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TWENTY-SECOND QUARTERLY REPORT

OF TECHNICAL PROGRESS

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January 1, 1971

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ABSTRACT

This report summarizes results during the period 1 October through 31 December 1970:

- a. Investigation of D'austriche Method for Measurement of Explosive Detonation Velocity;
- b. Application of Explosive Welding to Hardware Configurations;
- c. Flange Buckling of Explosively Formed Domes;
- d. Cylindrical Explosive Forming Dies;
- e. Explosive Forming of Domes in Vented Die;
- f. Explosive Forming of Domes for Ground Based Pressure Vessels;
- g. The Edge Pull-In of Explosively Formed Domes;
- h. Fracture Toughness of Explosively Formed High Strength Steel;
- i. Explosive Welding;
- j. Explosive Powder Compaction;
- k. Explosive Forming of Thick walled Domes;
- l. Theoretical Studies of Explosive Energy Transfer to a Thick Walled Cylinder Using a Radial Piston;
- m. Explosive Thermomechanical Processing.

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I. MARTIN MARIETTA CORPORATION

1. Investigation of D'austriche Method for Measurement of Explosive Detonation Velocity

Principal Investigator: W. Simon

One of the problems in using powder explosives in explosive welding is the determination of detonation velocity for the particular conditions of the weld. The detonation velocity is a function of packing density and powder cross-section. The expense of either streak photographs or any of the various pin techniques prohibits their use for routine determination of velocity for each new welding configuration. Thus the D'austriche method, which determines the relative velocity of two explosives, is being investigated for use as a simple, inexpensive method of measuring detonation velocity. Figure 1 shows the configuration used in this investigation.

The primacord and explosive welding charge are mounted on a sheet of aluminum. The junction of the detonation fronts traveling down the two legs of the primacord makes a cut in the aluminum, thus giving a measure of the ratio of the velocity of the primacord to the explosive welding charge.

The detonation velocity of the primacord was determined by comparison with 8 gm/in² detasheet. This detasheet is sufficiently thick that the specification value for detasheet (22,300 ft/sec) should be accurate.

On this basis, the detonation value of 25 grains/ft primacord is 19,200 ft/sec. This technique was then used to measure the detonation velocity of SWP-2. The configuration was 6 gm/in², 2-3/4 in. wide. The detonation velocity was 5780 ft/sec. The specification value, at a somewhat higher density, is 9000 ft/sec. Pin velocity measurements made at another company, on a somewhat different configuration of the SWP-2, but with comparable density, gave from 5000 - 5600 ft/sec.

Work will continue on techniques to assure accurate location of the primacord. Then the precision and repeatability of the method will be determined.

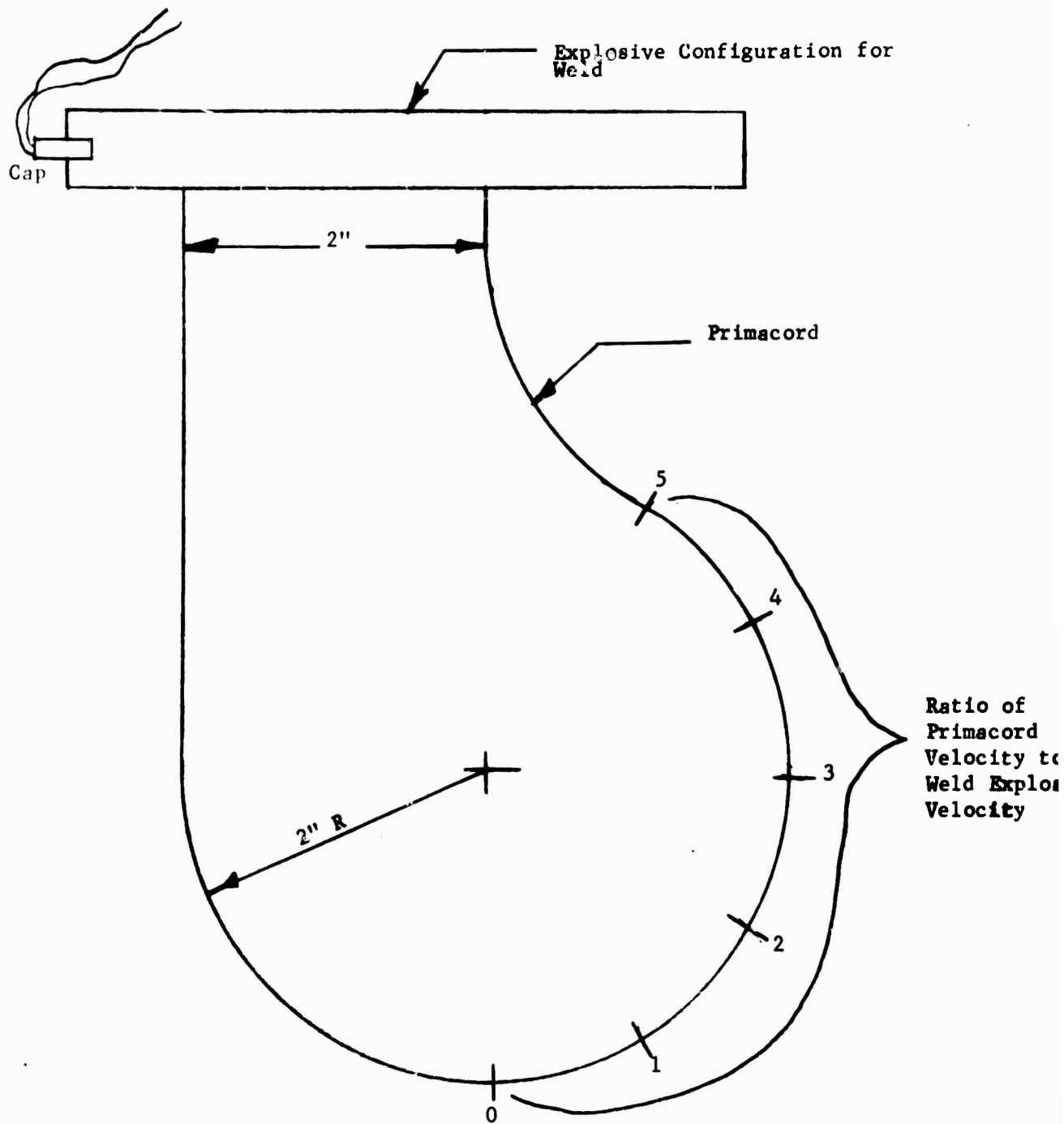


Figure 1 Sketch of D'aurriche Velocity Measurement Method

2. Application of Explosive Welding to Hardware Configurations

Principal Investigator: W. Simon

a. Explosive Welding of Copper Rotating Band to Projectile

An interesting problem has developed in connection with the rotating band on a high velocity 25 mm projectile. Due to the high torque requirements, a swaged band is not satisfactory. The planned technique was to use a weld overlay technique, but pickup of iron and carbon into the weld material has resulted in a rotating band with local hard spots. It was suggested that an explosively welded rotating band would solve the problem.

A short section of copper tubing (1 in. dia, .050 in. wall) was formed into a "V" configuration (10° angle), loaded with 1 gm/in² detasheet on the outside, and welded to the projectile (4340 steel). Figures 2 and 3 show 6X and 200X photos of the weld. Four projectiles have been assembled with the explosively welded rotating bands for test firings in the near future.

II. UNIVERSITY OF DENVER

1. Flange Buckling of Explosively Formed Domes

Principal Investigator: M. Kaplan

Graduate Student: H. Boduroglu

The stability analysis for the flange has been finished in the case of quasi-static loading. The predicted results agree very well with the experimental values provided by static testing. Parametric studies are now being carried out to determine the variation in the clamping pressure and the pull-in at the initiation of buckling with the material properties and geometric configuration of the flange. In order to correlate the static analysis with explosive dome formation, an estimate must be made of the additional clamping pressure provided by the blast wave.

2. Cylindrical Explosive Forming Dies

Principal Investigator: R. Knight

The effort at obtaining dynamic strain data as the blanks expand out to the wall of the die was successful. The data has been obtained using gages placed to measure hoop strains at the center of the blank and at a distance of one inch from each end of the blank. The data shows that an expansion wave travels down

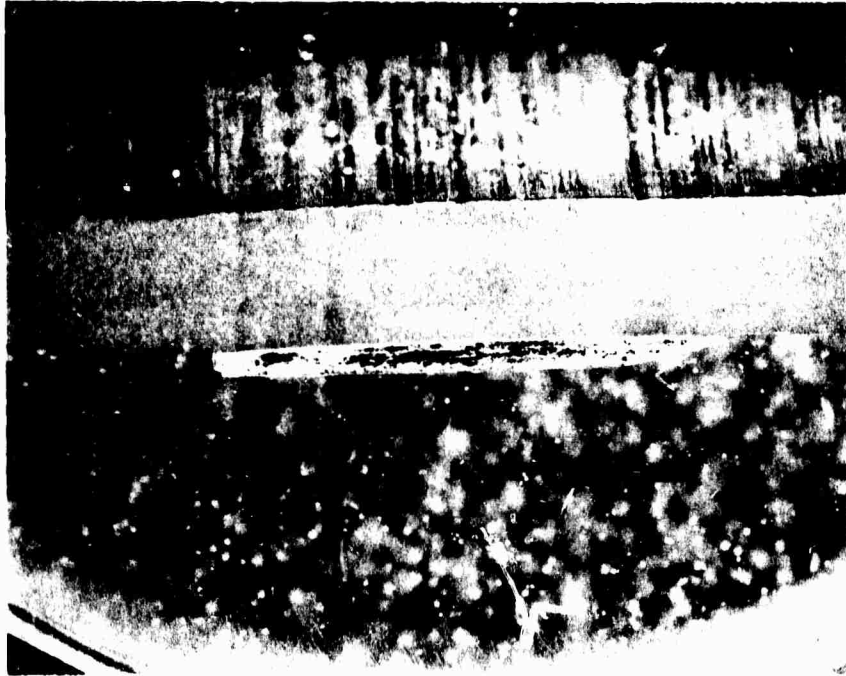


Figure 2 6X Photo of Explosively Welded Rotating Band



Figure 3 200X Photo of Explosively Welded Rotating Band

the tube from the ignition end. The strain signals are in good agreement until the blank strikes the wall of the die. The shock wave which travels back through the blank tends to break the strain gage material loose from its backing and the subsequent signals from the gages have no particular meaning and vary widely.

After the strain data had been obtained, a meeting was held to consider what the most useful information to be obtained in this program might be. It was apparent that the greatest need was a better prediction of the energy coupled from the explosive charge to the workpiece. Since this same information was the most needed portion of the dome forming problem, and since there is more activity in dome forming, it was decided to direct the effort toward the reloading problem in dome forming.

3. Explosive Forming of Domes in Vented Die

Principal Investigator: A. Ezra

Graduate Student: P. Hardee

During the last quarter a series of experiments were conducted using a five percent porosity die for the purpose of obtaining data on the pressure-time history between the blank and the die during the forming process. Because of the problem of mechanical shocks encountered when the blank struck the die, a slightly reduced charge was used which did not cause the blank to hit the die. Using this system, data was obtained which indicated that the computer program predictions were qualitatively correct although the predicted pressure levels were approximately twice that obtained experimentally.

In order to verify the computer program for a variety of points it was decided to conduct a series of experiments with different die porosities and with a uniform charge. The charge selected was the charge needed to free form the blank to the depth of the die used. A new die was constructed and the shock mount improved. An experimental program is planned in which three domes will be formed at each of five different porosities. These porosities will all be less than five percent starting from a value much less than one percent. Pressure data will be taken for each shot and qualitatively compared with the computer prediction for the same conditions.

4. Explosive Forming of Domes for Ground Based Pressure Vessels

Principal Investigators: A. Ezra, L. Alting

Graduate Student: R. Aderohunmu

The aim is to develop an optimum process of forming tank ends in which the present waste in material and time are significantly minimized. The first approach was to mechanically deep draw the blank and then dish it explosively while the punch served as hold-down device. While such process can be conveniently used in forming small parts it becomes unsuitable for relatively large parts. A modified process used was to cup the blank explosively and then skirt by deep drawing. The strain distribution of parts obtained by this second process is better and the drawing pressures required is small.

Two alternative forming processes were developed. For the above processes and these two alternatives, it was necessary to determine the minimum blank diameter that can be used without instability, thus minimizing waste in material. Using Dr. A. Ezra's criterion for minimum blank diameter, an analytical approximation was obtained. A practical minimum diameter was obtained by running experiments in which the B/D ratio was varied for different blank thickness. For materials with $D/t = 160$ and $D/t = 200$, the minimum B/D was found to be 1.25 with draw radius 0.5 in. and 1.167 with draw radius .25 in.

In the first of the two alternative processes the blank was formed with two shots. The first shot formed the blank into approximately a spherical shell and because of this initial shape the second shot draws more material into the die in such a way that a skirt is formed. This process is convenient and fast. There is no need to unclamp the part after the first shot. Parts obtained satisfy ASME requirements and have good strain distribution.

The other alternative was to dish the blank, sit it on a male die, and using a ring charge bend the flange into cylindrical skirt. While all four processes lead to substantial saving in material, the choice of process depends on the available facility. An automated die is to be designed for dishing and for completely carrying out the double shot process.

5. The Edge Pull-In of Explosively Formed Domes

Principal Investigator: M. Kaplan

Graduate Student: S. Kulkarni

The pull-in analysis is based on the rate of work approach. Originally, the Rayleigh-Ritz method was used to find an approximate tangential velocity field which satisfied the boundary conditions and rendered the rate of work integral stationary. This tangential velocity field was expressed in terms of arbitrary constants, the radius to the neutral surface " ρ " and the spherical angle " ϕ ". The analysis gave good agreement between the analytical and experimental values of pull-in for shallow to moderately deep draw depths. In order to improve the agreement for very deep draw depths, the tangential velocity was modified such that the arbitrary constants are now considered to be functions of draw depth. This change has been incorporated into the computer program and checkout is nearing completion.

6. Fracture Toughness of Explosively Formed High Strength Steel

Principal Investigator: H. Otto

Graduate Student: R. Mikesell

Impact tests have been conducted on several 4130 and 4340 steel specimens in the cold rolled and as-formed conditions. Prior tests had been conducted on the same type of material that had been austenitized and tempered at 600°F. Strain in the specimens was about 0.05. Specimens were taken with orientations longitudinal and transverse to the original rolling direction.

Although these tests are incomplete, some trends have been established. Results to date are presented in Figures 4 and 5. With the 4130 steel the effect of both original grain orientation and cold working modes does influence the impact strength and transition temperature. The combination of transverse grain orientation and cold rolling gave the highest impact strengths. In the transverse orientation, explosive forming appears to lower the impact strength and raise the transition temperature. Explosively formed specimens with a longitudinal grain orientation had higher impact strengths and lower transition temperature when compared to cold rolled counterparts.

Orientation effects were also noted with the 4340 steel that had been explosively formed. The ductile-to-brittle transition temperature of the explosively formed specimens with a

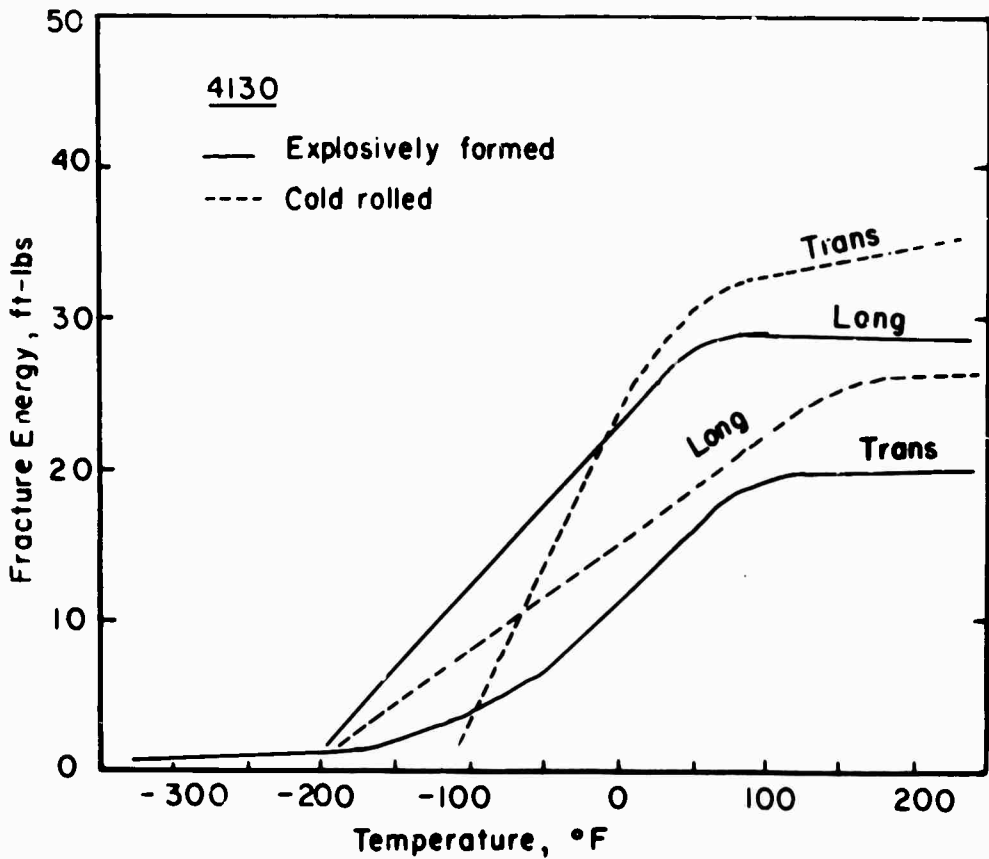


Figure 4 Preliminary Impact Results with Cold-Rolled and Explosively Formed 4130 Specimens without Subsequent Heat Treatment

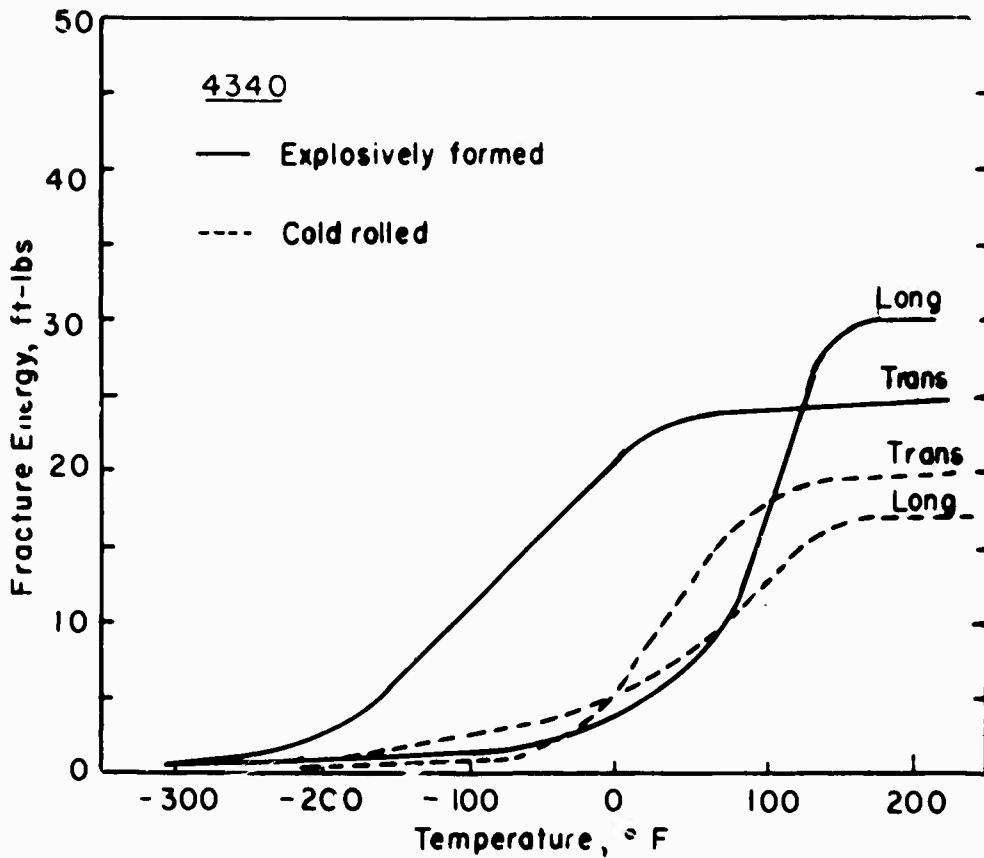


Figure 5 Preliminary Impact Results with Cold-Rolled and Explosively Formed 4340 Specimens without Subsequent Heat Treatment

transverse orientation had a much lower ductile-to-brittle transition temperature than any of the other groups. Explosively formed specimens, regardless of orientation, had higher impact strengths at ambient temperatures than cold rolled specimens. In this respect, these results are consistent with heat treated material.

7. Explosive Welding

Principal Investigator: S. Carpenter

a. Diffusion Studies

Graduate Student: M. Nagarkar

Work has continued with diffusion studies in explosively welded copper-nickel couples. Diffusion widths have been measured using diffusion data obtained with the aid of the electron beam microprobe. The explosively bonded interface exhibits a wavy pattern, and the diffusion width was measured across the crest and the trough regions of the interface. Widths were also measured across the interfaces of the roll bonded Cu-Ni couple used as the cladder plate and the base plate, and also in the as-received roll bonded strip. To determine the effect of diffusion on the bond strength of the explosively welded couples, tensile testing is being carried out. Work has also been started in explosive welding of Al and steel.

b. Residual Stress Measurements on Explosion Welded Composites

Graduate Student: R. Wittman

The explosion weld interface is characterized by severe local plastic strains and high temperatures of short duration, both conditions favorable to the development of residual tensile stresses at the weld interface.

Residual stresses in explosion welded composites have been investigated in a Japanese research program. Strain gauge and metal techniques identified a residual stress profile that becomes strongly tensile near the explosion weld interface. No attempt was made to determine the effect of residual stresses on mechanical behavior.

In the present study an attempt is being made to measure residual stresses across the interface of explosion welded 6061-T6 aluminum alloy. The two-exposure x-ray technique is being employed

in an effort to define the stress profile with a greater degree of precision at the weld interface where the stress is thought to change by a large amount in a short distance.

Several preliminary x-ray exposures have been made at the weld interface of 6061-T6 aluminum alloy. As expected, the diffraction lines are broad indicating the fine grain size and inhomogeneous strains at the interface. From these preliminary experiments, shifts in the (511) (333) diffraction line have been observed in the tensile direction, but accurate measurements of the residual stress have not yet been possible.

Improvements in the x-ray technique are being made in an effort to sharpen the diffraction line position so that it can be determined more accurately.

8. Explosive Powder Compaction

Principal Investigator: H. Otto

Graduate Students: T. McClelland, D. Witkowsky

Experimental work is divided into two areas: (1) an investigation for making rolling and extrusion preforms, and (2) methods of making composites. In the work with preforms, the influence of compacting environment and precompaction are being studied. Most of the work conducted in making rolling preforms has been with systems in which the powders were prepressed in a picture frame arrangement and the system evacuated prior to explosive loading. Aluminum foil has been used to seal the system. A series of tests was conducted in which the steel powder specimens were precompacted and explosively compacted without using a vacuum. Metallographic examination indicated no adverse effect from compacting in air. Subsequent sintering at 2050°F for one hour showed no expansion or void build-up as a result of expanding entrapped air. Explosively compacted specimens that had no precompaction had densities comparable to those that had been precompacted. Currently, the rolling preforms are being scaled up in size in an effort to determine if relationships established with smaller specimens are applicable for larger sizes.

A basic model has been selected for the reinforced compacts. These compacts will be made by placing a frame with 5 mil tungsten wire attached in a die to which the powder is added. The 5 mil tungsten wire has a tensile strength in excess of 400,000 psi. By varying the loading of wire with respect to total volume of the compact, relationships will be established for compact strength.

The compacting die is currently being fabricated and will consist of a double piston configuration in which both pistons are driven explosively. To obtain the frames with the wire, a hexagonal shaped jig is being made so six frames can be wound on a lathe at the same time. Each successive layer of wire will be separated by a spacer to prevent the wires from coming into contact during setup of the compacts. Actual compaction will be started in the near future.

9. Explosive Forming of Thick Walled Domes

Principal Investigator: L. Alting

The goal in this investigation is to form scale model hemispheres 10 in. and 12 in. in diameter in $\frac{1}{2}$ in. thick boiler plate.

In the last report a new concept to accomplish the forming was described. No die is used and the die action is established as a compressibility difference between different media, i.e., air/water, styrofoam/water, styrofoam/sand. The first shot was performed with detasheet as explosive and one inch thick rubber as a buffer. We changed the explosive to SWP-5 (20% TNT and 80% ammonium nitrate) which has a detonation velocity around 15,000 ft/sec. This explosive is more suitable for forming purposes and allows use of contact charges. A shot with a charge of 650 grams (10 in. dia) gave a dome with 7.3 in. in deflection and a mean diameter of 14 in. Due to the compression we had some wrinkling along the edge. After cutting 1.5 in. off the edge we sized the dome by shooting it through a tube (ID/OD - 12.5 in/14). The result was good--a dome 12.5 in. in diameter and 5.5 in. deep.

By cutting wedges in the edge of the blank the heavy buckling is prevented and we get a good control over the diameter variations ($\pm 1/4$ in. - $1/3$ in.). Due to lack of material and time, the precise geometry of the charge needed to form just the right shape was not determined.

This preliminary investigation has shown that the process is feasible and possibly has a lot of potential uses. The next step in the process development will have to be an extensive parameter study.

Concerning more detailed information on the process, a paper will be given at the Third International Conference for the Center for High Energy Forming in Vail, Colorado, July 12-26, 1971.

10. Theoretical Studies of Explosive Energy Transfer to a Thick Walled Cylinder Using a Radial Piston

Principal Investigator: H. Glick

Graduate Student: V. D'Souza

A computer program has been developed to give the residual stresses produced at the bore of a thick walled tube by the action of a radial piston. The program has been checked out and a number of results have been obtained. It has been found, for example, that for the cases previously tested experimentally that no re-yielding had occurred, and that the cause of the reductions of residual stress to values below 120,000 psi were due to the fact that the wall of the thick walled cylinder never became fully plastic.

For the geometry used in the experimental tests, if the initial pressure in the radial piston is equal to 70,000 psi or more, it is found that the wall would become fully plastic. A surprising result of the computations is that the radial piston is effective in preventing reyielding even for cases in which the initial pressure in the radial piston is as high as 100,000 psi. Thus, for the cases tested experimentally, reyielding apparently did not occur, and the reduced values of residual stress were due to the fact that the initial pressures in the radial piston were below 70,000 psi. A comparison of the results of the computer study with the observed residual deformations suggests that the initial piston pressures were about 50,000 psi.

A number of other results have been obtained from the computer study. For example, it has been shown that reyielding depends on the density and yield strength of the material of the radial piston. If the specific gravity of the radial piston is equal to unity and if the yield strength is zero (analogous to a membrane), partially plastic flow and reyielding occur at an initial piston pressure of 80,000 psi. Thus, reyielding is clearly related to the phase relation between the motion of the radial piston and the motion of the thick walled cylinder. Sometimes the frequencies of the pressure pulse and the cylinder breathing mode are close, and in this case the impedance match of the explosive to the thick walled cylinder depends crucially on this phase relation. This approximate matching of frequencies occurs for the cases tested experimentally and apparently insured high residual stresses at the cylinder bore. In the membrane case, the frequencies were quite different so that good impedance

matching did not occur. Also, it was found that varying the geometry or material properties moderately from the values employed in the experimental tests did not change the qualitative result that no reyielding had occurred.

11. Explosive Thermomechanical Processing

Principal Investigator: R. Orava

Post Doctoral Fellow: A. Dowling

Graduate Student: P. Khuntia

This phase of the investigation involves primarily two aspects of material behavior associated with explosive forming:

- (1) the evaluation of the terminal strength and impact resistance of SA-285 Grade C boiler plate steel,
- (2) the utilization of explosive forming as an ambient temperature mechanical stage in a thermomechanical processing or treatment schedule (ETMP) for selected precipitation hardenable iron and titanium base alloys.

The explosive free forming of 3/8 in. thick SA-285 steel was described previously. Explosive die forming was accomplished using a flat bottomed die. This yielded a dome with a circular flat area 8 in. in diameter with an effective strain of 5.3%. The properties of specimens cut from this area were compared with those obtained from a region of 5.3% effective strain, located at a particular radius of free formed dome. In the latter case, a flattening operation was required but this was concentrated in the region of one shoulder only since the gauge length was already flat.

The conventional forming of blanks of such a low diameter-to-thickness ratio (57) into dome shapes was found to be impractical. Consequently, a forming operation as such was replaced by uniaxial tensile straining to a strain of 5.3%. The strain state during deformation is also triaxial.

Tensile and Charpy impact specimens have been machined from material corresponding to all four conditions of strain--unformed, statically strained, and explosively die and free formed. All specimens were given the identical stress relief anneal: heated slowly to between 600 and 650 C; held for one hour and cooled slowly to below 300 C. To date, the tensile tests have been completed, with the results shown in Table 1. The values represent

means for 3 or 4 specimens. It can be concluded that the tensile properties of SA-285 boiler plate steel are not degraded by explosive die or free forming relative to more conventional forming when a standard stress relief anneal follows the operation. In fact, the explosively die formed specimens showed a tendency towards greater ductility than the statically deformed or explosively free formed ones without a decrease in yield or ultimate strength. A stress relief anneal does not completely restore the tensile ductility to the annealed levels.

The following ETMP schedule was adopted for semi-austenitic precipitation hardenable stainless steel (Armco 17-7 PH).

Preforming History:

<u>Designation</u>	<u>Thermal Treatment</u>
A	Condition A
B	Condition T
C	Condition A 1750
D	Condition R-100

Forming:

<u>Designation</u>	<u>Mechanical Treatment</u>
A	Undeformed (Control I)
R	Cold rolled; $\epsilon_1 = -\epsilon_2$, $\epsilon_3 = 0$ (Control II)
X	Explosively formed; $\epsilon_1 = -\epsilon_2$, $\epsilon_3 = 0$

Post-forming Heat Treatments:

The effect of the standard thermal treatments given below are being examined first. Subsequently, alterations in these schedules to achieve maximum strengthening will be investigated.

Applicable
Preforming
History

	<u>Designation</u>	<u>Thermal Treatment</u>
A	1	Convert to Condition CH 900
A	2	Convert to Condition TH 1050
A	3	Convert to Condition RH 950
B	4	Convert to Condition TH 1050
C	5	Convert to Condition RH 950
D	6	Convert to Condition RH 950

An attempt to stretch form two blanks of Condition A material using a die originally designed for explosive free forming into a semi-cylindrical geometry proved unsuccessful; the material strain was limited to about 2%. However, the amount of deformation introduced thereby into two workpieces was increased to about 7% by bolting them together at the edges and expanding the assembly as a hollow tube. The die is presently undergoing modifications. Serrated faces are being introduced to inhibit pull-in, along with a superior clamping arrangement to permit an increase of the hold-down pressure. It is expected that most of the forming of 17-7 PH and β -III titanium alloy will be accomplished during the next quarter. The characterization of 17-7 PH is underway. The first controls have been heat treated and electron transparent thin foils successfully prepared.

Table 1 Tensile Properties of Unformed and Formed SA-285 Steel
After a Stress Relief Anneal

<u>Property</u>	<u>Unformed</u>		<u>Statically Prestrained</u>		<u>Explosively Free Formed</u>	
	<u>Longitudinal</u>	<u>Transverse</u>	<u>Longitudinal</u>	<u>Transverse</u>	<u>Longitudinal</u>	<u>Transverse</u>
Upper Yield Stress (psi)	41,400	46,200	45,300	47,300	45,900	45,300
Lower Yield Stress (psi)	38,200	38,500	44,200	44,900	45,400	44,900
Ultimate Tensile Strength (psi)	60,600	61,000	61,500	61,500	61,900	60,900
Uniform Strain (%)	22.3	21.5	16.4	16.7	16.2	18.3
Elongation (%) (2 in. gauge)	28.6	29.2	23.5	25.0	23.4	26.1

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Energy Requirements						
Energy Transfer						
Strain Rate Effects						
Explosive Welding						
Mechanical Properties Before and After Forming						

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