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CENTER FOR HIGH ENERGY FORMING

EIGHTEENTH QUARTERLY REPORT OF TECHNICAL PROGRESS

Jimmy D. Mote

January 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

Sponsored by

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ABSTRACT

This report summarizes results during the period 1 October thru 31 December, 1969:

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 in vented dies.

g. Explosive forming of thick domes.

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

i. Fracture toughness of explosively formed high strength steels.

j. Terminal properties of titanium.

k. Explosive welding.

l. Explosive welding of dual hardness steel plate.

m. Explosive powder compaction.

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I. MARTIN MARIETTA CORPORATION

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

Principal Investigators: L. K. W. Ching, D. D. Louma

a. Introduction

Dynamic strain measurements have been made on a forming die while explosively forming aluminum domes. The method used was to mount strain gages on the outer surface of the die and record the corresponding strain output on polaroid film with the use of a wheatstone bridge, amplifier, and an oscilloscope. An analytical study is being undertaken to determine if these strains are predictable.

b. Experimental Setup

A die was used to form 6.0 inch diameter hemispheres. The blanks to be formed were 0.064 inch 2014-0 aluminum. The charge was 80 grains of Composition A-3 with a 1.0 inch stand-off. The forming was done in a pool of 135°F water. The description of the die is shown in Figure 1.

Four 45° rosette strain gages were mounted on the circumference of the die with a room temperature curing adhesive. The gages consisted of foil grids of stablized constantan on a polyimide backing. The gages were covered with a parting film of cellophane tape before applying the waterproofing so that the gage installation could be inspected and repaired without damaging the grids. An electrical shield covering the gages was found to be unnecessary and was removed after a few initial tests. A shielded pair of instrumentation lead wires was connected to each gage with a minimum amount of exposed unshielded cable. The resistance of the gage was nominally 350 ohms and the bridge was excited with 24 volt batteries. The wheatstone bridge was built using 350 ohm gages for the three resistor legs.

A trigger circuit, proven adequate in many previous tests, was used to establish time zero by triggering the beams of the oscilloscope. Zero test time was coincident with detonation of the charge. Immediately prior to each test all channels were zeroed and calibrated by shunting resistance across the active gages with the die underwater.

c. Test Results

Several elastic strain measurements were made. The first tests were made with the dual beam oscilloscopes in the chop mode so that four channels could be recorded simultaneously. These traces were difficult to read for the following reasons:

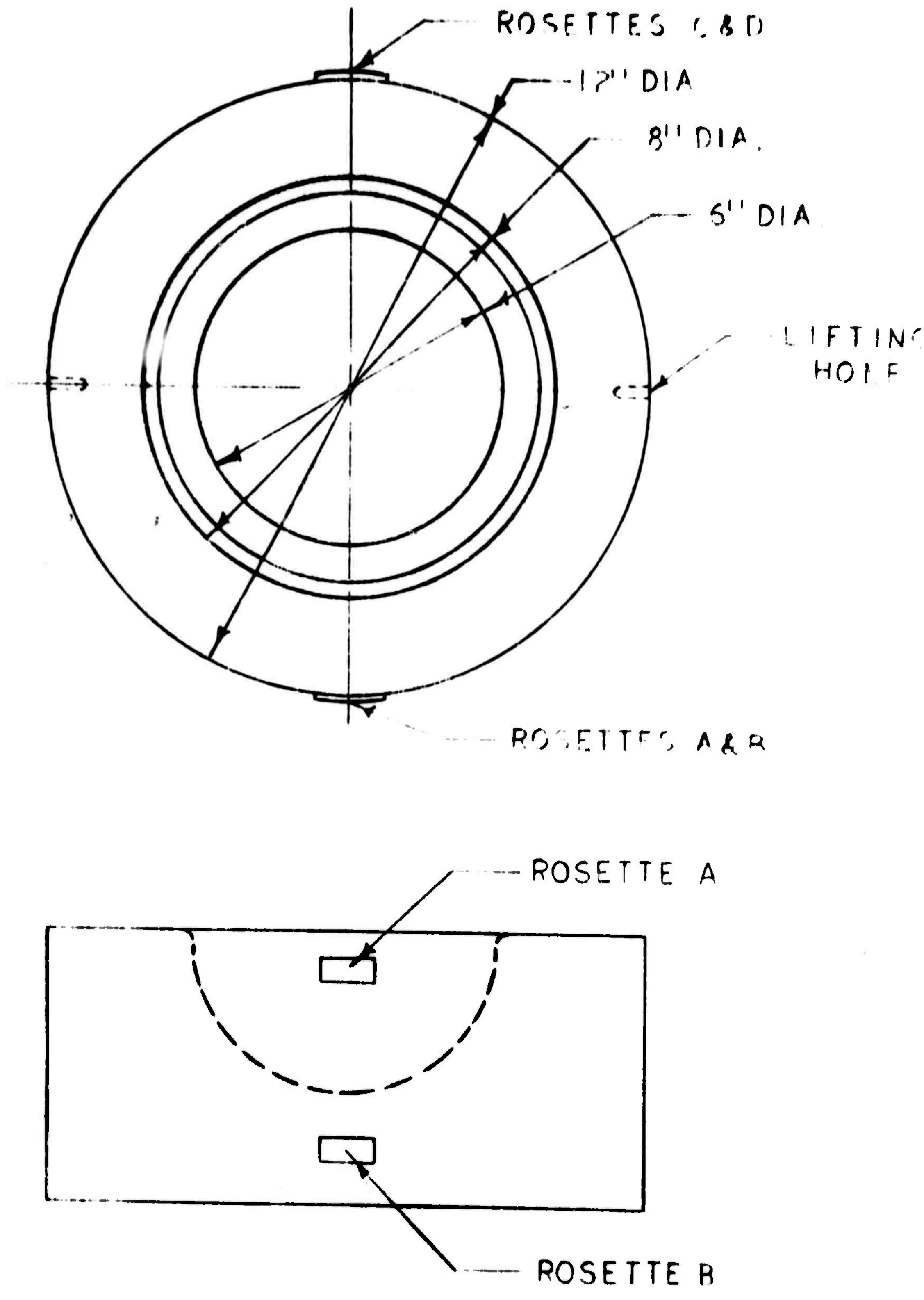

Figure 1 Die-Strain Gage Configuration

1) Electrical ringing in the system;

2) Too much cross-over of the traces such that the identity of each trace was lost;

3) The chopping of the beam plus the distance the beam had to travel exceeded the capability of the oscilloscope.

Several strain traces were made after eliminating the chop beam mode. This limited the recorded strain to two channels per test, but the traces were clear and repeatable.

The tests showed the strain to be a maximum of 100 micro inches per inch strain peak to peak. With the strain level this low, the validity of actual strain was investigated by exposing the instrumentation lead wires to the underwater blast while the die remained out of the pool. Two channels were recorded; one lead wire was exposed to the shock wave and one lead wire was not. In order to best simulate test conditions, 80 grains of Composition A-3 with an 8.0 inch stand-off were used in this test series. The test results show a maximum strain of 100 micro inches per inches zero to peak, although the die was not subject to strain. The gain of the amplifier was measured to be 400 so that the 100 micro strain noise corresponds to a bridge unbalance of 1.0 millivolts of noise.

The noise was minimized to 0.25 millivolt or 25 micro strain equivalent (zero to peak) by performing the above test and using a watertight conduit to protect the lead wire from the blast. Through more testing, it seemed evident that the conduit should be held rigidly to prevent erroneous noise signal because the lead wires were slapping within the conduit. When water was let into the conduit and the test repeated, the dynamic noise was about the same as no conduit. A rubber hose was substituted for the metal conduit and made watertight. This dynamic test again showed noise about 70 micro strain zero to peak. Knowing the effect of the blast on the instrumentation lead wire, the die strains should be able to be measured to within 25 micro strain for this size of charge. Die strain will again be measured during explosive forming with the use of conduit to protect the lead wires.

2. <u>Applications of Explosive Welding to Hardware Configurations</u>

Principal Investigator: W. E. Simon

a. Lap Joint for Construction of Composite Tank Liners from 2014-0 Aluminum (.016 inch thick)

A truncated conical preform has been explosively welded and successfully hydraulically formed to a segment of a 12 inch sphere.

Preparations have been made for welding of the end boss to a spherical cap which will subsequently be welded to the spherical segment already formed.

b. Attachment of 4140 Steel Shaft to 4340 Steel Gear

The feasibility of explosively welding a hollow shaft (2" O.D., 1/8" wall) to a gear (6" O.D., 1-1/2" wide) has been investigated. A corrugation was explosively formed in the shaft and the shaft inserted into the gear and welded. Micrographs indicated a good bond with a small melt pocket along the center of the corrugation.

c. Use of Cover Mass over Explosive to Reduce Explosive Requirements

One of the problems in seam welding thick plates is the amount of explosive required. A computational program has been developed to estimate the effect of cover mass on explosive requirements. Computations indicate that for a case where 1/8" Detasheet is required for a 0.090" aluminum seam weld, the use of a 0.090" aluminum cover mass would reduce the explosive requirement to 0.025", a reduction by a factor of five. An experimental investigation has been planned to test the results of the analysis.

II. UNIVERSITY OF DENVER

1. Flange Buckling of Explosively Formed Domes

Principal Investigator: M. Kaplan

Graduate Student: H. Boduroglu

Closed form solutions for the unbuckled flange stresses have been obtained for the case when friction effects are negligible. One solution was obtained with the use of the von Mises yield condition, while the other involved the use of the Tresca yield condition.

We have not yet obtained satisfactory experimental results with which to check these solutions. On the two domes we formed with flange lubrication, the draw depths were higher than expected. The resulting flange width was too small to obtain radial variations in thickness, radial strain, and hoop strain, and thus was of no value.

2. Explosive Punching of Dual Hardness Armor

Principal Investigator: W. G. Howell

Post Doctoral: A. R. Dowling

Several of the 70° wedge angle lined charges, evolved during the last quarter, have been shot in order to determine the optimum stand-off for this new charge size. These charges had explosive on the shaped ring only, not in the center, so that the penetration by the jet could be isolated from the total deformation produced. The depth of cut was less than expected and there exist two possibilities for this. First, due to the increased leg length and reduced wedge angle of the liner, the explosive had to undergo a much more severe shaping operation and tended to spring back off the liner material. Lack of good overall contact between the explosive and liner material would result in a loss of efficiency. Second, the reduced penetration could have been caused by the higher hardness of the material compared with that previously used. Consequently, the effects of material hardness on the resulting penetration are now being studied.

A considerable reduction in the cost of each charge has been achieved during the last quarter by eliminating the need for "line wave generator" material to obtain simultaneous circumferential detonation of the shaped charge. Instead a "top-hat" of Detasheet is constructed, symmetrical detonation of the main charge being achieved by placing the cap in the center of the top of the "hat".

3. Cylindrical Explosive Forming Dies

Principal Investigator: J. A. Weese

Graduate Student: R. E. Knight

As mentioned in the last quarterly report, this work formed the basis of Mr. Gordon Ney's Master of Science Thesis. A review of this work is available in a report published by the Center, "Design of Cylindrical Explosive Forming Dies" by Gordon B. Ney and John A. Weese. This work is being continued in greater depth and will serve as a doctoral thesis for Mr. R. E. Knight. Extensive modifications have been made to improve our ability to record dynamic strains at various points on the die. Several more sizes of tubing have been obtained for making work pieces. Considerable ground work has been laid to place the analysis of the dynamic response of the work piece to a line charge on a much firmer basis.

4. Explosive Forming of Domes in Vented Dies

Principal Investigator: J. A. Weese

Graduate Student: P. Hardee

Several 1/8 inch thick, 12 inch diameter, mild steel domes have been formed using a vented die. The die is a 1/4 inch thick mild steel dome containing 241 3/8 inch diameter holes. The holes accounted for 18% of the surface area of the die. The concept seems to work very well. The completed domes showed no evidence of air entrapment between the die and the dome and there was no indication of the domes becoming hobnailed due to pushing the metal into the holes of the die. Work is underway to see how much venting of the die is really required.

5. Explosive Forming of Thick Domes

Principal Investigator: R. J. Green

Simple mathematical models have been developed to describe the dynamic response of a flat plate into a dome making use of a die. The models developed enable the system to be described by ordinary differential equations in time. The analysis includes bending as well as membrane effects. The resulting equations have been numerically integrated and the results will soon be compared to experimental observations.

6. The Edge Pull-In of Explosively Formed Domes

Principal Investigator: M. Kaplan

Graduate Student: S. Kulkarni

Euler's equations using Hill's principle of maximum plastic work have been derived in both spherical and cylindrical polar coordinates for the dome and flange.

The use of spherical coordinates is appropriate for the dome. Cylindrical polar coordinates are being used for the flange with proper matching conditions at the dome-flange interface. The resulting equations are quite intractable and work is now being directed toward the investigation of reasonable simplifications. Past experimental and analytical results are being used in this regard.

7. Fracture Toughness of Explosively Formed High Strength Steels

Principal Investigator: H. Otto

Graduate Students: R. Mikesell, C. Yin

Explosive forming of one inch thick maraging steel plates supplied by the Naval Research Laboratories was completed. These plates will be evaluated by the Center for Stress Corrosion.

Mr. Mikesell

Two types of plane strain notches were evaluated for fracture toughness tests. One involved grinding a notch in 4130 steel in the as-quenched condition, starting a crack with a fatigue machine, and then tempering the sample. With a 0.0465 inch deep notch, the quenched sample was cycled for nearly 100,000 revolutions with no sign of a crack. At a fatigue stress of 100,000 psi, it was felt that fatigue damage would result if the test were carried further.

Therefore, it was decided to concentrate efforts on the EDM (electric discharge machine) method of making a notch. Several EDM electrodes were investigated: brass, graphite (the ordinary variety, the type used with welding, and the type adapted for EDM use), and tantalum. All of these electrodes wore too much upon penetration into the steel and did not produce a satisfactory notch finish. An alloy copper-tungsten was tried and showed very little wear on a penetration of about 0.050 inch. With only one pass of the electrode, the bottom of the notch was sharp and had a relatively good finish.

With a sample of 4130 (1600^{o}F heat treatment and 600^{o}F temper), a notch was made 0.065 inch deep with the copper-tungsten electrode. It required only 32,000 cycles to form a fatigue crack. The electrode was small enough in width that the cracking was well controlled. On testing, "pop-in" was detected with a strain gage glued to the back of the sample directly behind the crack. The load at "pop-in" is determined from a load-strain plot: the load at a "kink" or decrease in the curve is the "pop-in" load. A value of approximately 70 ksi (in.)$^{1/2}$ was computed for the value K_{Ic}.

Having established the technique, fracture toughness samples will be cut from explosively formed flat bottom domes of 4130 and 4340. The sample width and length is such that 8 samples can be cut from each dome. For comparison, toughness tests will be made on the parent 4130 and 4340 steel.

Mr. Yin

Mechanical properties of explosively formed HY 80 steel were determined after heat treatment. Heat treatments consisted of austenitizing at 1660°F for 35 minutes, water quenching and tempering at 1150° and 1300°F. As-received stock was simultaneously heat treated for comparison purposes.

The results of the mechanical property tests are presented below.

Material	Effective Forming Strain	Yield Strength psi	Ultimate Strength psi	Elong. in 1 inch, %	Reduction in area %	Hardness R_c
			1150°F Temper			
As-received	0	110,100	120,850	25.7	70.6	26.5
Dome 1	0.03	110,100	120,890	25.2	68.7	26.6
Dome 2	0.07	108,530	120,260	21.9	68.1	26.5
Dome 3	0.085	106,170	119,460	24.0	68.7	26.3
			1300°F Temper			
As-received	0	87,350	102,550	26.7	72.2	19.4
Dome 1	0.03	87,850	103,330	28.4	72.2	20.1
Dome 2	0.07	86,260	102,710	27.0	73.1	19.8
Dome 3	0.085	85,500	101,280	27.4	71.6	18.5

No large effects were noted as a result of strain or strain rate with respect to material properties after a post forming heat treatment. There is some indication that as the strain is increased there is a slight decrease in both the yield and ultimate strengths as a result of a post forming heat treatment. However, this difference is not too great and for all practical purposes the mechanical properties of the HY 80 after forming and heat treatment are the same as for unformed stock.

Metallographic examinations indicate that slight differences may be present in the prior austenite grain size after forming and heat treatment, but again, these differences appear to be relatively minor.

8. Terminal Properties of Titanium

Principal Investigators: R. N. Orava, H. E. Otto

Graduate Student: P. Khuntia

The relative influence of explosive and conventional (rubber-press) forming on the terminal behavior of unalloyed α-titanium (TMCA 50A) and α-β titanium alloy (6Al-4V) is being investigated. The study includes the evaluation of microstructure, hardness, tensile flow characteristics, stress corrosion cracking susceptibility, and thermal response.

Domes were fabricated explosively and isostatically from 0.040 inch Ti-6Al-4V sheet as described previously for Ti-50A. These have been sectioned and specimens prepared for tensile and stress corrosion tests during the next quarter.

Tensile test results for the second set of two explosively and isostatically formed domes confirmed the findings reported earlier that forming rate does not significantly affect the tensile properties of unalloyed α-Ti.

The study of the relative effect of explosive and isostatic forming on the susceptibility of α-Ti to stress corrosion cracking in methanol containing 0.5% HCl is nearing completion. Specimens of as-received and formed material were exposed to failure by continuous immersion at 90% of the terminal 0.2% offset yield stress in three-point bending. Time to failure, t_F, was used as a measure of susceptibility. The data were analyzed statistically. Forming strains ranged from 2.7 to 4.5% and orientations relative to the original sheet rolling direction, from 0^o to 90^o. Four series of tests, 12 specimens per series, have been conducted to date. When comparisons were possible within each series, both explosively and isostatically formed material was found to be more resistant to methanol cracking than unformed stock. Two out of three comparisons revealed that explosive relative to isostatic forming improved the resistance to cracking, and one showed no significant difference (95% level of confidence). In all instances, the mean failure time increased in the order: unformed, isostatically formed, explosively formed. There was a tendency for t_F to increase with forming strain, and with a decrease in the angular displacement of the specimen from the rolling direction. Since these trends were independent of forming rate, the data from all four series were combined yielding mean failure times of 14.7, 22.2, and 22.7 hr for unformed, isostatically formed, and explosively formed material, respectively. Therefore, from a statistical analysis at a confidence level of 95%, it was concluded: first, that the introduction of about 3.5% deformation by forming, irrespective of rate, raises the resistance of α-Ti to methanol cracking. Second, the resistance is independent of forming rate. To permit these statistical decisions, a refinement of the explosively formed sample was necessary, resulting in the deletion of the two extreme values of 77.0 and 128.5 hr. Clearly, their inclusion in the analysis would have favored the view that explosive forming is not detrimental to the stress corrosion susceptibility of unalloyed titanium.

9. Explosive Welding

Principal Investigator: S. H. Carpenter

Post Doctoral: A. R. Dowling

Graduate Students: V. H. Winchell, M. Nagarkar

The objectives of the present program are to develop pressure and strain relationships that are encountered during explosive cladding and then relate these to the material properties. As an adjunct study, the effect of explosive cladding on the diffusion characteristics of the cladding is being studied. There is some indication that a defect structure is generated, which, during post cladding heat treatments can alter the characteristics of the material adjacent to the bond. Also, the possibility of an enhanced Kirkendall effect has been noted in some dissimilar metal clads which may be undesirable in some DOD applications.

Dr. Dowling

The concept of using shock-hardening as an indication of pressures developed during explosive welding was the object of a study in welding aluminum plates. Hardening during the welding process can be attributed to both the compressive shock wave at the point of collision and the strain associated with the bending operation in the top of flyer plate and any upsetting that occurs in the lower plate. Although the induced wave is not plane, the use of an aluminum alloy anvil on top of a material with a lower acoustic impedance insures that the compression wave at the point of collision is dominant in the specimen plates. Experiments were conducted with aluminum alloys 2024-T3, 2014-0, 2014-T6, and 2219-T31. Welding was conducted using DuPont Red Cross Extra 40% Dynamite which has a detonation velocity of about 3500 m/sec. Loadings of 6 to 8 grams per square inch were used. The specimen size was held constant at 6" x 3" x 0.125" with hardness traverses being made at 1/2 inch areas 1" and 3.6" from the starting plate edge and normal to the welding direction. In the preliminary experiments, a great deal of scatter was obtained in the hardness values obtained. This scatter was reduced in several instances by aiming the plates, during welding, so they were caught in water which quenched the specimens.

DPH hardness readings were taken with a load of one kilogram. This loading was a compromise so the indentation produced was small enough to give an indication of gross variations, but large enough not to be influenced by differences as individual grains. Hardness traverses were taken across the weld from the top to the bottom of the welded plates. Hardness variations were noted across the welded plates with the highest hardness generally being at the interface and the lower hardnesses at the center of the two plates. The upper or cladder plate is subjected to a two way bending operation that introduces strain with subsequent strain hardening effects.

Assuming that the pressure is transmitted throughout the plates and plastic flow is present at the interface (see Mr. Winchell's strain measurements), then the truest indication of pressure alone would be that in the bottom plate, away from the plastic flow region.

A theoretical estimate of the impact pressure can be made from a two dimensional Gurney analysis of impacting plates. In this type of analysis, the approximate velocity of an explosively driven plate can be calculated. The velocity can be used then to determine the pressure.

Using the pressure versus hardening curves obtained by Mr. Otto to arrive at a pressure value and comparing these with gurney theory, fair agreement is obtained as is shown in the table. The lower values are generally those in the bottom plate, whereas the higher values are from the top plate or right at the weld. Results obtained with the 2014-0 (in which the bottom plate welded to the anvil) were not consistent with solution heat treated stock.

Theoretical Welding Pressures Obtained from Shock Hardness Values

Material	Calculated Pressure Kbars	Explosive Loading g/in.^{2}	Pressure Determined from Hardness Change, Kbars
2024-T3	60	5	70-220
2024-T3	70	6	50-70
2014-T6	70	6	60-80
2014-T6	80	7	60-80
2014-T6	90	8	80-160
2219-T3	25	6	<30 - <150
2219-T31	30	7	<30 - <90
2014-0 (1)	35	6	0-20
2014-0 (1)	37	7	0-20
2014-0 (1)	40	8	0-20

(1) Bottom plate welded to anvil.

The results to date would indicate that theoretical impact pressures agree fairly well with those determined from shock-hardening relations. Strain induced in the cladder plate by bending does increase the hardness over that obtained by transient shock strain alone. It would appear that the amount of shock-hardening can be used as an indication of the pressures developed during welding.

Mr. Winchell

Present studies are concerned with the strains developed in the cladder material as a result of the welding process. A plate of 6061-T6 aluminum 6" x 3" with a 1/4 inch thickness was selected for analysis. Nine groups of 0.088" diameter fiduciary holes were drilled completely through the plate. Each group was composed of a series of 11 holes spaced at 0.100" intervals. The holes comprising a group were made in a line parallel to the welding direction of the plate. Three groups were placed toward the start of the weld, three in the middle, and three near the end. This material was successfully welded to a larger piece (16" x 12" x 3/16") of 2024-T3 aluminum.

Measurements are now being made to determine material flow in the welding direction utilizing the fiduciary holes. One interesting feature observed was the movement associated within each hole group at the surface as a result of the welding process. The average of the three groups toward the start of the weld showed a contraction of 0.09% while the middle groups were elongated 0.40% and those near the end were further elongated to 0.76%. This observation indicates that the strain is not uniformly developed in the cladder plate. Even though some contraction is present at the start of the weld, an actual increase in strain or elongation of the cladder plate occurs. Although elongation of the cladder plate has been noted in several previous instances, the distribution of strain has not been determined previously. This distribution of strain could account for some of the difficulties that have occurred in long welds.

Mr. Nagarkar

Diffusion studies of explosively clad iron-titanium and iron-aluminum systems are being initiated. For these studies, diffusion bonded materials are being obtained. These in turn will be explosively clad to give a multi-layered composite. By using this approach, no differences in starting materials will be present so valid comparisons can be made of the diffusion processes. The particular systems were selected since iron-titanium has potential application in dual hardness armor systems and iron-aluminum is of interest in transition joints in missiles.

10. Explosive Welding of Dual Hardness Steel Plate

Principal Investigator: R. H. Wittman

Explosion welding experiments reported previously were conducted with the medium and high carbon steel plates in the normalized condition. The explosion bonded plates were quenched and tempered to maximum hardness. Because of extensive cracking in the higher carbon plate, probably due to differential transformation strains, the experimental effort has been shifted to explosion welding the plates in the hardened condition. In addition, Ti-6Al-4V ELI alloy has been substituted in some experiments for the lower carbon alloy in an effort to produce a dual property steel-titanium composite lighter in weight than the dual property steel-steel composite.

Experiments indicate that welding the steel plates in the fully hardened condition does not appear feasible (see page 14). Extensive cracking is produced in the base plate (58 R_c) and no welding is observed. When the hardness of the base plate is reduced to 48 R_c, welding could be produced when using an equally hard flyer plate and no cracking is observed in either base or flyer plate.

Similar results were obtained when attempting to explosively weld Ti-6Al-4V alloy to the hardened steel. Extensive fracturing of the base plate and no welding resulted when the base plate was 57 R_c. Explosion welding between the titanium alloy and the hardened steel and no fracturing were observed when the steel hardness was reduced to 48 R_c.

Metallographic examination of the Ti-6Al-4V to hardened steel bond reveals a non-symmetrical ripple formation and pockets of brittle titanium-iron compound. These band-line features are probably due to the large difference in flow stress and compressibility of the titanium and iron alloys.

The experimental explosive welding conditions are presented on the following page.

Explosion Welding Parameters and Results

		Flyer Plate		Steel Base Plate			
Specimen Number	Alloy	Thickness inches	Hardness R_c	Thickness inches	Hardness R_c	Explosive Loading g/in.^{2}	Remarks
DH-4	Steel	0.2	22	0.2	26	16 (2)	Welded; Repeat of DH-2
DH-5	Steel	0.2	48	0.2	48	30 (2)	Welded
DH-6	Ti-6Al-4V	1/8	32	0.2	48	30 (2)	Partially welded
DH-7	Steel	0.2	48	0.2	58	30 (1)	No welding; base plate shattered
DH-8	Ti-6Al-4V	1/8	32	0.2	57	24 (1)	No welding; base plate shattered
DH-9	Ti-6Al-4V	1/8	32	0.2	48	24 (1)	Welded

(1) DuPont Red Cross Extra Dynamite

(2) DuPont Free Running Dynamite

II. <u>Explosive Powder Compaction</u>

Principal Investigator: H. Otto

Graduate Student: D. Witkowsky

The literature survey on explosive compaction was continued. Most of the work reported in the literature has been highly empirical in nature with no real progress being made in reducing explosive compaction to the point where relationships have been established between explosive loadings, part configurations, pre-compaction density, particle size distribution, final density, and post compaction treatments. It is readily apparent that explosive powder compaction is not adaptable at the present time to high volume operations. The only approach to a volume production operation is through the use of Dynapak type of powder forgings. Using explosive powder compaction for large forging, extrusion or rolling preforms does appear to be attractive, particularly with high strength-high temperature alloys and refractory metals in which controlled grain size is of importance such as for turbine blades.

A series of experiments has been initiated making steel rolling preforms. Variables to be studied include amount and type of explosive, pre-compaction density, size of preform, and particle size. These variables will be related to green compaction density and post compaction treatment.

The experiment consists of using a steel frame to hold the powder with spall plates on top and bottom of the pre-compacted powder. Steel foil is glued over the openings in the frame so a vacuum can be maintained. If air is left in the assembly, hot spots can develop through adiabatic compression that actually leave melt pockets. Also, on post compaction treatment, voids can form as the trapped compressed air pockets expand.

A plane wave generator of the mousetrap variety is used to initiate the explosive so a uniform loading is maintained during compaction. Evaluation of compacted material has just been initiated.

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13. ABSTRACT

This report summarizes results during the period 1 October thru 31 December, 1969:

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