plastometer of reasonable cost be sponsored. The cam plastometer was reasoned to be the most feasible device for producing flow stress data in the laboratory which was typical of hot working operations.

### Recommendation

When the cam plastometer (or any equivalent test facility) becomes available, a program should be instituted to acquire a substantial body of flow stress data on engineering materials of DOD interest in the temperature and strain rate ranges appropriate to hot working operations.

It is important that the presentation of these data in printed form be accomplished by carefully aimed descriptions of how they may be used to solve real problems. It should be a purpose of this pilot project to make them available to the trade journals for data sheet and feature article presentation.

Since this represents something of an innovation in the United States, the experimental nature should be recognized by taking steps to determine the extent to which the people at operating level are reached and their reactions.

## C. LUBRICATION AND RELATED RESEARCH PROGRAMS

### 1. Lubrication in Metalworking (October, 1965)

This subject is too involved for the main committee. Moreover, some aspects require the counsel of specialists. The Panel on Lubrication was, therefore, organized. Their deliberations brought out the complex character of the subject and the weakness of the present state of understanding.

In metalworking operations, the lubricant serves not only to reduce friction, but to minimize tool wear, to control surface finish, and in certain circumstances, to retard rate of heat transfer between tool and workpiece. Although reduction of friction is generally considered the measure of lubricant quality, the elimination of wear or metal transfer between tool and workpiece is more often the dominating requirement.

If one includes all metalworking operations requiring lubrication, the conditions of lubricant service range over wide spans of temperature, pressure, surface conditions and sliding velocities. Even within the context of one type of operation,

a successful lubricant must possess an ability to perform over a wide range of pressure, temperature, sliding velocity and metal surfaces, as well as to provide freedom from discoloration or staining of the product, toxicity, odor and fire hazard. Ease of application, removal and cost are also important. A potential lubricant capable of lower friction or wear may be unacceptable on one of the counts listed.

Two kinds of lubrication are recognized--(1) thick film and (2) thin film (or boundary) lubrication. In practice a mixture of the two is probably most common. In thick film lubrication, the lubricant is present in the form of a continuous film, sufficiently thick to prevent contact between asperities on the two mating surfaces. The real area of contact is zero and the coefficient of friction (0.001-0.01, approx.) depends on dynamic viscosity or shear strength of the lubricant itself. Although thick film lubricants are more often liquids, they may also be solids or gases.

In boundary lubrication, the film is of molecular dimension and not necessarily continuous. Real contact exists between asperities but the applied stress to produce shear displacement is reduced either because the real area of contact is less or the shear strength of the bonds is less. Measured in conventional ways, with nominally elastic members in the friction couple, coefficients of friction in boundary lubrication are found to range between 0.01 and 0.20.

There is no very satisfactory theoretical treatment of the subject of boundary lubrication. Existing functional relationships contain terms whose numerical magnitudes have not or cannot as yet be determined. These relate to the identity and properties of the thin film and its bonding to the underlying metal.

In default of a theory which can orient the search for improved materials by defining in useful terms the character and properties of suitable lubricants, it is necessary to approach development by systematic evaluation and screening. For this, one needs laboratory methods of measurement which properly replicate the conditions of service. The methodology of experimental evaluation is highly developed for conditions of macro-elastic contact. Few studies have been carried out at pressures and temperatures and with metal pairs (one member entirely plastic, the other elastic relevant to metalworking).

In summary, the Panel on Lubrication came to the following conclusions and submitted certain appropriate recommendations for project support:

- (1) There is a lack of adequate communication between specialists in the lubrication field and specialists in the metal deformation field.
- (2) Little of the available basic knowledge on friction, wear and lubrication is being used to extend metal deformation processing limits.
- (3) Although a number of bench tests are currently used to evaluate lubricants empirically, little is known of the extent of their applicability to industrial metalworking operations.
- (4) There are few data on the mechanical properties of surface and surface films, such as shear strength of oxides, under conditions of pressure and temperature in metalworking.

#### Recommendations and Task Descriptions

##### Recommendation (1)

An individual or group should be commissioned to prepare a monograph on metalworking lubrication. In addition to bringing together modern practices and developments in lubrication and metalworking, it should deal with the distinct function which a lubricant can be required to perform. Since empiricism in this field is impossible to circumvent, it is important that a clear understanding be developed of the various functions of a lubricant and of the scientific knowledge relevant to each.

##### Recommendation (2)

Thick film lubrication represents the most advanced state of the art of

lubrication. Moreover, minimum friction and minimum wear are obtained under thick film lubrication conditions. Although only in wire drawing has serious effort been made to utilize thick film lubrication, the possibility of extension to other deformation processes is good and likely to yield rewards.

Specifically, carry out analysis and experimental studies on a selected deformation process such as tube drawing or extrusion with the aim of promoting thick film lubrication through die design, lubricant selection and other devices. Theoretical analysis, evaluation of rheological properties of lubricants under prevailing sliding conditions, and full scale trials should be part of the program.

#### Recommendation (3)

In selecting and studying boundary lubricants for bearing and related applications, simple screening tests, such as the pin/slider test have proven effective. The test presently used involves sliding of elastic bodies. There are differences of opinion regarding the application of such tests to metalworking operations involving a plastically deforming surface. Present theory and experience is not sufficiently broad to answer this question.

As pin/slider tests are fairly common, and yet easily modified to study a wide range of variables, they represent a potential asset to the development of metalworking lubricants if their results are relatable to metalworking conditions. It would be desirable to determine whether pin/slider tests are valid for metalworking, and to adapt or modify the tests as required. In particular, ascertain how far results of pin/slider tests are affected by bulk plastic deformation of the specimen and generation of new surface.

Specifically, pin/slider tests should be carried out with several tool/work-piece combinations under unlubricated and lubricated conditions. Load, sliding velocity and temperature should be varied over the ranges experienced in actual metalworking operations. Observation and measurements should be made of metal transfer, wear, friction, and metal-to-metal contact in both pin/slider tests and in

simple metalworking operations selected for comparison to emphasize changing surface area. Wire drawing or sheet forming would be considered ideal operations for comparison to emphasize changing surface area, and for comparison with test results.

#### Recommendation (4)

One class of lubricants used widely in metalworking is solids, including pre-formed films of soft metals, organic polymers, greases, soaps, fats and waxes, oxide coatings, inorganic conversion coatings and laminar-structure substances. Theoretically the efficiency of these lubricants depends on their shear strength, but little is known about their relative strengths under conditions of high pressures, temperatures and shear rates.

Specifically, measure the shear strength and observe the behavior of potential solid lubricants during sliding at high pressures, temperatures and shear rates. Use such data to test theories of friction as they may apply to metalworking. This could be a continuation and expansion of P. W. Bridgman's work (Proc. Am. Acad. Arts Sci., 71, 1937, 387-460).

#### Recommendation (5)

Research should be sponsored in the general area of compatibility or similarity of contacting metals with special emphasis on metal pairs of interest in metalworking operations. The results would be directly applicable to the problem of choosing the best tool material to be used in operations with marginal lubrication conditions and where danger of galling exists.

Specifically, testing should be carried out on unlubricated surfaces, and measurements of friction, wear, metal transfer, and surface finish should be made. It will be the purpose of the proposed study to find principles which are applicable to the development of adhesion or galling of unlike materials.

In order of priority, the panel considers recommendations (1), (2) and (3) of primary interest and more likely to yield returns in the near future and recommendations (4) and (5) of secondary interest and longer range in scope.

## 2. Heat Transfer in Metalworking Processes (June, 1965)

The need for control of heat transfer is becoming increasingly important in working operations. From the viewpoint of tooling, unrestrained heat transfer from the workpiece can lead to overheating, with consequent softening, thermal fatigue cracking, excessive wear (wash out), galling, and scoring. Under certain circumstances, lubricants may act as thermal barriers and parting agents, but these functions break down at critical interface temperatures. The temperature distribution in the workpiece is a more complicated picture. There is a loss of heat to the tools and a gain of heat by virtue of the work of deformation. The result of uncontrolled thermal gradients may be surface cracks, non-uniform metallurgical structure and residual stresses.

The approach to heat transfer problems continues to be empirical in most metal processing industries with the experimental adjustment of variables such as initial billet temperature, dwell time, and displacement velocities. The availability of an analytical treatment for heat transfer, permitting quantitative prediction of optimum and limiting conditions would result in the reduction or elimination of costly process experimentation. Even a semi-empirical approach which might link together existing experience to permit interpolation should result in a significant decrease in time and cost of process development. However, in undertaking such an effort, it is first necessary to determine which aspect can be treated and to estimate what the balance between effort and value received may be.

A survey of recent literature by DMIC makes clear that there has been little activity in this country on the subject. Work in other countries (chiefly Great Britain and Germany) has dealt largely with the prediction of average temperatures or the measurement of surface temperatures, whereas the full temperature profile is really necessary for effective action.

The mathematics of non-steady state heat flow for complicated initial and transient conditions are adequate. Large digital computers are probably necessary, but these are available. The precision of calculation is probably better than the

precision of measurement, particularly in view of the dynamic conditions encountered in most metalworking operations. The present capability of performing important calculations is hindered by the dearth of data on certain fixed parameters such as heat transfer coefficient and friction constants. However, such data can be derived indirectly by suitable combination of analysis and experiment through iterative procedures.

There is agreement that calculation of temperature profiles, their fluctuations, and consequent means for control in the tools is easier than the parallel problem in the workpiece. There are at least two reasons for this. The experimental difficulties of measuring temperature in workpiece impede the combined computation-experiment-iterative solution approach. The ability to describe properly the heat generation due to plastic deformation requires a complete description of the stress-strain-velocity distribution within the body, and this is presently a problem of almost prohibitive magnitude.

Sponsored research at this time could serve two useful purposes--the optimization of present capabilities, both analytical and experimental, to predict temperature profiles in real metalworking operations and the stimulation of interest within the heat transfer community in problems of this nature.

#### Recommendation

It is recommended that a modest program be initiated to apply advanced heat transfer analysis to a typical hot working process such as axisymmetric extrusion or high speed upset forging. An experimental program should accompany the analytical studies. The purpose of this work would be to demonstrate agreement between calculation and experiment. Necessarily involved would be the measurement of the heat transfer coefficient at the tool/workpiece interface, refinement of approximate methods of computing frictional heat generation, and the evaluation of simplified approaches to estimating the degree and distribution of adiabatic heating. The emphasis should be placed on temperature profiles rather than average values. The program should keep in mind the need for simplified presentation of data having regard for the general unfamiliarity of the users with the mathematics of heat transfer.

## D. APPLICATION OF COMPUTERS

### 1. A Broad Look at Computers in Deformation Processing

(June, 1965)

Various types of computers and various computer functions are prominent in modern plants and are clearly destined for much broader use in the future. The more important computer functions are as follows:

- (1) High speed calculation.
- (2) Information storage and retrieval.
- (3) Inventory control.
- (4) Process programming.
- (5) Process control.

Computers are usually tailored for each application and a given computer can perform more than one of the functions listed.

A number of considerations weigh in the decision to acquire some form of computer assistance or control. Capital investments for equipment alone range from \$20,000 to \$2,000,000. The more involved functions of process programming and control require special teams to log operational data and derive appropriate mathematical relationships in computer language. There are points of judgment as to whether a particular operation is best under operator or computer control. Balanced against these and other operational cost factors is the expectation of greater productivity, greater recovery, better quality, and reduced total cost.

The most advanced function is process control which is the one of primary pertinence to the interests of the committee. Most simply, this involves continuous sensing, interpretation of signal and activation of a machine adjustment. The computer interprets the sensor signal, selects the one or more adjustments to the machine, or auxiliary facilities, and commands a measured response from the machine. Obviously, to accomplish this, the machine must be inherently adjustable, the response time must be adequate, and the appropriate function relationships between sensor reading and process variables must exist.

Performance of the deformation system is improved while working is in progress by feedback control. At present, feedback control is only being applied to rolling mill applications and the most advanced application is to the direct control of hot strip rolling of steel. Flat rolling is an inherently adjustable process, and automatic gage control can be used. Unlike closed die forgings, extrusion and wire drawing, the roll gap is continuously adjustable, even while rolling is in progress. Specifically, the strip quality is controlled in terms of gage and finishing temperature. The points of control are the screw regulator, the speed regulator and water spray. The sensing points are mill deflections, temperature, and gage between stands and at the finish line. The operator adjustments have been reduced from twenty-four to four--finish gage, grade of steel, finishing temperature and load distribution by stand.

Advantages that are claimed for such computer applications are increased accuracy of gage, better and more uniform quality and increased mill capacity.

The spread of computer control usage in rolling operations will depend on maturing human judgment. The experience factor is inescapable. From a purely technological viewpoint, more varied and precise on-line sensing units appropriate to mill conditions are the primary need. Some of these might be:

- thickness gages for thin sheet.
- flatness gages for cold rolled sheet and foil.
- indicator of surface finish.
- indicator of roll wear.

Most other deformation processes are of the fixed gap type and while this circumstance exists, they must remain far less amenable to computer control. It was the committee's opinion, at that point in their deliberations, no obvious, specific, research tasks could be recommended to further the use of computer control in deformation processing. In subsequent pages note how this viewpoint changed.

2. The Use of the Computer in Forging Die Design  
(September, 1966)

Of all metalworking operations, closed die forging has the most intrinsic complexity. In a general sense, simplifications to a mechanics treatment of forging are difficult because there are no overriding shape symmetries or steady state conditions in material displacement and heat flow. Therefore, it should not be surprising that present success in producing a given end item is based largely on accumulated experience, the conditioned intuition of individual specialists and a substantial measure of cut-and-try experimentation.

This state of affairs is tolerable, provided the variety of materials to be handled is limited and their metallurgical control is relatively simple; provided the number of forgings of a given shape is large enough to easily amortize the cost of procedure and tool development; and provided that customer demands for dimensional limits recognize and accept existing capabilities. In fact, contemporary needs have introduced a wide variety of new materials whose metallurgical control is difficult, at best, and whose cost as unfinished bar and billet is so high that material removal methods of reaching finished shape very substantially increase final finished costs. Superimposed on this is a situation where only a limited production must bear the process development costs. While this might be stated as a generalization for all manner of wrought products today, the cost and output penalties in closed die forgings are the outstanding example.

The manufacture of a closed die forging represents an evolution in shape. Since die cavities are fixed profiles, the evolution of shape must be in fixed steps. The sequence of shape changes must meet certain requirements or face certain limitations.

- (a) The number of intermediate shapes must be minimal because of capital costs in die blocks and die sinking and because of operating costs in the number of machines occupied or the wasted time involved in die changes.

- (b) The force demand to forge from one shape to the next must be within the capacity of available machines as well as within the strength of the die blocks. Probably an even more common limitation is the wear resistance of the die surfaces which relate to local pressures between the die and workpiece.
- (c) The maintenance of integrity in the forging, i. e. , freedom from laps, tears and cracks.
- (d) Minimal extrusion of metal into the flash which will be removed and which constitutes largely irrecoverable scrap.

Obviously factors (b), (c) and (d) counterbalance the objectives of (a).

There are various paths by which the art of die design might evolve to a technology. At one extreme is the development of analytical procedures for the detailed calculation of forces, displacements and strains. Less ambitious but perhaps more within present grasp, is the more systematic use of existing experience. To this end a computer approach to information storage and retrieval in a design program merits consideration.

A scheme is in an advanced state of development by which a computer can construct the instructions to numerically controlled machine tools for the machining of a given finished shape from a given initial shape. The essence of "automatic program tooling" (APT)\* is a computer language for the analysis of the shape of machined components in terms of surface geometrical elements and the description of the basic motions of the tool needed to machine this shape, together with limits on motion defined by accumulated experience. The language in its present state of development comprises some 300 basic words and a capacity for about  $10^6$  instructions.

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\* For more details of the APT system and its capabilities, inquiries should be directed to the IIT Research Institute, Chicago, Illinois. For machining purposes, the system is presently in use by more than 50 major industries.

It is reasonable to believe that an analogous approach to forging die design is feasible. In practice, the starting point would be an examination by a designer of a drawing of the finished forging with dimensional tolerances and similar requirements. He would add machining allowances and classification of shapes. At this point the computer would take over, drawing on a score of forging rules and intermediate forging shapes right back to the raw material, perhaps in the form of bar stock. For each step, it would compute the shape and dimensions of the dies required and convert these into instructions for the die sinking machines.

Advantages of this system can be seen in terms of reduced die inventories, closer product tolerances, higher machine productivity, shorter lead times, ease of inspection and modification, and the profitability of batch productions smaller than presently allowable.

Clearly the APT system is no substitute for basic knowledge of the forging process and the computer could not take the place of a skillful inventive designer. What it can do is memorize in well ordered form, the best of existing practices and apply it in a routine manner. Moreover, it can upgrade its instructions by continuously absorbing new information on improved practices. The computer's three virtues are total memory recall, high speed scanning and processing of available language, and consistency. These could enable it to match and maintain the best performance capable of a highly experienced, though not particularly inventive, die designer.

Given that a useful language can be developed to store and constructively retrieve information on die design sequences, its output instructions can only be as sophisticated as the extent of information and experience input. Obviously, this would be maximized if all forging companies pooled their resources. This is an unlikely event, but the APT system does not depend on willingness to share proprietary data and experience. The computer can be instructed to compartmentalize proprietary data. In fact this may be necessary because a given set of forging steps may reflect the equipment resources of one company. The die design solution

offered by a potential APT scheme would, in general, at least optimize the individual company's experience. The success of an APT system would offer advantage to pooling experience and possibly stimulate such activity.

It is not the purpose of this committee to anticipate and weigh the problems of industry acceptance. Its responsibility is to identify the nature of valuable technology and scientific achievements; evaluate their feasibility; and point out the most advantageous and expeditious route. In the present case, the issue is whether forging shapes and die cavities can be translated into a useful computer language by which existing experience of any given aggregation can be utilized more effectively and consistently. The recommendation below is designed to establish feasibility.

#### Recommendation

It is recommended that a pilot study be undertaken of the feasibility of the design of forging dies by computer on lines similar to the APT scheme, together with an appraisal of the practicability and economic value of the method. Information should be gathered about a limited number of forgings now manufactured and belonging to a difficult class of shapes. Half of this information should be used to provide the needed data to establish the computer procedure; the other half to test the predictive power of the method. The support of leading forging companies for the scheme should be enlisted, in the first instance, on the understanding that it does not require the pooling of proprietary information about die design methods. Advantage should be taken of existing success in codification of shapes of components achieved both in this country and elsewhere.

### 3. Incremental Forming (February, 1968)

Involved wrought shapes having no longitudinal symmetry are made by closed die forging. This may be broadly described as a process whereby a block of metal is constrained by simple motions of a machine to conform to the confines of a complex rigid cavity. The evolution of a shape may require several stages, but the unit operations themselves primarily involve simple motions and rigid tools of complex profile.

The major cost and time factors in closed die forging derive from the problems associated with the die cavities. The design of die cavities is largely an art dependent on the accumulation of prior experience. For the same finished part, probably no two forge shops would design their die cavities identically. There is an operational trial and error period. Die sinking is an expensive procedure. Wear and checking impose limited lifetime and repair possibilities to expensive investments. As a result short runs make for abnormally high unit costs.

It is useful and stimulating to consider the possibilities of alternative methods of forging that utilize tools of simple contour, controlled tool motions and highly versatile and controlled workpiece manipulation. Both tool motions and workpiece manipulation are amenable to programming. It demands not very much imagination to conceive of an automated forging machine, capable of making parts of various shapes according to an input tape or card instruction.

This is an ambitious concept; yet, most of the parts and features are within the present technology. Numerical control of machining operations is a reality. The present ability to program the carving of involved shapes from metal blocks using sophisticated machine tools and control equipment makes the mental transposition to a forging or forming operation deceptively easy. The control and integration of tool advance and workpiece manipulation in open-die forgings, and program control of the complete operation of forging oblongs has been accomplished in Great Britain. This work demonstrates both the principle of feasibility and the basic problems

If we define "Incremental Forming" as a process by which complex product shapes are generated by means of tools of simple shape which deform the workpiece by numerous small amounts, then a number of existing operations fall into this category. Of these may be listed flat rolling, rolling of sections, some sophisticated swaging operations and shear forming or shear spinning. These operations, while falling into the general definition, are each of very limited versatility. Whether one pursues the obstacle to advances in these limited operations or labors with the idea of plastic forming with the spatial freedom of a sculptor, the root problem turns out the same.

In machining, shape is created by removal of material. The removal of material from one location has no effect on the shape elsewhere. However, shape by forging results from material displacement. A cavity is formed only by spreading metal away from the tool and piling it up around it. Thus, there are general shape changes as well as local shape changes. For automatic forging, the details of each subsequent tool advance and workpiece positioning requires specific knowledge of the prior shape of the workpiece. Since this is continuously changing, there must be a means for estimating or sensing the progression.

The dilemma lies herein. Even in the simple case of squeezing a rectangular bar between narrow, flat-faced overhanging tools, the ratio of spread to elongation cannot be computed from any first principles. For the British automated forging operation referred to previously, it was necessary to develop essentially empirical relationships upon which to work out a program. No one can anticipate when the appropriate new "first principles" will be forthcoming. They were the subject of earlier recommendations by this committee. Therefore, the conclusion has been reached that the furtherance of progress in incremental forming operations, whether they be of limited or universal versatility, requires the accumulation of empirical relationships.

The relationships are more profitably chosen when they relate to some useful operation. Since the forging of rectangular bars has been worked out in considerable detail, the next reasonable step is the category of shapes characterized by airframe members with thin webs and ribs and often a complete lack of symmetry. The present practice is to forge these between closed dies, irrespective of their size. This leads to the need for monstrous machines. The thought that such shapes could be fabricated by smaller machines with versatile tool and workpiece motions is unquestionably inviting. For this, empirical relationships describing shape changes by indenting tools are required. It should be possible to acquire these for the typical engineering materials of aircraft construction.

#### Recommendation

Adapt as the vehicle for study, the evolution of shape from a solid block of metal by successive indentations in open die operations to the preform for a thin web - thin, high rib configuration. By combined theory and experiment, develop functional relationships which describe the shape changes with successive indentations. Demonstrate, in principle, that these relationships can be used to provide a program of shape evolution to a typical airframe structure member.

### E. NEW APPROACHES TO METALWORKING

#### 1. Vibrational Energy in Metalworking (March, 1965)

It has been demonstrated that the application of vibrational energy to metal undergoing plastic deformation can reduce the magnitude of static stress required to produce that deformation. Further, many workers have demonstrated that application of vibrational energy to deformation-type metalworking process such as upsetting, extrusion, and wire drawing, can result in decrease in the static forces required to carry out these operations. To date, these accomplishments have been attributed to:

- (1) The decreased flow stress required for plastic deformation of the metal referred to above.
- (2) Reduced friction between the workpiece and the die.

Taken at face value, the influence of 20 kc vibration on the static stress-strain curve of Al and Zn single crystals is very impressive. For example, an Al single crystal will yield at about 1.3 kg/mm<sup>2</sup> under conditions of uniaxial tensile testing. With the superposition of 50 watts/cm<sup>2</sup> of ultrasonic energy, the static stress to accomplish plastic strain over the same strain range is less than 0.5 kg/mm<sup>2</sup>. The thermal energy concentration required to produce the same apparent softening is about 10<sup>7</sup> times larger than the ultrasonic energy applied.

Polycrystalline stainless steel with tensile flow stress of about 23 kg/mm<sup>2</sup> (~33,000 psi) proof stress and 33 kg/mm<sup>2</sup> (~47,000 psi) tensile strength (~25% elongation) yields at no more than a few kg/mm<sup>2</sup> under the action of 25 kc vibration at a calculated acoustic stress of  $7.5 \times 10^7$  dynes/cm<sup>2</sup> (~1100 psi). Polycrystalline Be flows plastically at similar acoustic stress levels. In both cases the tensile ductility at fracture was unaffected by the action of the vibration irradiation. Clearly the calculated acoustic stress can only be an average number. In order to account for the yielding action, it is necessary to postulate either that large local stress intensifications develop or that somehow the yield strength is reduced.

To justify appreciable expenditure of research and development effort on this subject, there must be some appreciation of its probable advantages. At this point there are two potential features which are attractive. The decrease in static forces required to perform a given plastic displacement would reduce the size of machinery, increase the capacity of existing machinery, and increase the rigidity of machinery and tools. Each of these factors has a great bearing on the operational cost processes limitations and product accuracy. The use of vibration to reduce friction enhances the efficacy of lubricants and conceivably in some instances simulates lubricity where normally lubrication is difficult or impractical.

The mechanism by which vibration reduces static flow stress is presently only in the speculative stage. The consensus holds that local intensification of stress, or local generation of heat through energy absorption (or both), must be occurring. The chief dilemma is the scale of this local zone. The design of experiments to prove hypotheses is very difficult. The mechanism of enhancing lubricity is another vague issue despite the fact that the use of vibration in the smooth feeding of parts on conveyors and elimination of sticking of hydraulic valves has been known for a long time.

Preliminary experiments using ultrasonic energy in such operations as up-setting, extrusion, and wire drawing have been made and in each case reduced static flow stresses have been recorded. However, none of these experiments has yet demonstrated a capability which cannot otherwise be attained by simpler and more conventional means. It is important to the future of ultrasonic energy applications that such exploratory tasks should choose objectives which are clearly challenging. It is all the more important to provide impressive justification because it is already clear that serious roadblocks can be recognized to the scale-up and application to real machines and processes. It may be that deformation processes applied to bodies of significant size may require kilowatts of acoustical power in the megacycle range. Such a combination is not presently feasible, either technically or economically.

Assuredly, it will be necessary to concentrate power in local areas which is not always technically feasible by present design approaches. During deformation processing, the varying conditions of coupling between transducer and load may require the ultrasonic generator to respond instantaneously with large changes in impedance and frequency. This ability is not yet technically feasible.

It is clear that a progression of accomplishment in logical sequence of priority is necessary to further this subject in an efficient manner. There are elementary experiments to be performed before anything further is justified. In this respect, there is first a need to know the relationships between static flow

stress over the entire plastic strain range, vibration frequency, vibrational energy (in the specimen), or vibrational strain amplitude (if this is measurable), and strain rate for representative engineering materials in their characteristic microstructural conditions. Second, there is a need to assess the contribution of vibration to reduce friction in lubricated systems. This will probably involve drawing operations wherein the draw force is measured. However, since the draw force is a composite of flow resistance stresses and friction stresses, the answer to the question of enhanced lubricity cannot be separated without the results of the first pattern of experiments. There is reasonable expectation that the lubricity factor can be directly measured by the Pawelski method. The lubricity studies must be done over a typical range of drawing speeds and ancillary observations should be made on workpiece surface condition and die wear.

#### Recommendation (1)

Initiate a new program or modify an existing program to measure the flow stress and ductility of representative and important engineering materials in their characteristic metallurgical states as a function of:

- (a) frequency of vibration.
- (b) energy input into the specimen, or alternatively, cyclic strain amplitude. In any event, the results should be qualified by measurement of coupling efficiency between the energy source and the specimen, and the experiment should be so designed that acoustic stress levels can be measured precisely at the point where yielding is occurring.
- (c) strain rate as regards the pseudo-static component of load.
- (d) degree of prior plastic strain.

### Recommendation (2)

Measure the coefficient of friction in a strip drawing operation under the influence of vibrational energy. The scope of the program should include appropriate frequencies and energy inputs (with measured coupling efficiency) and drawing velocities up to those characteristic of commercial operations.

### Recommendation (3)

Develop methods for improved coupling efficiency between energy sources, tool and workpiece, and methods of measuring same. This task should follow upon recommendations (1) and (2) and be predicated upon their success.

All phases of research and development of this subject should be preceded by a critical assessment of prior and existing work. Furthermore, a general qualification of the process should include post-examination of the properties of worked materials processed in this fashion, including uniformity of structure, soundness, ductility, toughness and fatigue damage.

### Some Later Comments on Vibrational Energy in Metalworking

Since early 1965, there has been much progress in coupling efficiencies to where 75-85% are now common; in impedance matching, in frequency control, and in increasing the power output of ultrasonic generators. Modular generators producing 50 KW are now readily available. The cost of producing ultrasonic power has now gone from \$4.00 per watt, using electron tube frequency converters, to \$1.00 - \$1.50 per watt, using solid state generators.

Additional metalworking progress has been made. There has been more evidence of success in tube drawing and tube shaping where production status has been reported. Here breakage reportedly has been reduced, surface finish improved, reduction per pass increased, chatter eliminated, and the number of interstage anneals reduced.

Large improvements in coupling have been made through the use of a force-insensitive mount for transducer-coupling systems. Here, the transducer is applied at a nodal point in a standing wave system.

It has been found in ultrasonic wire drawing that as the velocity of the workpiece is increased, the reduction in the work force decreases from 50% to a value of about 6%. This velocity, at which the minimum force reduction has been encountered, is about four meters per second. (The velocity has been defined as "RMS" velocity of the workpiece being vibrated). This effect of drawing rate has been explained as a relationship between mechanical power and ultrasonic power. To maintain the low velocity relationships at high velocities, the ultrasonic power must also be increased.

From the standpoint of understanding, there remains the need to further clarify the various possible operating mechanisms: local intensification of stress, local generation of heat, reduction of friction between tool and workpiece and others.

It would seem inevitable, as techniques improve and equipment capacities increase, that practical application of ultrasonic energy in metalworking will broaden. The applications are to be anticipated in sophisticated forming operations where unusual criteria are to be met, rather than in applications of direct substitution for more conventional and less costly forms of energy and materials.

## 2. Hydrostatic Extrusion (March, 1965)

In this process, a cylindrical billet flows through an extrusion die by the action of hydrostatic pressure. Several distinctive features of the process are:

- (1) no contact between billet and container walls.
- (2) the billet is supported laterally by the hydrostatic pressure.
- (3) the die angle is usually smaller than in conventional extrusion.

The hydrostatic fluid pressure may be generated either with a high-pressure intensifier or by compressing the fluid in the extrusion container with a moving ram and seal. In another variation of the process, the extruded product may exit into ambient pressure or into a pressurized container. The latter method (the two chamber system), using a pressure differential (fluid-to-fluid extrusion), appears necessary for the successful extrusion of brittle solids.

#### Potential Advantages of Hydrostatic Extrusion

- (1) Friction between the billet and container wall is largely eliminated by the separating character of the hydrostatic fluid. This removes a major limitation on the length of billet in those systems designs which replace the punch by a ramless pressure intensifier. Maintenance of continuous fluid film between the die and the exiting extrusion and consequent low friction is verified in hydrostatic extrusion by observations of fluid on the outside of the extruded product, of preservation of machine marks originally on the billet onto the extruded product, and of low die wear and pickup.
- (2) The redundant shear deformation is low because of the low die angles permissible in hydrostatic extrusion. Hardness profiles indicate almost complete uniform working across extrusion sections.
- (3) The above factors result in reduction of extrusion pressure. In certain experiments with aluminum, the relationship between extrusion pressure and extrusion ratio in hydrostatic extrusion is nearly equal to that for homogeneous ideal deformation.

- (4) Because high hydrostatic pressure restrains fracture, it is possible to extrude brittle solids in a two-chambered system that would crack in conventional extrusion. Similarly, marginally brittle materials extrude with less frequency of cracks in hydrostatic extrusion. Brittle solids do not retain ductility after removal from the hydrostatic pressure environment unless some vital change in structure has accrued.
- (5) The billet is laterally supported by the uniform hydrostatic pressure and because of this, it lends itself to the extrusion of wires or filaments.
- (6) Simplified die construction is permitted because the extrusion die can be externally supported by the pressurized fluid.
- (7) Through hydrostatic extrusion, the potential exists for producing complex shapes in difficult materials which are not now feasible.
- (8) The conditioning of cast materials which are unforgeable or difficult by cold reductions of modest magnitude has potential value. Smaller cold reductions followed by annealing can produce grain refinement equivalent to that accomplished by larger reductions (conventionally practiced) at elevated temperatures. A number of superalloys are regarded as unforgeable simply because there is no way to deform the cast structure without cracking.

#### Present Limitations of Hydrostatic Extrusion

The chief deterrent to wider adoption of hydrostatic extrusion is the current lack of engineering equipment to sustain quite high fluid pressures in a vessel

with an ID of about 6 inches. Assuming ideal deformation (certainly an optimistic assumption) the fluid pressure required to extrude a material with a flow stress of 100,000 psi varies with extrusion ratio in the following manner:

<u>Extrusion Pressure, psi</u>	<u>Extrusion Ratio</u>	<u>% Reduction</u>
69,000	2	50
139,000	4	75
230,000	10	90
300,000	20	95

As presently practiced, hydrostatic extrusion is essentially a room temperature process. The maximum reported operating temperature of 700°F. is too low to lower, significantly, the flow stress of superalloys and refractory metals. Thus, the potential advantages of minimizing oxidation and contamination in refractory metals are obscured by the necessity to work with tiny billets at low extrusion reductions, e. g., molybdenum alloy TZM required 350,000 psi to extrude from 0.15 to 0.125 inches in diameter (30% reduction).

Static high pressure units, based on the General Electric Company's belt apparatus, have been used for high pressure research and the commercial production of synthetic diamonds. The belt apparatus is not suitable for scale-up. However, a hinged cubic apparatus involving six three-inch diameter rods stressed in shear has been built by Barogenics, Inc. This unit employs a force of 2,700 tons per head. A large unit (10,000 tons per head) which is capable of producing up to 25 kilobars (350,000 psi) to a volume of one cubic foot has been designed but not yet constructed.

The pressure transmission fluid presents a problem in this area. All known fluids freeze above about 30 kilobars. High pressure equipment above this level use pyrophyllite, but this is far from an ideal pressure transmitting medium.

Conventional design of high pressure cylinders is limited by stress distribution. Although considerable advantage can be gained by using shrink-fitted rings, the maximum safe limit for present steels is 6 to 9 inches ID at 250,000 psi pressure.

A design which eliminates this design limitation is the pin jointed plate cylinder. In this design, the stresses developed by the internal pressure are carried by the shear pins.

Another problem in pressure vessels is end closure. Bayonet type closures can be quick opening, but they are difficult to seal. A T-ring seal developed by Barogenics does not need preloading. This has been tested in a 20,000 psi hydrostatic unit of 30 inch length.

Opinion has been expressed that it should be technically feasible to construct equipment to carry out hydrostatic extrusion of alloy steel at room temperature to pressure up to 450,000 psi with an extrusion ratio of 20:1. A typical billet size would be 18 in. x 36 in. A 50,000 ton press would be needed for this operation.

Illustrations presented were largely design concepts. While they incorporated numerous novel approaches which seemed very attractive and promising, the fact remains that little has been done in prototype construction and testing. The present position is that we have enough design concepts to be encouraged, but the feasibility of hydrostatic extrusion on an industrial scale will not be advanced until these design concepts have been subjected to detailed analysis and prototypes constructed and tested.

#### Recommendation

Institute a program of detailed engineering evaluation of available design concepts with a view to selecting and qualifying an improved two chambered hydrostatic extrusion system applicable to the harder engineering materials of special billets with primary chamber pressure in excess of 300,000 psi.

### 3. Exploration of Hydrostatic Forming (October, 1965)

The Panel on Application of Deformation Theory to Practice was established to give more thorough study of the possibilities of applying unexploited phenomena and principles to new metalworking processes. Its first action has been to explore more diverse utilization of hydrostatic pressure to forming operations. The meetings of this panel fortuitously coincided with the first publication\* of a development program in this subject area at the Engineering Research Center of the Western Electric Company, Princeton, New Jersey. The opportunity was taken to discuss with the author the logical areas for further expansion of the capabilities of the process.

Briefly, the Western Electric Company development involves the novel design of a very high pressure container (up to 500,000 psi) which makes use of secondary hydrostatic pressure to support the working liner. The system has been engineered for rapid opening, closure, sealing and actuation so that it can be applied to production operations with substantial economic gain. The following forming operations have been demonstrated; each representing achievement of a final shape which would require, by normal procedures, a number of successive operations. Whereas a cupping operation is usually limited to blank/cup diameter ratios of about 2:1, the hydrostatic cupping permitted a blank/cup diameter ratio of 4:1. Perhaps more significant is the fact that the primary active force is compressive against the blank periphery rather than tensile around the punch.

Tube expansions were accomplished with 100% increase over the original diameter without reduction of wall thickness, whereas, a 30% expansion is normally considered limiting. For the retention of wall thickness, an axial compressive stress was applied in conjunction with the expansion pressure. Flanges were formed on thin-walled tubes with flange thickness of more than four times the tube wall thickness. In normal spinning operations, the flange thickness would not be appreciably different from the tube wall. These operations were applied to soft metals such as Cu, Al and mild steel.

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\* F. J. Fuchs, Jr., Production Metal Forming with Hydrostatic Pressures, ASME Reprint No. 65-PRCD-17, June, 1965.

Discussions of the subject brought out a number of salient points:

- (1) Hydrostatic pressures up to 500,000 psi had been used.
- (2) The common engineering materials including copper, brass, and mild steel did not require pressure greater than 200,000 psi for significantly increased ductility.
- (3) The forming of molybdenum cups had been successfully accomplished with the Western Electric apparatus.
- (4) Cycle time for producing parts using the Western Electric apparatus has been as short as 20 seconds.
- (5) Most of the metal properties of the parts formed in this fashion had not been determined.
- (6) The viscosity and lubricity of the hydraulic fluid under high pressure is of considerable significance.
- (7) The unique dual pressure tooling system of the metal forming device suggests a number of ways for further exploitation of high pressure processing.
- (8) The fatigue resistance of the pressure chamber is apparently adequate and the system is very promising.
- (9) The large shape changes accomplished in one operation indicate that the flow of metal was always under hydrostatic pressure (i. e., tensile stresses were at all times low or negligible).

At this point, the real challenge is the application of hydrostatic pressure to more difficult materials which are stronger and more prone to cracking with small plastic strains. Undoubtedly, higher hydrostatic pressures will be needed to prevent cracking and the minimum requirements are important matters to be defined.

The forming of short-length tubes from sheet blanks represents an end product of present importance; the operation now has precedent at least in softer metals; and successful development would have great value in by-passing the expensive and cumbersome procedures presently followed. Certain recommendations were directed toward evolution of tooling.

Recommendation (1)

(Priority A) Disseminate the information on the Western Electric Company's work to makers of equipment and to the users of metal forming equipment in order to stimulate spontaneous exploitations of the opportunities demonstrated for high pressure, hydrostatic metalworking.

Recommendation (2)

(Priority A) With pressure as the primary variable, demonstrate the applicability of hydrostatic forming to more difficult-to-form metals such as appropriate titanium alloys, superalloys, alloy steels, refractory metals and beryllium in the three operations:

- (a) Determine limiting ratio of blank to cup diameter for sizes suitable as tube blanks.
- (b) Determine drawing limits of thin-walled, short length tubes using the tube blanks from (a).
- (c) Determine the capacity to form end flanges on thin-walled tubes from (b)

Assume recommendations (1) and (2) lead to improved deformation processes for the less ductile metals, then recommendation (3) below is appropriate.

Recommendation (3)

Determine process and equipment variables and metal limitations for the extension of the high pressure hydrostatic metal forming techniques that have already been demonstrated.

- (a) (Priority B) Investigate tools, pressure fluids, lubricants, pressure transmission and measurement, friction, and wear to permit extending the new technology to higher pressures and to allow greater efficiency at current pressures.

- (b) (Priority B) Investigate properties of materials of construction for the desired higher pressures and faster cycling times.

4. Practical Application of Superplasticity (February, 1968)

A few years ago, the substance of this committee's recommendations was that a better understanding of the nature and origins of superplasticity and of the diversity of susceptible materials was necessary. Research, subsequently, in various laboratories has provided much of this. There are many more examples of the phenomenon now. There are recognized criticalities in microstructural condition, temperature range and strain rate range. There is a reasonable grasp of the fundamental processes that are responsible.

It seems timely and appropriate to give some consideration to the potential roadblocks to engineering exploitation. We may assume that the roster of susceptible alloys will increase substantially by the momentum of existing activity, but the restriction to a temperature and strain rate range can pose some awkward consequences. For all of the important engineering alloys, the critical temperature range is quite high, e. g. , above about one half of the absolute melting temperature.

Furthermore, the maximum allowable strain rates are in the range of  $10^{-3}$  to  $10^{-1} \text{ sec}^{-1}$  which is much lower than that associated with most conventional metalworking processes.

Because of the low strain rates, it is necessary for the workpiece to have a long dwell time on the dies--should the dies be used in a conventional sense. Therefore, the dies would have to be held at the same temperature. Accordingly, "superplastic" deformation must be regarded as isothermal deformation. Existing hot die technology is probably adequate for alloys based on Al, Cu and Mg; but, it is probably not adequate for Fe, Ti and Ni alloys which seem to require temperatures in excess of 1500°F.

The obvious applications of superplasticity are related to sheet forming. With materials such as titanium alloys, the temperatures and dwell times pose special problems of oxidation and contamination, which are already problems in simple stress relief operations between heated dies.

The exploitation of superplasticity in the near future will probably follow two directions:

- (1) Manufacture of thin-walled shapes of complex contour by pneumatic or hydraulic forming in a female die using sheet of aluminum and perhaps magnesium or zinc alloys. These are single step operations not presently possible.
- (2) Extension of conventional forming operations in difficult materials to sharper bends, larger stretch and fewer stages.

Direction (1) is being pursued by private enterprise. It is not very likely that progress will soon overlap into defense industry operations where the difficult-to-form materials abound. It is timely to instigate a manufacturing development task which will reveal the potential for improvement in conventional forming and also make more clear the magnitude of the problems associated with hot dies and show displacements.

#### Recommendation

For the near term, concentrate on a single and relatively simple forming operation such as bending to a small bend radius (less than 1 t). Choose a titanium alloy which can be superplastic, a number of which are available. Utilize the best available technology for hot dies. Analyze the ability of present dies and machines to produce very sharp bends without serious contaminating embrittlement. Compare the strains allowable under best operating conditions to those obtained in laboratory tensile tests under superplastic temperature and strain-rate conditions. From this work, determine the control features necessary (and present availability) for a production forming operation.

#### 5. High Energy Rate Forming (February, 1968)

The subject of high energy rate forming is very current. A substantial amount of government funding supports R and D in this area. Accordingly, there is no lack of discussion, technical meetings and guidance committees. After a limited sortie into the subject area, this committee decided its efforts should be directed along less well travelled paths.

However, a number of questions of some consequence were raised that did not seem answerable by previous or present work. These might be briefly noted:

- (1) The service properties of materials experiencing high energy rate forming and particularly shock hardening are not well known. Specifically the transition temperatures of shock hardened materials was in question. Information on post-hardened toughness and ductility in general seemed lacking.
- (2) In what way is critical strain and subsequent abnormal grain coarsening by annealing to be avoided in high energy rate forming and shock hardening? This subject does not seem to enter into present thinking.
- (3) The influence of very high strain rates on useful ductility does not seem to be resolved in any generalized fashion.
- (4) There seems to be very little information on the efficiency of energy transfer in explosive forming and the factors which influence it.

#### 6. Thin Sheet Rolling (October, 1965)

The two major issues in thin sheet production are control of gage uniformity and shape. Shape connotes all nonplanar convolutions which make for deviations from flatness when a length of sheet in the absence of applied tension rests on a table. There are several varieties of planar deviation. These include, for example,

simple curvature across the width; approximately sine wave ripples along the sheet edge or along the center line; periodic and aperiodic markings whose long axes are inclined to the rolling direction (herringbone).

Shape and gage control are interdependent. Given that one acquires reroll stock from primary rolling operations which is acceptably flat and has a certain gage variation from edge to mid-width, the final flatness of the finished sheet will be governed by how closely the final gage variation, across the width, replicates the initial condition.

If in the cold finishing operation, the gage variation is changed, it is inescapable that a change in the flatness character will result. This is simply because some points across the width are extended more than others. Should the relative extension be such as to compensate the initial condition, the flatness will improve. Alternatively, the out-of-flatness can worsen. It is important to realize the differential strains to produce significant edge or center ripple are less than 1%.

In the control of gage and flatness, the roller has a number of process variables at his disposal--strip tension, screwdown pressure, roll cooling, unstressed roll profile (camber), and lubrication.

The present dilemma is that the roller cannot really judge the success of his control until a coil has been rolled. On-line control requires some form of instrumentation that indicates out of flatness while the sheet is being rolled and is under the tension applied by the coilers. With such a device, one can readily imagine a new dimension in feedback control of the processes.

In broader view, the final sheet quality is governed by three phases of processing factors. The first of these, and one of almost dominating importance, is the character of the reroll feed stock. The closer this matches the allowable tolerances in the finished product in gage variation and flatness, the easier it will be to produce the final product to quality specifications by finishing cold rolling. The second of these is the control the roller has in the mill operation itself, as briefly outlined

on the previous page. The third factor is the ability to correct final rolled flatness by other than rolling operations--notably by the bend-stretch principle of roller leveling.

All of these will be contributory to the quality of the final product, but the most room for future improvement seems to lie in the direction of more positive control of the finish rolling operations.

Part of this problem is quantitative appreciation of the relationships between certain operational factors and gage variations. The obvious ones seem to be reasonably well understood as, for example, the origin and character of edge or center ripple. What does not seem to be understood at all is the nature and origin of "herringbone". As its nick-name implies, the defect is periodic and its major dimension is inclined from the direction of rolling. Its occurrence is not specific to any metal and the circumstances of its occurrence do not represent any special set of critical conditions by existing observation. It is not likely, therefore, that it can be brought under control until a better understanding is attained.

The ability to control flatness variations of all kinds in process depends on the development of means for measuring the condition quickly and while the coil is being rolled. One can envision a sensor at the exit from the rolls, or at least somewhere between there and the coiler, which registers a signal quantitatively related to the flatness variation across the width. One such device has been described recently by Pearson,\* and his paper would be required reading for anyone concerned with this subject. The method, though simple in principle, is not at all simple in the instrumentation. It is to be hoped that alternative, preferably non-contact, means can also be developed. This should be the subject of a task. There are two basic approaches. One, as with Pearson's method, measures the out-of-flatness while the strip is under tension. The second would measure the stress variation in the strip across its width. This might be inherently more tractable because large stress variations are expected to exist even with small variations in flatness.

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\* W. K. J. Pearson, *Journal Institute of Metals*, 93, 1964-1965, 169-178.

Flatness control is of sufficient interest to the whole thin sheet industry that it is probable that substantial efforts in this direction are already in progress. Therefore, the committee will not make a special case for a government sponsored program to identify physical methods for on-line flatness measurement. However, it is the committee's opinion that if some new concepts are presented to the agencies supporting research and development, then these should receive favorable consideration in the light of the significance of the flatness problem to the difficult materials.

The "herringbone" defect, however, has been neglected as a subject for analysis and prevention and, therefore, merits special attention. The following describes a research task whose results would be of value to the whole sheet rolling industry.

#### Task Description

The objective is to define the nature, origin and process factors governing the occurrence of the "herringbone" defect in thin cold rolled sheet. The approach must be both analytical and experimental such as to provide generalized conclusions. From examination of actual cases in terms of gage pattern, surface profile and surface character, it is expected that appropriate deductions as to origin can be made. These deductions must be proved out on an experimental mill so that the defect can be produced deliberately. The remaining portion of the program should be devoted to a study of process factors (possibly roll surface condition, roll profile, rolling speed, tensioning and lubrication) which influence "herringbone" occurrence and provide the background information by which an operator can intelligently impose corrective action.

7. An Appraisal of the Contact-Bend-Stretch (CBS) Mill  
(February, 1968)\*

As a support activity, the potential of the Contact-Bend-Stretch (CBS) rolling mill was the subject of discussion and study by the Panel on Application of Deformation Theory to Practice. An elementary rolling mill deforms by compression. Sophisticated strip mills deform by combined compression squeeze and tensile stretch. The CBS mill achieves deformation by an unusual combination of compression, tension and bending. By minimizing the compression load contribution, considerable simplification is allowed in the mill frame. Some of the problems associated with roll deflections and distortions become of lesser significance.

Basically the CBS mill is a three-roll configuration with a very small diameter roll nested between two relatively large diameter rolls. The center line of the small roll is offset from the line of centers of the larger two and the magnitude of offset is one of the control features. The larger rolls rest in a mill frame with appropriate bearings, while the small roll is contained by the strip feed which is threaded around so that a zone of contact exists between the small roll and each of the larger rolls. For a more complete description, reference is made to a recent article by the author.\*\*

A succinct appraisal of its interesting design and operating feature and some of the areas of inadequate information follows:

- (1) The CBS mill has a smaller work roll (also called floating bend roll) and is unique in the simple effective manner of supporting a small diameter work roll.
- (2) Tandem design may be simpler to build and control. An additional stand requires one more floating bend roll and one more contact roll and control of the ratio of the speeds of the added contact roll and the exit contact roll of the up-stream stand.

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\* This date refers to the date of the report by the Panel on Application of Deformation Theory to Practice on the Contact-Bend-Stretch Rolling Mill.

\*\* L. F. Coffin, "Status of Contact-Bend-Stretch Rolling", Journal of Metals, August, 1967, pp. 14-22.

- (3) There is the possibility that rolling in a warm medium will be easier than with conventional mills.
- (4) From a production point of view, the mill's design and concept must be considered untried. For example:
  - (a) The life of the floating roll is not known, although 10,000 ft. of steel strip has been rolled at 500 ft. per minute with no evidence of failure.
  - (b) Little is known about friction and lubrication of the floating roll. In rolling titanium, reductions must be limited to 20% per pass to avoid pick up (20% per pass is good for titanium and thus is not a serious limitation).
  - (c) The mill's drive system has not been worked out.
- (5) The floating roll has the capability of bending into the gap between the contact rolls and compensates for lateral variations in the roll gap.
- (6) Gage control lengthwise is apparently good. This is done by control of the ratio of the speeds of the two contact rolls, not by control of roll gap as in conventional mills. Longitudinal gage is thus independent of variations in separating forces.
- (7) Reduction is apparently accomplished with fewer passes without structural damage and in the case of titanium with fewer interstage anneals. Actual competitive sizing on identical material using best practices with cluster mills of the Sendzimer type is not available.

- (8) With light passes, it appears possible to obtain a given reduction with less work hardening.
- (9) The mill provides apparently good edge control.
- (10) It provides an opportunity to examine the effects of complex stresses on metalworking processes since it combines bending with rolling.
- (11) Threading the mill with the stiffer material and heavier gages may require special equipment.

#### Specific Applications

- (1) The mill has the possibility of making titanium foil and strip more available and at lower cost. This follows from experimental evidence on a 3" CBS mill that it can reduce titanium and its alloys with fewer passes and with fewer interstage anneals.
- (2) The mill may make it possible to roll superalloys not otherwise rollable.
- (3) The texture of the product may be different and may be advantageous

#### Potential

To ascertain precisely what potential exists (and at minimum expense) the panel believes that certain evaluations (at relatively small cost) can be made before proceeding to the larger scale evaluations.

#### Recommendation (1)

Proceed with development and tests and with additional analytical and experimental studies to establish the potential of the CBS mill. This program should be on 3" wide strip. The General Electric Company's experience should be used

as much as possible but the program should also bring in new people, preferably those with substantial experience in rolling titanium. The experiments should include:

- (a) Rolling alpha titanium and alpha-plus-beta titanium alloys.
- (b) Determination of maximum allowable total reduction between anneals and comparison with results on a conventional (cluster) mill of the Sendzimer type.
- (c) Determination of gage variation and shape variations with comparisons from a cluster mill of the Sendzimer type.
- (d) Measurement of mechanical properties (including structural damage) of the mill's output and comparison with a cluster mill of the Sendzimer type.
- (e) Rolling titanium in heavier gages, i. e., up to 0.150".

Recommendation (2)

If the results from the recommended analytical and experimental program are sufficiently favorable, then it is recommended that a conceptual design study of a 24" CBS mill should be made. The study should include cost estimates and information for final design.

Recommendation (3)

If the results from Recommendations (2) and (3) are consistent with the military needs for the difficult-to-roll metals in wide sheet, then it is recommended that a 24" CBS mill be constructed to provide wide sheet capability.

### III. SOME THOUGHTS ABOUT THE FUTURE

Plastic working of metals today is largely a triumph of art. With relatively few tools of knowledge, but with a mounting inventory of successes and failures, the empirical approach to processing has been highly refined. Unfortunately this approach, while long on exploitation, is usually rather short on innovation.

The future of plastic metalworking processes is bound up with the transition from art to science and from science to engineering. The components of this transition emerged from this committee's activities.

Repeatedly the question arose of how to anticipate in detail the displacement of unconstrained metal under the general action of compressive stresses. With the solution to such a general problem will come new approaches to shape evolution. The keys to automated forming processes are to be found here.

Process failure is most often described in terms of fracture--cracking or tearing. To a large extent such process failure is presently regarded as some immutable limit of a particular metal. This fatalistic viewpoint derives from the frustrations of post mortem analyses. Yet we are very close to some detailed understandings of the subject. The simple recognition of the role of secondary tensile stresses is spawning new approaches to tooling that involve die shape, mechanical restraint or hydrostatic compression. When some of the engineering limitations have been worked out, many present operations will be more foolproof and many new operations, heretofore unfeasible, will be eminently feasible.

We shall see materials whose design recognizes processing requirements as well as service attributes. The success in achieving a large shape change is partly soluble by large force machines, partly by ingenious die design, partly by appropriate use of lubricants and finally, partly by the attributes of the plastic metal--flow stresses and strain capacity. Out of the basic studies on the subject presently called superplasticity comes a recognition that certain combinations of structure, strain rate and temperature make for remarkably low flow stress and large strain capacity.

The near future points to important exploitations. Metallurgical features such as inclusion population, grain size, and microsegregation which are presently recognized as germane to cracking will be more specifically characterized as to tolerable limits when their role in fracture is more clearly rationalized.

From the vantage point of more than four years of dialogue by this committee, it is not very difficult to foresee more versatile machines, economic short runs, close tolerances that require little or no machining, largely foolproof materials, and intricacies of shape presently reserved for casting processes as in glass and plastics. But this view was possible primarily because of the constitution of the committee whereby both the fundamental engineering and economic viewpoints were actively represented. The real dilemma is how to sustain this constructive interaction, for, if the committee accomplished anything, it was the demonstration of the efficacy of the contest and compromise of diverse viewpoints.

Unfortunately, however obvious this may seem, adequate interaction is not a common natural phenomenon. Prejudices, ignorance and language barriers work in opposition. A leadership factor is necessary. The R and D programs supported by DOD can be the vehicle for sustaining the interaction of fundamental and engineering viewpoints until it becomes a national habit. Interaction is not commonplace at present. Funded research tasks are carefully segregated today in terms of personnel, attitudes and training in accordance with the nature of the objectives. This antiseptic treatment will only perpetuate the schism.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D		
<i>(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)</i>		
1. ORIGINATING ACTIVITY (Corporate Author) National Academy of Sciences-National Research Council Materials Advisory Board 2101 Constitution Avenue, N. W., Washington, D. C., 20418		2a. REPORT SECURITY CLASSIFICATION Unclassified
3. REPORT TITLE Final Report by the Ad Hoc Committee on Metalworking Processes and Equipment		2b. GROUP
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report		
5. AUTHOR(S) (First name, middle initial, last name) Materials Advisory Board Ad Hoc Committee on Metalworking Processes and Equipment		
6. REPORT DATE August, 1968	7a. TOTAL NO. OF PAGES 76	7b. NO. OF REFS
8a. CONTRACT OR GRANT NO. DA-49-083 OSA-3131	8b. ORIGINATOR'S REPORT NUMBER(S) MAB 206-M	
b. PROJECT NO.	9a. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
c.		
d.		
10. DISTRIBUTION STATEMENT Qualified requesters may obtain copies from DDC Releasible to CFSTI		
11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY ODDR & E, The Pentagon Washington, D C.	
13. ABSTRACT In 1963, the Assistant Director (Materials) of the Office of Director of Defense Research and Engineering, Department of Defense, requested the Materials Advisory Board to provide advice and guidance to the Steering Group of the Government's Metalworking Processes and Equipment Program. The Government Metalworking Processes and Equipment Program is a coordinated effort of the Army, Navy, Air Force and NASA to identify salient factors which limit metal deformation processes and concurrently to sponsor research to extend these limits for improvement of manufacturing capabilities. Accordingly, the Materials Advisory Board Committee on Metalworking Processes and Equipment was organized to provide technical guidance to the program.  This is the final report of the committee. The advice of the committee and its two panels (one on Lubrication in Metalworking and the other on Application of Deformation Theory to Practice) is in the form of 34 recommendations for R & D in the following areas of metalworking: Vibrational Energy; Hydrostatic Extrusion; Laboratory Measurements of Mechanical Properties; Superplasticity; Ductile Fracture; The Application of Computers to Deformation Processing; Heat Transfer; Crystal Mechanics; The Function of Continuum Mechanics in the Analysis and Design of Metalworking Processes; Lubrication; Application of Deformation Theory to Practice; Limitations of Extrusion Processes; Thin Sheet Rolling; The Use of Computers in Forging Die Design; The Use of Model Experiments in Forging Die Design; The Application of Plasticity Mechanics to Forging Die Design; Mechanics of Ductile Fracture; Formability limits; Incremental Forming; High Energy Rate Forming; Plastic Strain Cycling.		

DD FORM 1473  
1 NOV 66

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Security Classification

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Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Metalworking Superplasticity Information packaging Incremental Forming Ductile Failure Formability Limits Plastic Strain Cycling Closed Die Forging Computers in Forging Die Design Model Materials In Forging Lubrication In Metalworking Hydrostatic Pressure In Metalworking Extrusion Rolling Thin Sheet Continuum Mechanics In Metalworking Processes Crystal Mechanics Heat Transfer In Metalworking Vibrational Energy In Metalworking Laboratory Measurement of Mechanical Properties Contact-Bend-Stretch Rolling Mill						

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