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CENTER FOR HIGH ENERGY FORMING

NINETEENTH QUARTERLY REPORT OF TECHNICAL PROGRESS

Jimmy D. Mote

April 1, 1970

Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172

Martin Marietta Corporation
Denver Division
Contract DA 19-066-AMC-266(X)
The University of Denver
Denver, Colorado

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ABSTRACT

This report summarizes results during the period 1 January thru 31 March 1970:

a. Measurement of the dynamic loads on an explosive forming die.

b. Applications of explosive welding to hardware configurations.

c. Flange buckling of explosively formed domes.

d. Explosive punching of dual hardness armor.

e. Cylindrical explosive forming dies.

f. Explosive forming of domes in vented dies.

g. Explosive forming of domes for ground based pressure vessels.

h. The edge pull-in of explosively formed domes.

i. Fracture toughness of explosively formed high strength steels.

j. Terminal properties of titanium.

k. Explosive welding

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I. MARTIN MARIETTA CORPORATION

1. Measurement of the Dynamic Loads on an Explosive Forming Die

Principal Investigators: L. Ching, D. Bouma

a. Introduction

Dynamic strains are being measured on a forming die while forming aluminum domes with explosives. The purpose of the measurements is to study the mechanics of energy transfer and establish parameters for a more efficient die design. The measurements conducted so far have been mainly concerned with developing instrumentation techniques to measure small strains.

Die measurements to date have measured peak strains of 100 micro-inches per inch. These measurements were made on the outer surface of a massive die which was available for testing the instrumentation system. The test parameters, such as charge size and standoff distance, were established to explosive form 6 inch diameter domes. Higher die strains could be achieved with larger size charges which involve over-shooting the part.

The shock wave acting upon the instrumentation wires was found to contribute to the actual die strain, but this effect was minimized to less than 15 micro-inches per inch with the use of water tight electrical conduit. All strain measurements in the report are relative and include the shock effect upon the lead wires. Tests so far indicate that the maximum die strain results from the initial shock wave from the explosive detonation if the forming is done on a flat blank.

In an attempt to measure the energy utilized in forming the part, several tests were made with no blank in the die. Using the dome forming data, die strains were measured to be 180 micro-inches per inch as contrasted to the 100 micro-inches per inch strain measured when a blank was utilized. Since the forming data (i.e., charge size, charge type, and standoff) was identical when a blank was present, these tests indicate that approximately 40% of the charge energy was absorbed in the blank forming. Subsequent tests revealed that identical results could be achieved if an extremely thick rigid plate was substituted for the blank. Substitution of the thick blank resulted in an easier test set-up in addition to protecting the die from blast damage.

b. General Set-Up

The die was made of 4340 steel and had a 12 inch outside diameter and measured 6 inches in overall height. The die cavity was a 6 inch diameter hemisphere. The die was built to be used in a die stand (as shown in Figure 1) so that vacuum and clamping fixtures could be applied. The blanks were 0.064 inch thick 2014-0 aluminum and 9.5 inches in diameter. The domes were formed using 80 grains of Composition A-3 and a 1.0 inch standoff.

Strain gage rosettes were mounted on the 12 inch diameter of the die. The strains were recorded on film using Wheatstone bridges, d.c. differential amplifiers, and oscilloscopes. The bridges were excited with 24 volt batteries as shown in Figure 2. Although an excitation voltage in excess of 24 v.d.c. would result in a higher bridge output and signal to noise ratio, the gage vendor recommended that the 24 v.d.c. voltage level not be exceeded. If the 24 v.d.c. level were exceeded, the gage factor would not be linear.

Immediately prior to each test, all channels were zeroed and calibrated by shunting known resistances across the active gage while the die was underwater. The zero adjustment compensates for the 135°F water temperature and no other temperature compensation was necessary since the temperature was constant during the test event.

Zero test time was coincident with the detonation of the explosive charge. This was established with a break wire electrical circuit which triggered the oscilloscope. Hence, time zero on the trance was coincident with the time at which the charge detonated.

c. Results of Test

Several tests to measure strains were conducted. The first tests were made with a dual beam oscilloscope in the chop beam mode so that four channels could be recorded simultaneously. These tests were not totally successful for the following reasons:

1) Electrical ringing in the system;

2) Excessive crossing over of the traces such that the identity of each trace was lost;

3) The chopping of the beam plus the writing speed which was required exceeded the capability of the oscilloscope.

Using the dual beam oscilloscope along with a storage oscilloscope, it was possible to record three channels of strain that were satisfactory and repeatable.

The effect of the explosive blast on the instrumentation wires was studied in a series of tests. This was done by exposing the lead wires to an underwater blast while the die remained outside the pool of water. Two channels were recorded for comparison; one exposed to the blast while one was not. The same size charge and distance were

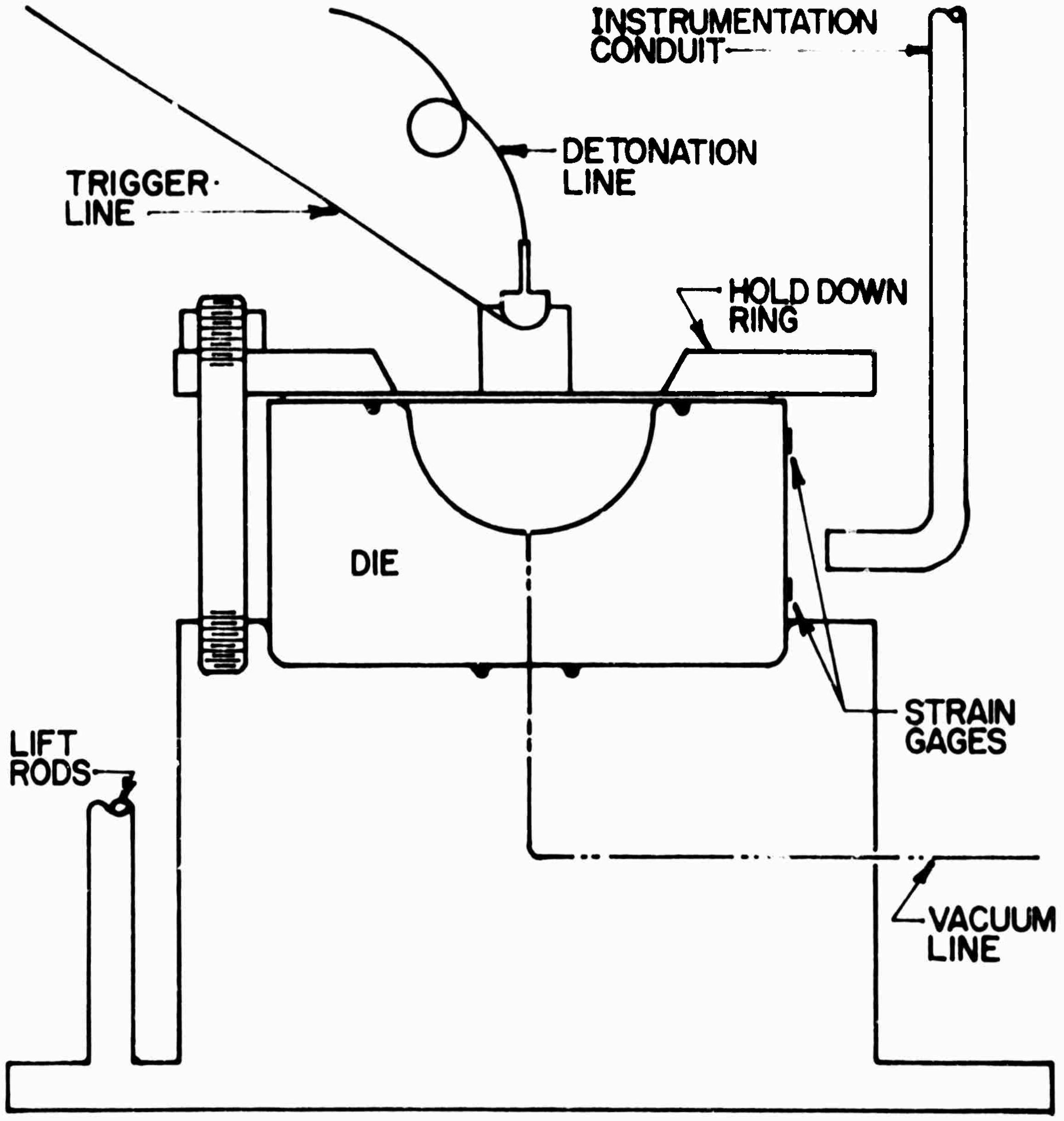


Figure 1 Schematic of Die Set-up.

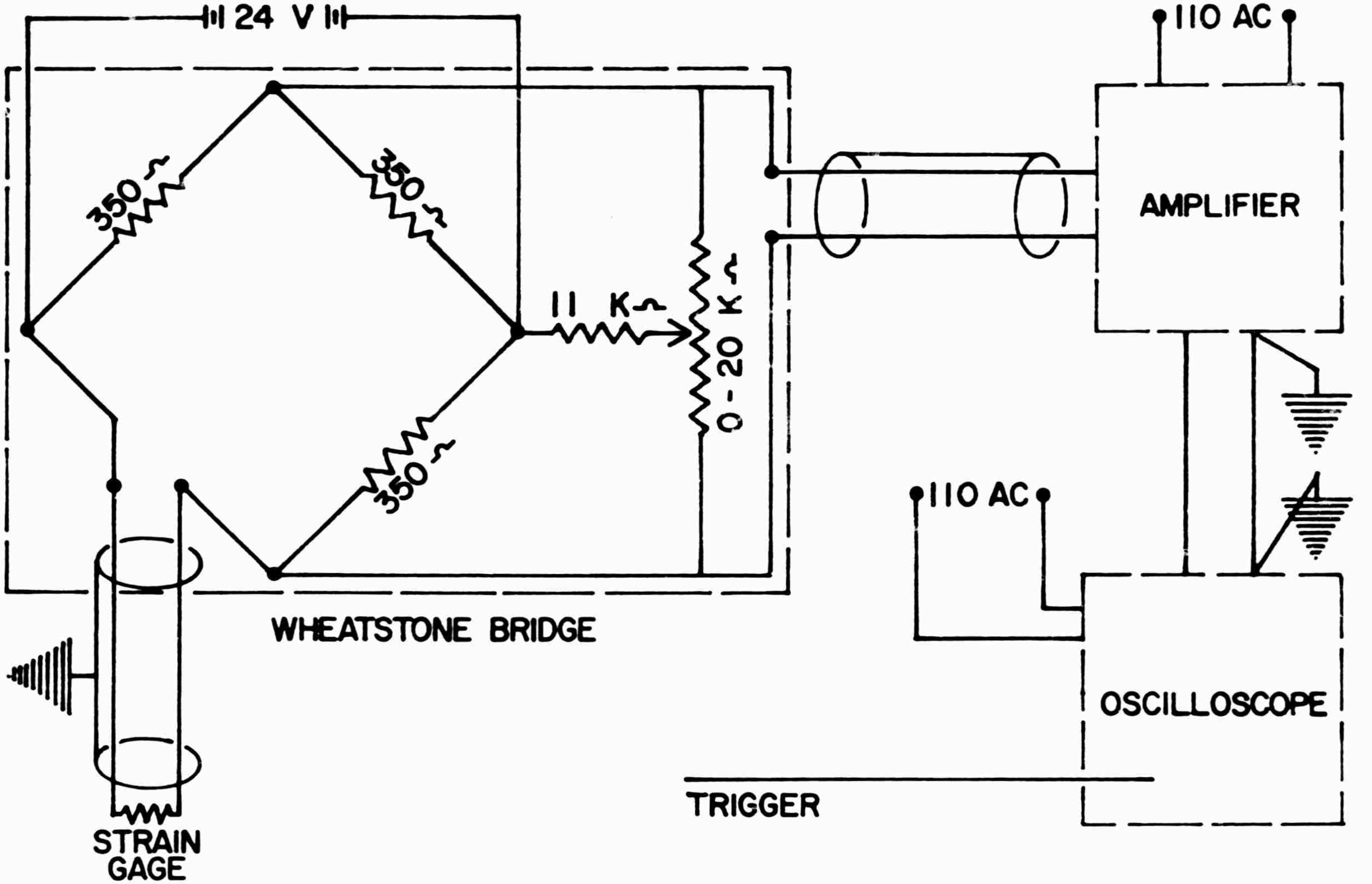


Figure 2 Schematic of Strain Measuring Circuit.

simulated as much as possible. This test measured a false strain of 100 micro-inches per inch. Several more tests showed that this false strain could be minimized to less than 15 micro-inches per inch with the use of a water tight conduit to protect the instrumentation lines and the use of shield pair wire for lead lines.

The die strains were now measured to be about 100 micro-inches per inch. Examples of the raw data can be seen in Figure 3. With these instrumentation developments, further die strain measurements are planned for other dies in a die stress study program.

2. Applications of Explosive Welding to Hardware Configurations

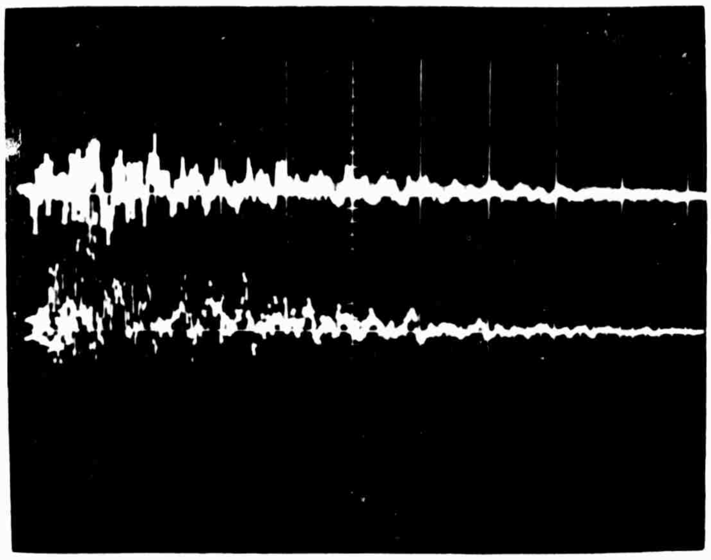
Principal Investigator: W. Simon

a. Lap Joint for Construction of Conical Ring from OFHC Copper (.005 inch thick)

Test welds have been made with .005 inch OFHC copper. Tensile test gave 35,000 psi ultimate strength compared with 41,000 psi for the parent metal. Micrographs of the weld are being prepared.

b. Use of Cover Mass Over Explosive to Reduce Explosive Requirements

An experimental verification of the computed effect of cover mass has been obtained. A seam weld with initial flange angle of 7^o in .090 inch 7039-T6 aluminum has been successfully made with .042 inch Detasheet. Computed parameters are: impact pressure/yield stress = 5.7, collision angle = 11.9^o, Reynolds No. = 15.2. With explosive load reduced to .025, no weld occurs. Parameters are: impact pressure/yield stress = 3.4, collision angle = 9.6^o, Reynolds No. = 9.4. Finally, if explosive load is reduced again to .015 inch Detasheet with a .090 inch aluminum cover, a good weld is again obtained. Computed parameters are: impact pressure/yield stress = 6.8, collision angle = 12.6^o, Reynolds No. = 17.9.



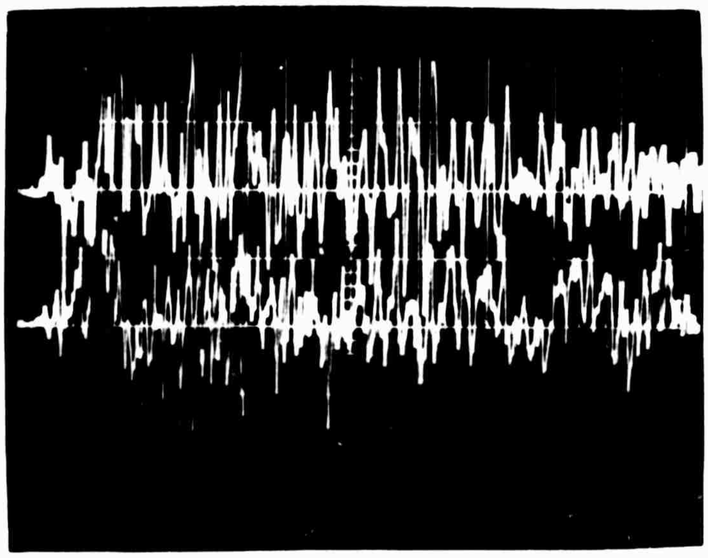


Figure 3 Die Strains - Raw Data

II. UNIVERSITY OF DENVER

1. Flange Buckling of Explosively Formed Domes

Principal Investigator: M. Kaplan

Graduate Student: H. Boduroglu

Two analytical solutions for the stress and strain fields in the prebuckled flange have now been obtained. The first solution was obtained from a rigid-perfectly plastic model with no flange friction. The second solution was obtained from a model which considered both work hardening and friction.

In order to check the analytical results, four experiments were done. In two of them the contact surfaces of the blank and the die were lubricated to reduce friction effect; the other two were done without lubrication.

The analytically determined strain fields for both solutions were in excellent agreement with the experimental strains along the entire width of the flange. The results indicated that friction effects are small and that work hardening, while significantly effecting the stress field, has little effect on the strain field.

2. Explosive Punching of Dual Hardness Armor

Principal Investigator: W. Howell

Post Doctoral: A. Dowling

The effect of material hardness on the penetration produced by the shaped part of the charge was studied using small linear wedge segments. The results showed that penetration was reduced by increasing the hardness of target material, confirming that the velocity of the jet was around the value where strength effects are significant. This was further reinforced by the fact that for the hardest material, greatest penetration was obtained using a standoff less than the theoretical optimum. This showed that the cutting effect came mainly from the fastest part of the jet which is formed from the apex end of the wedge. Due to waver, the further the jet travels before reaching the target, the shallower the penetration.

A more important result which came from these tests was that the penetration in R_c50 material with the linear wedge segments was approximately 50% greater than that obtained from circular shaped charges. Since there is greater jet confinement in the circular arrangement, this result should have been reversed. Consequently, another series of tests using the circular configuration was carried out, care being taken when sticking the Detasheet on to the liner. The results were no different--

leading to the conclusion that the 1/2 inch leg length, 70° angle circular wedge involves too severe a forming operation for Detasheet. It tries to spring back off the liner, forming air pockets which drastically reduce the efficiency of energy transfer. New charges will be tried where the explosive is cast on the liner, thus eliminating the adhesion problem.

3. Cylindrical Explosive Forming Dies

Principal Investigator: J. Weese

Graduate Student: R. Knight

A few 6061-T6 aluminum specimens 0.064 inch thick were expanded. These shots were used to check out the instrumentation. Some of the strain gages have been replaced and the leads to the strain gages are being run through a conduit to prevent the shock wave in the water from causing spurious signals when it passes the lead wires. The work to complete six new current sources is almost completed. When this is finished, a total of ten channels can be recorded at the same time. Work on the problem of the impact of the workpiece on the die has been started.

4. Explosive Forming of Domes in Vented Dies

Principal Investigator: J. Weese

Graduate Student: P. Hardee

Additional testing of different materials in the vented die was accomplished. A dome was successfully formed out of .059 thick mild steel with no hobnailing. However, the charge size was critical. Domes were formed from aluminum blanks both 1/8 and 1/16 thickness. These were not completely successful. One test was made with 1/3 of the holes plugged. In the course of the shot half the plugs were knocked out, but the area reduction still amounted to 1/6 of the area of the holes. This reduced the porosity from 18% to 15%, approximately. There was no indication of resistance to forming. An analysis is being done in an attempt to form a mathematical model from which to make estimates of porosity and hole size requirements. With this information a new die will be made for further testing.

We are giving additional consideration to conducting tests to determine directly the pressure time-history of the region between the blank and the die.

5. Explosive Forming of Domes for Ground Based Pressure Vessels

Principal Investigator: A. Ezra

Post Doctoral A. Dowling

Pursuant to achievement of technology transfer objectives, certain types of domes for ground based pressure vessels have been selected for scale model work. The objective is to establish explosive forming parameters for specific full scale applications for steel domes having a fairly wide range of draw depths and D/t ratios. Families of curves will be prepared to provide easy access to parametric values necessary to form a particular dome.

6. The Edge Pull-In of Explosively Formed Domes

Principal Investigator: M. Kaplan

Graduate Student: S. Kulkarni

Effort has been directed toward finding means of simplifying the extremely complex governing equations. In particular, we have conducted experiments to determine if the pull-in in statically formed domes would be the same as in those formed dynamically. We conducted our tests with 2014-0 aluminum blanks and a die to assure the same final shape in both cases. The results indicate that even though the strains are somewhat different in the dome, the edge pull-ins are nearly identical. This result, of course, is only valid for the standoff/diameter ratio of 1/6 which was used in the dynamic tests. For this particular L/D, however, the inertia terms in the governing equations may be neglected in determining pull-in as a function of draw depth.

7. Fracture Toughness of Explosively Formed High Strength Steels

Principal Investigator: H. Otto

Graduate Students: R. Mikesell, C. Yin

Impact specimens have been fabricated from explosively formed stock of 4130, 4340, and HY-80 steel. Specimens of the 4130 and 4340 were selected at equivalent strains of 0.05 and 0.10 inch/inch. The HY-80 specimens were selected at a strain of 0.10 inch/inch. For comparison purposes, base stock of all the steels was cross rolled to the same equivalent strains. All impact specimens have been fabricated to ASTM specifications for sub-size Charpy V-notch (0.197 x 0.394 inches cross section). Specimens are currently being heat treated.

Fracture toughness tests of the explosively formed and heat treated 4130 and 4340 steels are currently underway.

Metallographic investigations of the microstructures of explosively formed and heat treated HY-80 were concluded. A trend had been observed with the mechanical properties of the formed and heat treated specimens in which increasing forming strains resulted in lower mechanical strengths after heat treatment. Grain size measurements were made and the data obtained was treated by statistical means. The statistical results indicated no difference existed in the grain size after heat treatments which could explain the observed trend.

Specimens from the explosively formed domes are currently being impact tested in the as-formed and formed and heat treated conditions.

8. Terminal Properties of Titanium

Principal Investigators: R. Orava, H. Otto

Graduate Student: P. Khuntia

The objective of this investigation is to generate information concerning the relative influence of explosive and conventional forming on the terminal behavior of unalloyed α-titanium (TMCA 50A) and α-β titanium alloy (6Al-4V). The study includes the evaluation of microstructure, hardness, tensile flow characteristics, stress corrosion cracking susceptibility, and thermal response. Test samples were selected from explosively free-formed and from isostatically rubber pressed domes.

Except for the determination of the effect of forming rate on recovery and recrystallization characteristics, the work on Ti-50A has been completed. The dependence on strain and rate of the microstructure, as examined optically, was reflected in the following twin densities.

Forming History*	Effective Forming Strain, ϵ^* (%)	% of Grains with Twins	Twin Density (cm^{-2})
UF	0	0	0
IF	2.9	1.1	0.4×10^4
EF	2.9	30.2	16.9×10^4
IF	6.0	7.0	4.0×10^4
EF	6.0	68.2	52.5×10^4

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* UF: unformed; IF: isostatically formed; EF: explosively formed.

As expected, the higher forming rate is considerably more conducive to mechanical twinning than the lower rate.

However, this difference in twin density either does not contribute to a rate dependence of terminal mechanical properties and stress corrosion resistance, or if it does, the contribution is almost exactly counterbalanced by the contribution from a difference in defect substructure. The latter possibility seems unlikely.

Typical mechanical properties of as-formed Ti-50A are given below for 3% effective forming strain.

Forming History	0.2% YS (ksi)	UTS (ksi)	True UTS (ksi)	Ultimate Strain (%)	El. (%)	R.A. (%)
UF	46.5 (LY)	62.1	70.7	14.0	25.1	60.1
IF	50.2	60.5	67.7	10.0	27.9	60.0
EF	51.2	60.9	68.1	11.0	29.9	61.8
EB	82.5	90.5	91.1	1.8	8.0	47.3

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* EB: Explosion bonded

A statistical analysis of true ultimate stresses showed that there is no reason to expect any difference in strength between explosively formed and isostatically formed material. The true ultimate stress is considered to be the best measure of the terminal strength. Consider, for example, the results in the last row of the previous table for explosion bonded Ti-50A. The true ultimate stress clearly illustrates the large effect due to shock loading--an increase in strength of nearly 30% over either unprestrained or formed material.

The effect of forming strain and rate on the susceptibility of Ti-50A to cracking in a methanol-0.5% HCl solution at 90% of the yield stress can be summarized as follows:

a. In all cases

$\bar{t}_f$ (isostatically or explosively formed) > $\bar{t}_f$ (unformed);

b. In all cases

$\bar{t}_f$ (explosively formed) > $\bar{t}_f$ (Isostatically formed) where $\bar{t}_f$ is the mean failure time.

In conclusion, forming to effective strains of 3 or 4% enhances the resistance of Ti-50A to methanol cracking. Moreover, explosive forming, as compared with isostatic forming to an equivalent strain, probably does not influence cracking susceptibility; if anything, resistance may be slightly improved.

Methanol cracking tests on the shock-deformed Ti-50A cladder plate are incomplete. Preliminary results have revealed that $\bar{t}_f$ is approximately the same as for unformed material at 90% of the yield stress. However, it must be emphasized that the absolute stresses applied to the shocked and unstrained material were 41.9 and 72.0 ksi, respectively. The latter is greater than the stress which unprestrained Ti-50A can sustain in the absence of an adverse environment.

The average tensile properties of Ti-6Al-4V formed to 6.0% effective strain were:

Forming History	0.2% YS (ksi)	UTS (ksi)	True UTS (ksi)	Ultimate Strain (%)	El. (%)	R.A. (%)
UF	137.3 (LY)	142.6	153.0	7.3	11.2	36.5
IF	128.8	148.1	152.9	3.3	8.4	33.3
EF	127.6	147.4	153.6	4.2	8.8	33.0

Differences among the true ultimate strengths of unformed, isostatically formed, and explosively formed material are not significant.

The evaluation of the terminal susceptibility of Ti-6Al-4V to cracking in a methanol-0.05% HCl solution at 50% of yield is nearing completion. Although all three statistical decisions indicated that the resistance of explosively formed material is the same as that of isostatically formed stock, the mean failure time of the former exceeded that of the latter in each instance.

9. Explosive Welding

Principal Investigator: S. Carpenter

Graduate Students: V. Winchell, M. Nagarkar

Strains developed in cladder plates are being defined to determine what shear stresses can exist that might limit applications of explosive bonding. Diffusion studies are being conducted on a comparative basis with conventionally bonded dissimilar metals.

V. Winchell

The first study concerned with the determination of strains in a cladder plate of an explosively bonded sample has been completed. A line scribed across the surface of a 6061-T6 aluminum specimen (6" x 3" x 1/8") was used as the reference for all measurements taken before and after welding. A series of 99 holes (0.008° diameter) was used as fiduciary markers. Eleven holes 0.100 inch apart comprised a "group" with three groups being drilled parallel and aligned in the direction of welding (along the 6 inch dimension of the specimen) near the start, middle, and end of the cladder plate.

Momentum arresters enclosed the specimen during welding. Surface measurements before and after welding revealed greater movement in the end hole groups and the least elongation in the material near the start of the weld.

To determine the nature of the shear flow developed in the cladder, the region of the hole groups was removed by milling parallel to the weld interface. In relationship to this interface, machining was done to relative thickness of 1/2T, 1/4T, 1/8T, and 1/16T. Hole positions were evaluated in terms of tensile strains with respect to the original hole positions. Utilizing the deformation within each plane, the spacing between planes allowed shear stresses to be calculated.

An average of the calculations with respect to an internal reference revealed that an originally vertical marker would have the final configuration given in Figure 4.

Flow through the top three-fourths of the plate can be attributed to deformation resulting from the detonation of the explosive. The region at 1/4T directly above the weld interface shows a decided change in the marker configuration. This is the result of the bonding mechanism. Material near the weld surface has been stretched which would result in residual stresses. Stresses of this nature would dish the welded plate which is in agreement with experimental observations. The conclusion can be made that the flow characteristics developed within the cladder plate contributes to the dished configuration commonly found in welded specimens.

Current cladder plate flow studies are involved with a 24" x 8" x 1/4" piece of cold-rolled steel welded to a base plate of an identical size and composition. In this investigation, 18 specifically placed holes (0.0135 inch diameter) are being used. The purpose of this experiment is to determine if tensile strain and shear stresses increase with increasing length.

10. Explosion Welding of Dual Hardness Armor

Principal Investigator: R. Wittman

During the past quarter the program objective has been to produce a steel/titanium alloy armor plate that is suitable for ballistic testing.

Previously reported welding parameter studies demonstrated the feasibility of welding Ti-6Al-4V alloy to the steel armor plate. Analysis of these coupon welds indicates the armor steel/titanium alloy direct bond is of marginal quality due to the large differences that exist in the flow characteristics of these materials. To overcome this difficulty, a third more ductile metal between the steel and titanium alloy was included.

Two larger scale explosion welding experiments were conducted in an attempt to produce a 6" x 12" steel/titanium alloy plate for ballistic testing. The first experiment used a 12" x 12" x .2" steel armor plate at the base for welding. To this an attempt was made to explosion weld 12" x 12" x 0.020" of unalloyed titanium to serve as a compatible intermediate layer. The titanium to steel weld that resulted was not of high enough quality to warrant a second explosion weld of titanium alloy onto the surface of the unalloyed titanium.

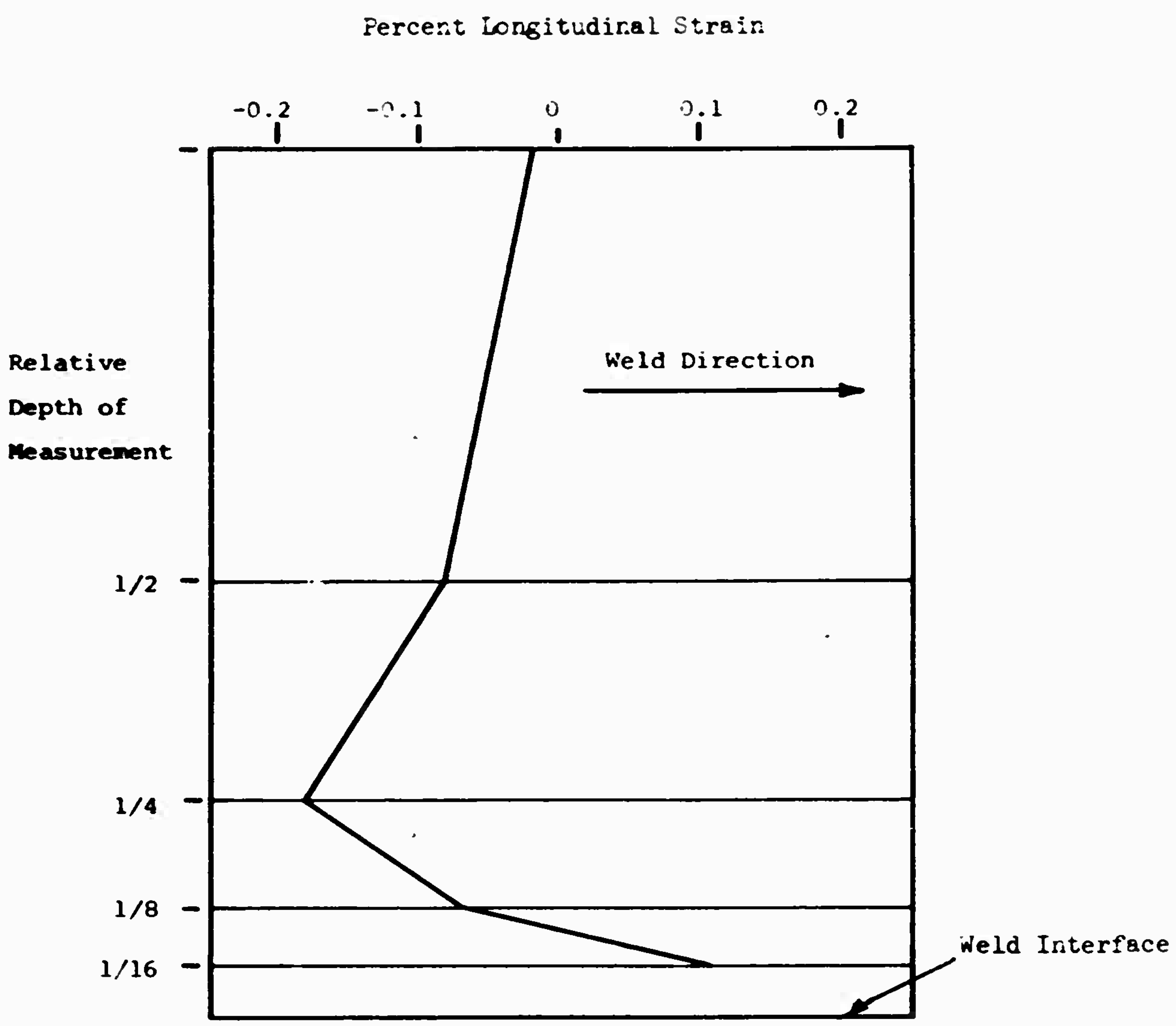

Figure 4. Strain Distribution Through Thickness of Explosively Welded Flyer Plate

The second experiment used a 12" x 12" x .2" steel armor plate as the base. To this was explosion welded a 0.032 inch thick iron sheet to serve as a ductile intermediate layer. The weld appeared to be of high quality. In preparation for explosion welding a Ti-6Al-4V alloy plate to the surface of the iron previously welded, it was necessary to flatten the iron/steel composite plate. The flattened plate was then mated to a one inch thick cold-rolled steel anvil by a thin layer of solidified lead-tin alloy, thus providing for good shock wave coupling. A 0.090" x 12" x 12" thick Ti-6Al-4V alloy plate was explosion welded to the iron surface of the iron/armor steel composite. A 20 g/in.^{2} loading of Red Cross 40% Extra dynamite was used on the titanium alloy flyer plate. The parallel standoff was 1/8 inch. The appearance of the explosion welded plate was good. The normal region of non-bond around the periphery of the plate was cut away and the remaining steel/titanium alloy armor plate was given to the Army Materials and Mechanics Research Center for further evaluation.

11. Explosive Powder Compaction

Principal Investigator: H. Otto

Graduate Student: D. Witkowsky

The literature survey on explosive compaction of powders was completed. This survey indicates that several different methods are available for compaction of powders, but in most instances the time involved is greater than for conventional techniques. However, densities of explosively compacted powders are considerably higher than can be achieved by press type operations. Higher compaction densities generally result in lower sintering temperatures and time. Resultant grain growth is not as pronounced which means higher strengths can be realized.

Several powder compacts have been made with steel powder for rolling preforms. These experiments are designed to give data on how explosive loading will affect the compacted density and also any post compaction heat treatment. DuPont Red Cross 40% Extra dynamite has been used to date. In making a sheet approximately 1/4 inch thick, the post compaction density varies from about 94% to 98% of theoretical by varing the weight of explosive to metal ratio from 0.6 to 1.1. The density prior to explosive loading was held constant at 74% of theoretical. Compact thicknesses are now being varied to determine explosive bonding to metal ratios for high density compacts.

Experiments have been conducted in which carbide tool compositions and composites have been made. These materials are currently being evaluated.

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11. **SUPPLEMENTARY NOTES:** Use for additional explanatory notes.

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