AMRA CR 66-05/16

CENTER FOR HIGH ENERGY FORMING

THIRTEENTH QUARTERLY REPORT

OF TECHNICAL PROGRESS

Jimmy D. Mote

October 1, 1968

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

The analysis for the impulse delivered to a blank using a modified Taylor analysis has been programmed in Fortran IV language and compiled. The next quarters effort will be devoted to checking out the program and comparing theoretical results with experimental measurements.

An improved technique for bonding strain gages has been developed which provides strain measurements on explosively deformed blanks up to 5.5%.

Initial experimental work has been initiated on the energy delivered to dies.

Additional results on strain rate effects is reported.

The preliminary work on explosive forming and punching of armor has started.

The safety system for the capacitor bank has been installed and is operational.

Preliminary results on the effect of explosive forming on stress corrosion cracking, terminal materials properties, and recovery and recrystallization are reported.

Recent results on the mechanics of energy transfer and high velocity metal deformation are reported.

CONTENTS

I. MARTIN MARIETTA CORPORATION

1. Springback and Mechanics of Blank Deformation

Principal Investigator: G. A. Thurston

The Twelfth Quarterly Report of the Center reported an analysis for impulse delivered to a flat circular blank by a central explosive charge. G. I. Taylor's theory for a plane wave impacting an infinite plate was modified to account for the oblique incidence of the spherical wave front produced by a charge at a close standoff distance.

This impulse analysis has been included in a new computer program to predict the dynamic, plastic response of circular blanks to explosive charges. The analysis has been programmed in FORTRAN IV language and compiled. The next quarter's effort will be devoted to checking out the program and comparing theoretical results with experimental strain measurements reported in earlier Center reports.

The degree of correlation between theory and experiment will guide further analysis in this area. If the final results are as good as the preliminary calculations indicate, the analytical effort can take several directions. The proposed scope of the complete analysis is outlined in the Third Annual Report of the Center. The main computer program allows for subroutines to be added later with few programming changes in the main program.

For example, the impulse analysis for a central charge is written as a subroutine. The impulse from contact explosives, gas detonation, electro-hydraulic shock, or electro-magnetic pulses can be added as subroutines without the need for writing a new program to handle each type of energy source.

Another option is to add incremental plasticity theory as a subroutine to generate the constitutive relations for the deforming blank. The current version of the program has a subroutine for deformation theory. The incremental theory w ll be essential to compute unloading during springback.

Previous programs written for problems at the Center have proved useful since the logic can be transcribed directly for inclusion in subroutines for the new computer program. The bulge test program reported by R. Harris in the Third Annual Report is one of these helpful programs. Further investigation of the bulge test analysis shows that the lower bounds on the instability strains reported by Harris are very close to the actual values. Closer examination of the numerical results and the governing differential equations revealed a noteworthy fact.

The instability strain in the bulge test is defined as the apex strain in the blank at maximum pressure. At higher strains, the specimen has necked down so that the equilibrium pressure drops off. The interesting fact is that near the instability strain the character of the differential equation changes. Before instability, it is a second order differential equation with a regular singularity at the apex of the shell. This singularity is related to the cylindrical coordinates used for the analysis and merely reflects the fact that the solution must be finite at the apex while the actual value is determined by the boundary condition at the outer edge. After instability, a change occurs where another regular singularity of the differential equation moves out from the apex to another radial location. A singularity in the interval of integration is rare in physical problems, turning points are more common. The radius at the singularity seems to be the boundary between the stable outer portion of the deflected blank and an unstable inner region whose radial deflection depends on a prescribed deflection at the singular point.

2. Strain Gage Measurements During Explosive Forming

Principal Investigator: D. Bouma

The Eleventh Quarterly Report of the Center reported strain gage measurements recorded during explosive forming of domes. High elongation gages were used. The maximum strains before gage failure in the dynamic application were well below the static strain measurement capability of the gages, and reasons for this difference have been studied with the aim of increasing gage life during forming tests. The problem areas were:

a) Failure of the adhesive bond between the strain gage and the blank. The post-test microscopic examination showed the adhesive to be upon the gage but not upon the aluminum parts.

b) Failure of lead wires which electrically connect the strain gage tabs and the terminal strips. This failure caused the recording instruments to show a gage failure when in fact the gage was still good.

To solve the adhesive bonding problem a better etchant was sought to improve the bond strength between adhesive and the aluminum that must be superior to that recommended and supplied by the strain gage manufacturers. Through coordination with the Materials Engineering Section, an etchant was obtained and used as a metal preparation prior to bonding the gage. The etchant is commonly known as dichromic-sulfuric acid and can be prepared by the following weight mixture:

17 parts of H_2O

2 parts $Na_2CR_2O_7 \cdot 2H_2O$

7 parts H_2SO_4 (commercial pure)

This etchant was used to prepare the gage area for bonding by applying for one hour at room temperature. The solution was then washed off with tap water, allowed to dry and the gages were applied in the normal way.

The previous method of attaching lead wires was to solder a copper wire, size AWG, number 36, between the strain gage tab and the terminal strip with sufficient wire length to allow for movement during the straining of the part; thus isolating the strain measurement to the gage. The whole gage installation was then covered with waterproofing and in the process the lead wires were embedded in waterproofing. A new approach is to form the lead wire into a coil or spring for the entire distance between the gage tab and terminal strip. The coils are formed by winding around a .030 inch diameter wire and annealing to remove the cold work stresses induced by forming. Before applying the waterproofing, the coiled lead wires are covered by an overlay of cellophane tape. This provides a pocket within the waterproofing for lead wire movement with little restriction.

These improvements have enabled a strain of 5.5% to be measured at the rate of 100 inches per inch per second without fracturing the gage, adhesive or the lead wires. The highest strain previously measured was 4.9% but the gages, adhesive bond and lead wires failed. The upper strain limit using the new techniques are not known at this time. A new series of tests is planned with higher charge weights than previous tests. The larger charges will produce higher strains and the maximum strains that can be measured by the new techniques will be determined.

Since the waterproofing appears to have impeded movement of the lead wire causing it to fail prematurely in earlier tests, another approach was to seek a less rigid waterproofing. Because of its dielectric and water resistant properties, silicone grease was substituted for the GW-5 (Budd Company) waterproofing. This proved totally unsuccessful as the gages were blown completely off, and the method of coiling the lead wire to increase its flexibility appears to have the best results.

3. Energy Transfer to Dies

Principal Investigator: J. Mallon

In order to fully evaluate the problem of energy transfer it is desirable to investigate the energy delivered to the die itself. Preliminary experiments have been performed to determine die shell configurations which will undergo typical sizing shot deformation without die growth.

Three 12" diameter dies were built using in each case an explosively formed die shell of A-36 mild steel .10" thick. This steel exhibits little cold working effects and is therefore suitable for reflecting linear increments of deformation when subjected to a series of identical explosive charges. This steel with its low yield stress value of 33,000 psi, will show permanent deformation when impacted with relatively low loads. The low strength shell, therefore subjects the back up medium to the most severe test conditions. A charge of 60 grains of "Composition A-3" and a 6.9 grain cap was used on each test at a 2.125" stand-off. This magnitude of charge and stand-off distance is representative of sizing shots that are often required in seating a blank intimately into the die cavity. It is also the most severe shock to which dies are generally subjected.

Table 1 presents a summary of the data generated during the preliminary experimental program and Figure 1 defines the symbols appearing in the table. Other data common to all experiments are as follows:

a) Tests were conducted in a 7 ft diameter pool under a 6 ft heat of water; and,

b) The radius of curvature of the die shell at the center was determined from a template on which the change in contour is recorded.

The essential results of these preliminary experiments are summarized in the following paragraphs.

The most effective back up medium is high strength concrete. However, the concrete cracked after the first shot, hence it is not clear if this material could be used for repeated shots.

The die shells with an infinite water back up and contained sand back up exhibit about the same amount of deflection. Hence, to utilize these die concepts the shell must be of sufficient thickness to reduce the stresses to the elastic range.

The die shell backed up by water in a closed cylinder exhibited the greatest deflection. The contained water back up medium serves

TABLE I

Permanent Deflection of Die Shell with Various Back-up Mediums

Test No.	Die No.	t	W	Back-up Medium	r	Δ_w	$\Delta_w^{(E_p)}/r$	Δ_c
I	1*	---	2.90	Air (Water Barrel with 20" head)	11.0	.23	.0209	----
II	1	---	3.13	Water(unconfined)	11.0	.05	.0045	----
III	2	.125	4.35	Water(Confined)	6.1	.05	.0082	.04
IV	2A	.125	4.40	Water(Confined)& Reinforced Die	6.1	.05	.0082	No Change
V	3	.315	2.62	Dry Coarse Sand	7.0	.04	.0057	N.C.
VI	3	.315	2.66	Dry Coarse Sand (Sand added)	7.0	.04	.0057	N.C.
VII	3	.315	2.70	Wet Coarse Sand	7.0	.04	.0057	N.C.
VIII	3	.315	2.74	Dry Fine Sand	7.0	.04	.0057	N.C.
IX	3	.315	2.78	High Strength Con.	7.0	.01	.0014	N.C.

*Note: Die #1 has no cylinder or bottom plate but is tripod supported.

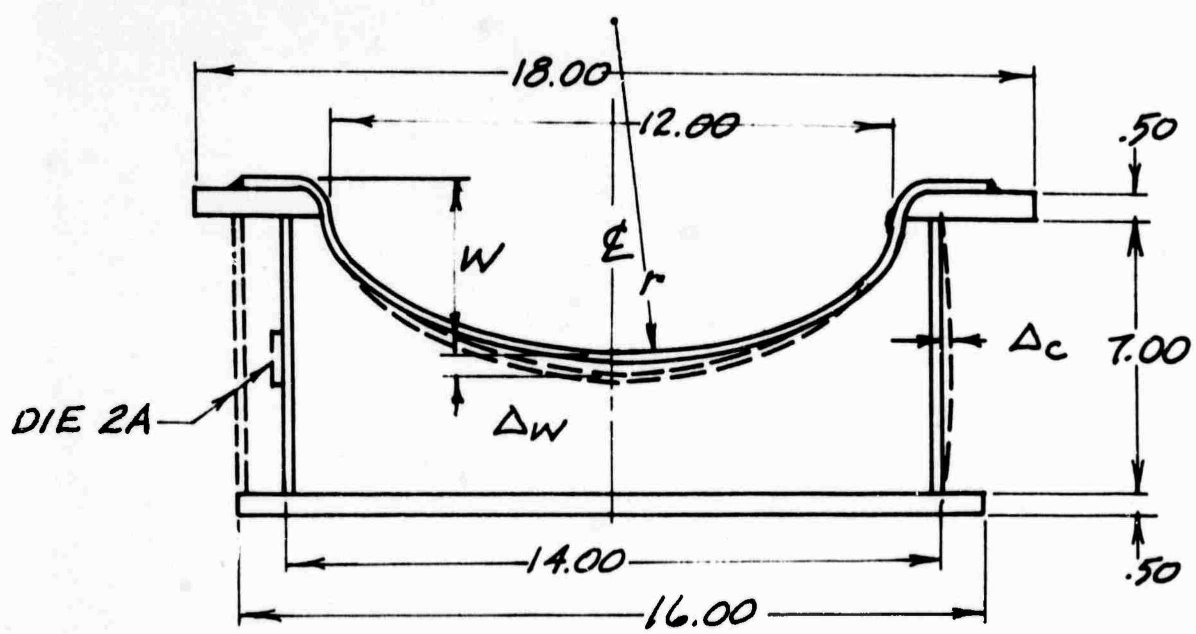

Figure 1. Parameters for Evaluating Energy Transfer to Die

to transmit the energy to the cylinder wall and end closure. Even it the die cylinder is made strong enough to resist permanent deformation the elastic deformation of this cylinder will allow enough change of volume so that the die shell will grow.

Future work will be directed at the design of shells of sufficient strength to always remain in the elastic range. Since most of the deformation occurs in the center portions of the shell appropriate support structures will be investigated. Additional work will be carried out on lightweight reinforcement techniques.

II. UNIVERSITY OF DENVER

1. Strain Rate Effects

Principal Investigator: C. Hoggatt

During this report period the dynamic stress-strain behavior of 2014-0 aluminum was determined using the expanding ring technique. Within the strain rate range considered (500 to 7,000 sec^{-1}), the stress-strain relationship established for this material can be represented by a single dynamic curve as shown in Figure 1. In this figure it can be observed that the dynamic curve lies above the average static curve, with the most significant increase in flow stress occurring at the lower strain values.

Supplemental test data was also obtained for the 6Al-4V-titanium alloy. Following the reduction of this data, additional data points will be added to the dynamic stress-strain curve previously presented for this material in the last quarterly report (Twelfth Quarterly Report of Technical Progress, July 1, 1968), and resubmitted in the next quarterly report of technical progress.

Dynamic property determinations for two additional materials will commence in the very near future. Both 4130 and 4340 steel have been ordered and received, and specimens are presently being machined. It is anticipated that initial tests for both materials will be conducted on specimens heat treated to a hardness level of approximately 35 R_c. The intent of these tests will be to determine the effect of strain rate in the tensile behavior of high strength steels.

2. Explosive Punching & Forming of Composite Armor

Principal Investigator: W. Howell

Pending the delivery of composite armor material from the U. S. Army Mechanics and Materials Research Agency, preliminary work has been done fabricating a die and evaluating different explosive punching concepts. At the present time the most promising approach seems to be the use of a linear shaped charge made into an annulus of the required diameter, initiated simultaneously by means of a cone of detasheet above it with a detonating cap at the apex. Preliminary experiments will be conducted by explosively punching a $\frac{1}{4}$" thick plate of 4130 steel, to verify analytical methods for determining charge size, to determine the best relationship between the diameter of the explosive annulus and the diameter of the hole to be punched, and the quality of the hole. The results of this preliminary investigation will be applied to the composite armor material when it arrives, with the proper modifications to account for the different material properties.

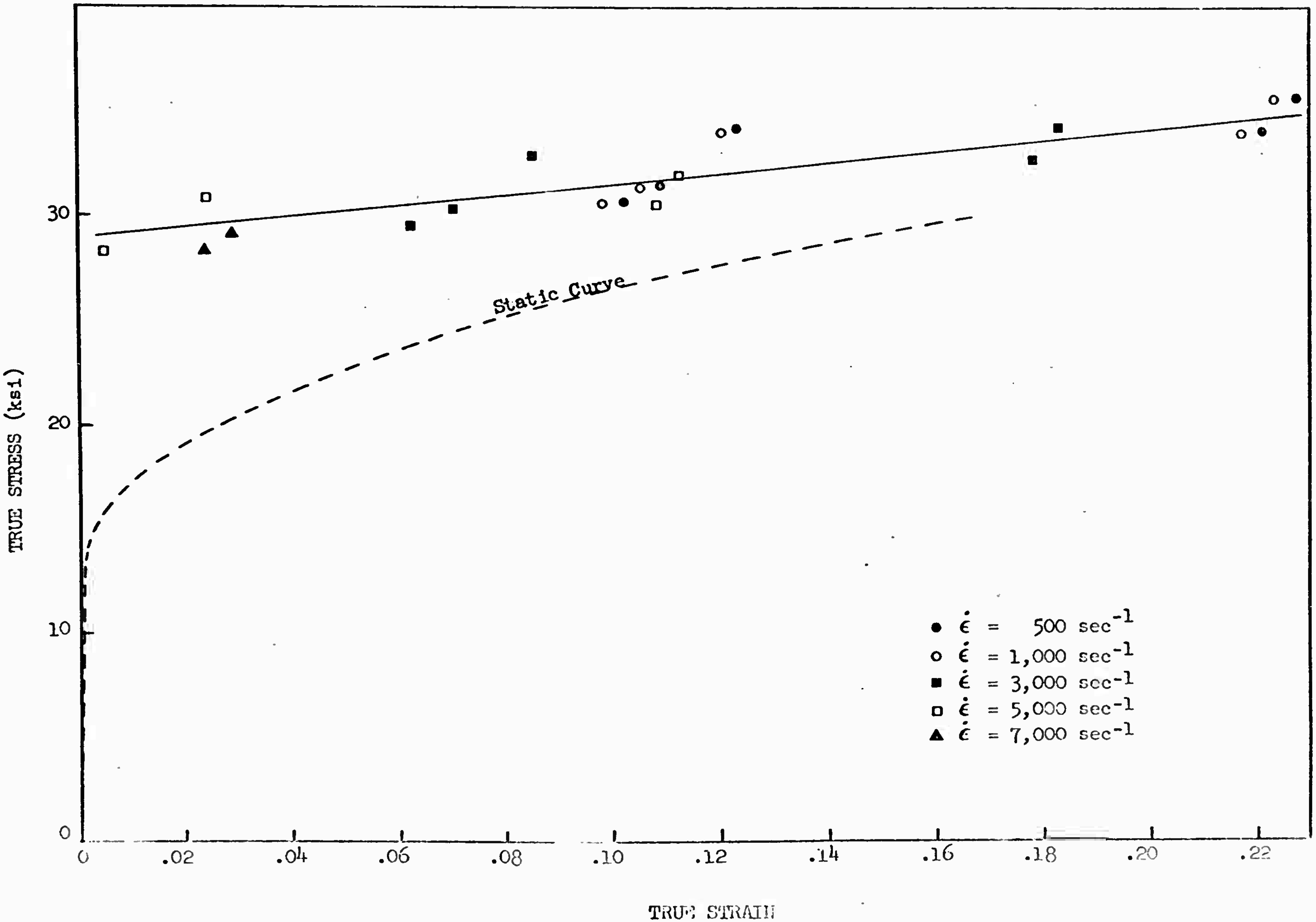

Figure 1. Dynamic Stress-Strain Curve for 2014-O Aluminum.

3. Electromagnetic and Electrohydraulic Forming

Principal Investigator: William N. Lawrence
Graduate Student: Lloyd Gilbert

Early in the third quarter of 1968, the assembly of the second half of the bank was completed. The installation was tested, according to the procedures used before, to design specification limits. The bank is now considered operational although the final rack, which is to be removable with removable capacitor units for application to experiments at remote locations, is not complete. There is, however, sufficient energy available for any of the experiments under consideration at the present time.

The remainder of the effort during the quarter was spent on preparing the annual report and a paper for presentation at an ASTME meeting, additional work on Gilbert's thesis and the installation of safety equipment. The thesis work on the design of magnetic forming coils grew to be more extensive than contemplated for the sake of theoretical completeness, but the laboratory work and calculations are now essentially complete and will be submitted during the Fall Quarter in partial fulfillment of the requirements for the degree.

The principles of the design of the safety interlock system were included in the annual report. The system has been installed on the capacitors and is operational. It is designed to insure that shorting bars fall across the capacitor terminals to totally discharge the capacitors. They will prevent recharging of the capacitors as well as acting as a safety override on the normal discharge circuitry.

4. Stress Corrosion Cracking Susceptibility of Explosively and Conventionally Formed 2014 Aluminum Alloy

Principal Investigator: R. N. Orava
Graduate Student: G. S. Whiting

The relative effects of explosive and conventional forming on the susceptibility to stress corrosion cracking of 2014 aluminum alloy are being investigated. The program was divided into two main phases. In the first, the influence of heat treatment subsequent to forming is under study. The second involved the more basic problem of changes in stress corrosion behavior introduced by the forming operation directly without intermediate thermal processing. Since forming of Al alloys is usually effected in the -O condition followed by a hardening treatment, e.g. -T6, the former phase is considered technologically more important. Accordingly, the major effort thus far has been in this direction.

Domes of 12 in. diameter were free formed explosively by standoff, or by rubber pressing at a very low rate, from 1/8 in. thick 2014-O and Alclad 2014-T6 plate. The latter are being reserved for second phase studies which also will include an examination of overaging effects. Bent-beam stress corrosion specimens with similar effective strains were selected from rapidly and slowly formed 2014-0 domes. These, along with unformed 2014-0 control coupons, were heat treated to the -T6 condition according to Martin Company specifications. The samples were then exposed, at 75% of the macroscopic unstrained -T6 yield stress, to a 3.5% NaCl solution at ambient temperature by alternate immersion (10 min. in solution, 50 min. dry in air) for periods of 30 or 15 days. As expected, intergranular stress corrosion cracks developed during the 30 days exposure, but the average crack length and general appearance did not vary significantly from explosively formed to rubber pressed specimens irrespective of effective strain (up to 15%). The unformed heat treated coupons did exhibit somewhat less pronounced cracking but this was readily attributable to a grain size difference. On the other hand, after 15 days exposure, no markings were present in the formed heat treated material which were identifiable as stress corrosion cracks. However, one small crack was found in one of the unformed specimens. One can conclude from these observations that when 2014 aluminum alloy is formed in the -0 condition and then heat treated to the -T6 temper, the stress corrosion behavior is independent of the forming strain and rate. That is, explosive forming is not detrimental to stress corrosion properties when forming is followed by solutionizing, quenching, and aging. This is not too surprising in view of the fact that extensive aging experiments conducted in this laboratory have indicated that the response of 2014-0 to the -T6 treatment is insensitive to prior deformation and deformation rate. It is probable that the above conclusion applies to all of the precipitation hardening Al alloys in the 2000, and also 7000 series.

Future plans include the initiation of the second phase studies discussed above, the conduct of stress corrosion tests of die-formed 2014 in bending and tension, and structure characterization by transmission electron microscopy.

5. Terminal Properties of High Strength Low Alloy Steels

Principal Investigator: H. Otto
Graduate Student: R. Mikesell

Explosive forming of the high-strength low-alloy steels using the flat bottom die previously described, was initiated at the Martin Company. Although one blank was formed successfully, trouble was encountered in maintaining a vacuum. The die is being modified to incorporate 'O' ring seals to overcome this difficulty. Coupons from the "as-received" stock are being heat treated to establish base line data for heat treatment response and comparison purposes. Heat treatment and testing of the formed parts will begin during the next quarter.

6. Recovery and Recrystallization of Explosively Deformed Titanium

Principal Investigator: L. F. Trueb
Graduate Student: P. Khuntia

A study of the annealing characteristics of explosively deformed titanium by means of transmission electron microscopy and electron diffraction has been initiated.

It is known that explosive forming produces a very high density of defects in titanium, due to the high-amplitude pressure pulse and the resulting very rapid plastic deformation. These defects (aggregates of point defects, dislocations, dislocation loops, twins, stacking faults) are bound to affect the annealing kinetics of the material since they provide a considerable driving force for recovery and recrystallization processes. The deformed material will be given a series of isothermal and isochronal heat treatments and the recovery and annealing processes will be studied by means of high-resolution transmission electron microscopy and diffraction. In order to better understand the specific effects of explosive forming, samples that were explosively formed and cold-rolled to similar hardness values will also be investigated.

The first stages of this investigation included a thorough literature search and definition of the experimental variables, the set-up of an inert-gas annealing facility for the deformed, cold-rolled and shocked specimens, the development of a reliable chemical thinning method for titanium and the preparation of 3 mm diameter thin-film specimen disks which can be inserted directly into the microscope specimen holder.

It is anticipated that a series of unalloyed 50-A titanium domes will be explosively formed within the next 3-4 weeks, which should coincide with the delivery of the quartz furnace specially designed for the heat treatments. In the meantime, special emphasis will be put on sample preparation and the microstructure of the starting material.

7. Mechanics of Energy Transfer & High Velocity Metal Deformation

Principal Investigator: John A. Weese
Graduate Students: L. Ching, G. Ney, S. Kulkarni

a. Explosive Forming of Rings:

Repeatability shots have been made which successfully demonstrate the reliability of the process of explosively forming rings. The die has been machined out in preparation for making shots at larger strains. In this phase it is planned to explore the limits of formability by progressively increasing the die size until the rings fail in the process of being formed. The graduate research assistant on this project, Larry Ching, has almost completed the first draft of his M.S. thesis.

b. Analysis of Stresses in Cylindrical Dies:

Results from the program for elastic waves in a cylindrical die have been checked out for the case of suddenly applied constant pressure at the inner surface. The program is being modified to accept a variety of radially symmetric time varying pressures applied at the inner surface as well as input functions for the velocity at the inner surface.

c. "Bongo Drum" Experiments:

These experiments are designed to measure energy transfer from underwater explosions by determining the kinetic energy imparted to a spring supported heavy steel plate (the assembly resembles a bongo drum, hence the name). The instrumentation to measure the velocity of the steel plate has been designed and built; it is now being checked out. The bongo drum was obtained from the Martin Company.

d. Prediction of Explosive Charge Requirements for Explosively Forming Domes:

The approximate mathematical model for predicting explosive charge requirements which was described in the previous report is being improved by the inclusion of blank diameter and blank pull-in. The blank pull-in is a parameter in the expression for total strain energy of deformation. The amount of blank pull-in is the value that makes the strain energy a minimum.

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