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Henry E. Otto

Denver Research Institute

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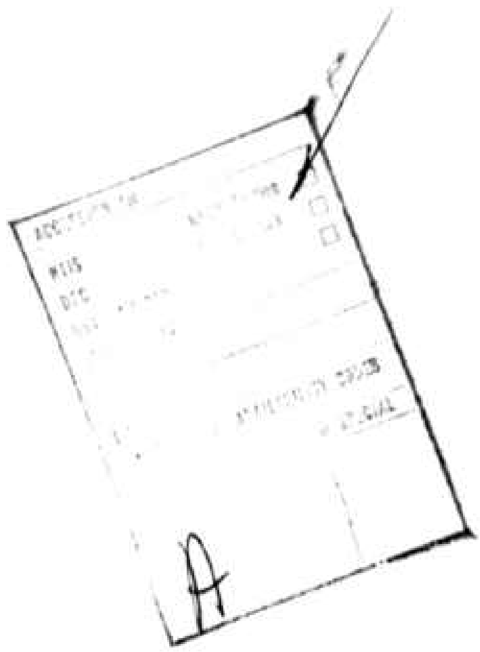

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13. ABSTRACT

This report summarizes results during the period 1 July through 31 December 1972.

a. A Metallurgical Investigation of Explosion Welded Copper-Nickel Composites;

b. Determination of the Optimum Parameters for Explosion Welding A515 Steel;

c. Analysis and Design of an Explosion Cladding Facility;

d. Free Forming Steel Domes with D/t Ratios of 56 and Greater;

e. The Mechanics of Energy Transfer from Underwater Explosions;

f. The Explosive Free-Forming of Arbitrary Shapes from Thin Metal Sheets;

g. Stress Corrosion Cracking Behavior of Explosively Deformed Austenitic Stainless Steel;

h. Explosive Thermomechanical Processing of Beta III Titanium Alloy;

i. Explosive Compaction of Nickel Base Superalloy Powders;

j. Dynamic Strain Measurements on Explosively Autofrettaged Thick Walled Cylinders.

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1. A Metallurgical Investigation of Explosion Welded Copper-Nickel Composites

Faculty Advisors: S. H. Carpenter and H. E. Otto

Graduate Student: M. D. Nagarkar

It has been previously reported that explosion welded copper-nickel composites subjected to post-welded heat treatment exhibit enhanced diffusion as compared to roll-bonded composites. To obtain a suitable explanation of this phenomena, further experimental work has been performed in the current investigation.

Efforts were made to determine the effects of annealing treatments on the strength of the explosion welded composites. Room temperature tensile tests were carried out after each anneal to determine the ultimate tensile strength of the welds. The tensile specimens were prepared as per the 'ram' design developed by Du Pont personnel[1]. This design ensures that the specimen will fail in the bond zone enabling one to determine the bond strength of the weld. Initially, explosion weld specimens made from the as-received roll-bonded composites, Ni-Cu-Ni-Cu were tested. Due to the thinness of the specimen (each layer being only 5 mills thick), and to difficulties in adhering to close machining-tolerances, some of the specimens did not fail in the bond zone, giving erroneous results. To overcome this problem, thicker specimens were used. A 1/4-inch thick copper plate was explosion welded to a 1/4-inch thick nickel plate and tensile specimens were fabricated out of this weldment. The specimens were subjected to heat-treatments at 500°C, 750°C, 900°C, and 975°C, in the same manner as the specimens used in diffusion studies.

The tensile test results were as follows:

Heat-Treatment Annealing Temperature	Ultimate Tensile Stress lbs/in^2
Room Temperature	52,400
500°C	32,360
750°C	30,150
900°C	23,020
975°C	16,200

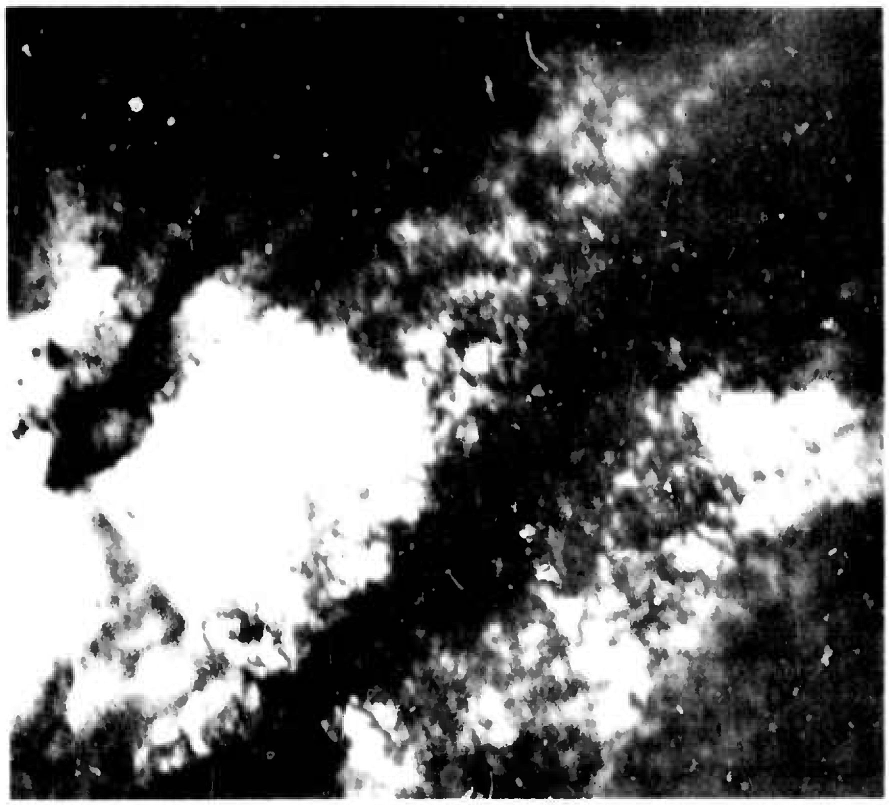
These results show that there is increasing weakening of the bond strength with increasing annealing temperatures. The question of formation of hard and brittle intermetallics during annealing is ruled out since copper and nickel have complete solid solubility in all ranges of concentration. However, with the intense plastic deformation at the weld interface, a large number of vacancies and other defects can be expected. During annealing significant diffusion of the vacancies occur, some of the agglomerating into voids along the interface. Optical micrographs[2] of the welds have shown evidence of Kirkendall type of voids at high temperature anneals. The loss of bond strength appears to be a result of the large concentration of voids. Further investigation by electron microscopy is underway.

As reported earlier, there is a necessity to characterize the defect structure along the weld interface to study the shock loading effects and the effects due to subsequent annealing. Transmission electron microscopy is being used to observe enhanced diffusion behavior of explosion welds. In the case of dissimilar welds, specimen preparation for TEM is very difficult. Standard electrolytic thinning techniques are not quite successful due to the differential etching rate of the two metals. Recourse to the Ion-Bombardment Thinning technique was taken in this investigation. Considerable difficulty has been experienced in making the ion-bombardment machine operational. However, the machine is functioning and some specimens have been successfully thinned. Results of transmission microscopy appear in Figures 1, 2, and 3.

References:

1. T. J. Enright, W. F. Sharp and O. R. Bergmann, Metal Progress, Vol. 98, No. 1, 107 (1970).

2. S. H. Carpenter and M. D. Nagarkar, "The Effects of Explosive Welding on the Kinetics of Metallurgical Reactions," Proc. of the 3rd International Conference of the Center for High Energy Forming, Vail, Colo. 1971.



43000X

Figure 1. Transmission Electron Micrograph of Cu-Ni Explosion Weld in As Welded Condition. (The area is .019 mm from the weld interface in the copper side. Shows very high dislocation density, approx. 10^{11} cm^{-2}. Structure is typical of the shocked zone of the weldment.)

3500X

Figure 2. Transmission Micrograph of Cu-Ni Weld, Annealed 750°C for 10 Hours. (Area on copper side .028 mm from bond zone. Shows evidence of recovery and cell formation.)

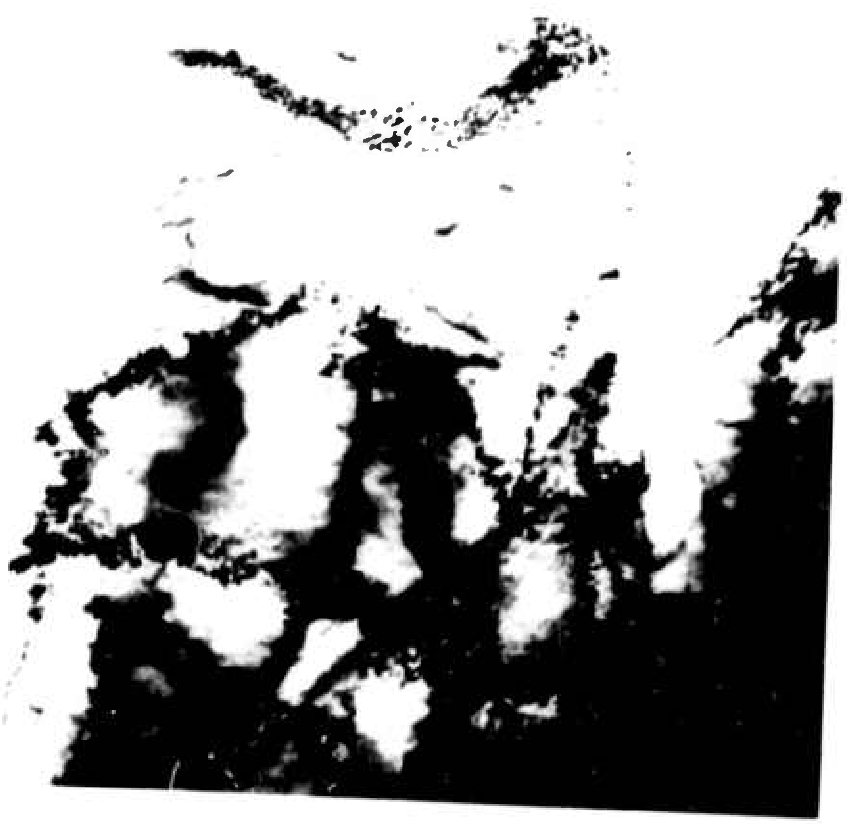


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Figure 3. Transmission Micrograph of Cu-Ni Explosion Weld, Annealed at 975°C for 10 Hours. (Area in copper side .045 mm from weld interface. Shows recovery and recrystallization with dislocations arranged neatly in sub-cells.)

2. Determination of the Optimum Welding Parameters for Explosion Welding A515 Steel

Faculty Advisor: H. Otto

Graduate Student: Steven Stivers

Previous work done with A515 steel has shown an improvement in the wave structure as well as a decrease in the melt layer at the interface with explosive loading increasing from 8.7 gms/sq. in to 15.2 gms/sq. in. at 1/4-inch standoff using DBA-10HV IRECO explosive. Increasing the explosive loading of DBA-10HV at 1/4-inch standoff resulted in further breaking up of the continuous layer of melt. However, at the highest explosive loading of 19.6 gms/sq. in. at the 1/4 standoff, the wave pattern was still poorly defined and the melt layer, while improved, was far less than desired. The yield strengths of the weld interface reflect the decrease in the continuous layer of melt. At the lowest explosive loadings, the ultimate yield strength was 109,600 psi, which is much greater than the parent metal yield strength of 77,300 psi. At the highest loadings, the ultimate yield strength was 95,720 psi characterizing the partial breakup of the melt layer at the weld interface.

In an effort to overcome both the excessive melt layer and the poorly defined wave pattern the standoff distance was increased from 1/4-inch to 3/8-inch. The increased standoff distance produces, among other things, a larger collision angle and thus allows less of the jet to be trapped at the interface. Also, the increased standoff distance allows fhe flyer plate to attain a greater velocity and therefore is more able to plastically deform the interface leading to a larger and more clearly defined wave pattern.

Results at this time partially support this approach as well as suggest alternatives. The wave pattern is improved considerably and the ultimate yield strength had decreased to 83,000 psi with the further break-up of the melt layer. However, at loadings necessary to achieve sufficient plastic deformation at the interface (19.6 gms/sq.in.), cracks are produced at the interface. While not fully understood at this time, it is thought that the cracks are a result of the high explosive loading. Since this cracking appears at the 3/8-inch standoff distance, the high explosive loading coupled with the larger collision angle is perhaps causing excessive shear stress at the interface.

While the wave pattern is more clearly defined at 19.6 gms/sq.in. at the 3/8-inch standoff, there appears to be interference in the formation of the sinusoidal waves at the interface between the base end flyer plates. This phenomenon is thought to be related to the similarity of the detonation velocity of DBA-10HV IRECO (~4000m/sec) and the sonic velocity of A515 steel (~5500m/sec). To determine significance of the relative velocities on the wave formation, tests are being conducted using Red Cross 40% dynamite which has a detonation velocity of less than 3400m/sec and at the explosive loadings to be used, the detonation velocity will be approximately 3200m/sec. In the initial tests using 40% dynamite, the primary interest will be in obtaining the optimum conditions to produce improved wave formation. Once well defined formation is obtained, explosive loadings can then be adjusted to minimize melt pockets at the interface.

3. Analysis and Design of an Explosion Cladding Facility

Faculty Advisor: A. Ezra

Graduate Student: A. Eriksen

An explosive cladding facility is being designed as a shell structure to cover the charge and the immediate work area in order to reduce blast pressure to personnel and equipment.

A hemispherical shell of mild steel was found to be the most feasible structure to resist internal blast loading. The diameter of the shell was determined to be 20 feet and the thickness 1 inch. The stress level in the shell under repeated loads will be elastic to meet the purpose of design. The use of mild steel for the shell will insure sufficient ductility to avoid failure if localized stresses become excessive. To decrease the blast pressure it was decided that a certain degree of vacuum maintained during the explosion would be advantageous.

The behavior of this structure exposed to a blast wave may be considered under two main headings. The first is called the "loading," i.e., the magnitude and duration of the blast pressure. The other is the response of the structure due to the blast loading. There are numerous factors associated with the characteristics of a structure which influence the response to the blast wave accompanying an explosion. The most important include the modulus of elasticity, stiffness, mass of the structure and structural shape.

A theoretical analysis based on the membrane theory was developed and appears to give a good approximation of the stresses in the shell as long as the ratio of the shell radius to the shell thickness is large. Where bending stresses do occur, they will be localized in nature, occurring primarily near the base.

The calculations of hoop stresses based on some simplifying assumptions has to be verified by testing. The most efficient way to do this is to use a small scale model. The model to be used is 1/20 scale, having a diameter of 12 inches and a thickness of 0.05 inches.

A model hemispherical dome was formed using explosive forming. It is assumed that this method also is applicable for the prototype. The dynamic strain measurements on the scale model will be carried out in the near future using strain gages attached to the surface of the dome.

4. Free Forming Steel Domes with D/t Ratios of 56 and Greater

Faculty Advisor: E. Wittrock

Graduate Student: J. Freeman

Previous work has shown that steel blanks can be explosively free formed from 14-inch diameter 1/2-inch thick steel blanks, D/t = 28, (A-36, A-285, and A-515 steel) into a shape that is very close to that of a hemispherical cap. These domes can be made (using one forming shot and one sizing shot) relatively free of edge wrinkles and with a smooth surface finish. A test program was conducted to determine if there is an upper limit to the D/t ratio which can be free formed using essentially the same method used on the 1/2-inch thick blanks.

The study was begun using 14-inch diameter - 1/4-inch thick A-36 steel blanks for a D/t ratio of 56. The weight of charge which would draw the domes to the optimum initial draw depth was determined experimentally to be 110 grams of SWP-5 in a pancake measuring 6.0-inch diameter by 0.25-inch thick. The charge was initiated with a primadet positioned to detonate at the center. Domes formed in this manner were close to their optimum depth and exhibited deep edge wrinkles where the material gathered and buckled.

After the domes were formed, they were sized. The sizing method known as the "clamshell" method has been the most successful. This technique places both domes in a clamshell arrangement with the charge suspended in a plastic, water-filled liner. In the usual case, the charge is spherical and, when optimized, produces domes which are nearly free of edge wrinkles, have a smooth surface, and are very close to the shape of a hemispherical cap. In addition, these domes have a thinout profile such that the center is thinned out by about 35 percent of the original thickness whereas the edges are somewhat thicker than the initial thickness. In the present case, using the 1/4-inch thick domes (D/t = 56) the optimum forming charge has not yet been determined since the experimental evidence indicates that a spherical charge of approximately the correct weight either tends to blow out the domes or it does not straighten the wrinkles as expected. Thus, a pancake shaped sizing charge is being tested to determine if this shape can be used to size the 1/4-inch thick domes. To date, charges up to 170 grams of SWP-6 have been fired in pancakes 5.3 inches diameter by 0.75 inches thick without making significant changes in the shape. Apparently, this charge geometry is relatively inefficient as presently used and more work will be required to determine the optimum geometry and weight of charge required.

In summary, it has been found that the 14-inch diameter by 1/4-inch thick A-36 blanks can be formed with much the same results as for the 1/2-inch thick blanks. However, sizing is a more difficult problem since sizing charges tend to be either too strong, in which case the dome is cracked, or too light, in which case no work is done on the dome. New charge geometries for the sizing shot will be tried to determine if some method can be found to size the 1/4-inch thick domes.

5. <u>The Mechanics of Energy Transfer from Underwater Explosions</u>

Faculty Advisor: William Howell

Graduate Student: Valeran D'Souza

The solution to the motion of a bubble in incompressible fluid can only be used when the pressure inside the bubble is low enough so that compressibility effects in the fluid can be neglected. For an explosion in water, this condition would be reached when the gas pressure is of the order of 15,000 psi. The initial motion of the bubble has thus to be calculated, along with the shock wave pressures from the Kirkwood-Bethe theory, till the bubble pressure is about 15,000 psi. The radius, rate of growth and pressure of the gas bubble, when the gas pressure is about 15,000 psi, obtained from Kirkwood-Bethe theory are used as the initial conditions for the incompressible solution to determine the subsequent bubble motion. Computer programs to give the initial conditions and then to obtain the bubble motion have been written.

The computer program to compute the motion of the plate, which is being solved using Newton's Method, is being corrected to include the matching conditions at the junction of flange and dome. For the frictionless die assumed, these conditions at the junction are:

1) σ_Y in flange = σ_Y in dome, and

2) u_1 the radial displacement is continuous

6. The Explosive Free-Forming of Arbitrary Shapes from Thin Metal Sheets

Faculty Advisor: M. A. Kaplan

Graduate Student: S. Y. Aku

The basic aim of the study is to learn enough about the role of the important prrameters in the explosive forming process to enable arbitrary shapes to be formed without the need for extensive trial and error testing. In the first phase of the study, the effects of charge shape, weight, and location are being studied on the deformation of an "infinite" sheet. The infinite sheet is being used so that there will be no influences of the boundaries on the deformation of the workpiece.

In the experimental program, small charges (1/2 gm of C_1 or C_2 Detasheet in contact with a #6 cap) were used to deform AISI 1020 steel sheets. Because of the relatively small area of deformation, 6-inch diameter plates were found to be a fair approximation to an infinite plate. To date, only point charges at different standoffs have been used. A simple theoretical model is being developed for predicting the deformed shape as a function of the geometry and charge. The model will be checked initially against the results of the point charge experiments. Additional tests will then be made in which two or more charges are detonated either simultaneously or sequentially.

A continuation of this procedure should lead to the ability to form arbitrary shape parts from infinite sheets. The final phase of the study will be concerned with finite blanks and the role of boundary conditions.

7. Stress Corrosion Cracking Behavior of Explosively Deformed Austenitic Stainless Steel

Faculty Advisors: H. E. Otto and R. N. Orava

Graduate Student: E. L. Chang

Previous work has shown that explosive forming relative to conventional forming is detrimental to the stress corrosion cracking (SCC) resistance of the 300 series austenitic stainless steels. The only exception is some recent unpublished Dutch work on AISI 304L. Cold pressed and explosively-formed products exhibited the same decrease in failure time of about 30% relative to undeformed control material. Heretofore, the SCC problem has represented one of the major blockages in the application of high energy rate techniques to the fabrication of austenitic stainless steels.

The objectives of the present investigation are to establish the influence of explosive forming and shock loading on the propagation of stress corrosion cracks in austenitic stainless steel, to evaluate the SCC mechanisms, and further, to develop preforming and/or postforming thermal treatments which will serve to eliminate any detrimental effects which might arise.

The materials to be studied are AISI 304 and 310 stainless steels. The former is much more susceptible to the formation of strain-induced martensite than the latter. This should permit a distinction between substructure and second-phase contributions. Comparisons will be made among explosively free-formed, cold-rolled, and undeformed material. The main effort will be devoted to explosive forming but the effects of shock loading will also be assessed in view of its importance in explosion bonding applications.

To date, all studies in this area have involved the measurement of time-to-failure of smooth specimens. Current practice dictates that one approach environmental effects from the crack propagation viewpoint. Accordingly, the rate of crack progagation and time-to-failure of cantilever beam pre-cracked specimens in 3.5% NaCl at room temperature will be measured and the threshold critical stress intensity factors for SCC, K_{ISCC} will be determined.

Explosive forming has been completed and the design and fabrication of a SCC test facility is underway.

It is postulated that deformation will reduce the resistance to crack propagation. However, by controlling the substructure through thermal recovery treatments, it should be possible, based on previous experience in mechanical-thermal treatment, to raise the SCC resistance above that of undeformed material.

8. Explosive Thermomechanical Processing of Beta III Titanium Alloy

Faculty Advisor: R. N. Orava

Graduate Student: M. B. de Carvalho

A number of recent studies have revealed that Beta III titanium, (11.5Mo-6Z4-4.5Sn), an isomorphous-beta alloy with good cold formability, is responsive to cold thermomechanical treatment or processing (TMP) utilizing conventional working techniques such as rolling. Normally, strain is applied in the solution treated condition, followed by aging to precipitate α phase.

The purpose of the current investigation is primarily two-fold: (1) to ensure that explosive forming, if desirable or necessary, is not detrimental to TMP strengthening; and (2) to examine the potential of dynamic TMP for the improvement of mechanical properties, including both explosive forming and shock deformation. It has been demonstrated that shock TMP can produce beneficial effects in alloys based on iron, aluminum, and nickel, over and above those attainable by conventional TMP. Arguments in favor of shock deformation are based on: (1) small dimensional changes; (2) strain homogeneity and isotropy, thereby precluding nonuniformity and directionality of strengthening; and (3) refinement of dispersal of slip, leading to higher strengths, and less internal concentration of stress, a factor which can be important to ductility, toughness, and cyclic and environmental behavior.

It was reported previously that Beta III is formable explosively and that the transient ductility is enhanced at the high rates of loading characteristic of such forming operations. However, one of the problems encountered was the apparent deterioration of residual room-temperature tensile properties after forming to high strains in the solution treated condition (1350°F WQ) and aging at 900°F for 8 hours. Both strengths and ductilities fell below the levels for thermally processed Beta III. To examine whether these property reductions were the consequence of deformation or aging, solution treated and as-deformed specimens were tested, with the results given in Table 1. These data indicate that part of the softening may indeed have been due to the straining process but an appreciable contribution appears to derive also from aging response differences. This is better illustrated in the case of shock-loaded material where the as-shocked strengths are well below as-rolled values and yet, after aging, shock TMP is similar to that observed by Kalish and Rack[1] after conventional TMP by cold rolling to 50% reduction in thickness. However, shock TMP ductilities are higher. The factors which actually are responsible for the apparent explosive TMP softening, and the mechanism of shock TMP strengthening, have not been resolved and are presently under study. Accelerated aging may well account for the former phenomenon, and alternative aging treatments will be examined.

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[1] D. Kalish and H. J. Rack, Met. Trans. 3, 188F, 1972.

Information generated in this laboratory on the shock TMP of other alloys indicate that the best properties are likely to be achieved by shock deforming in the partially aged condition. Whether this applies to Beta III, and whether it applies to TMP by explosive forming, will be investigated.

It has been found that the utilization of hardness values as measures of strain hardening and strength of Beta III titanium should be treated with some reserve. There seems to be little correlation of Rockwell C hardness with yield or ultimate strength.

Table 1. Room Temperature Tensile Properties of Unaged Beta III Titanium Deformed in the Solution Treated (1350°F, WQ) Condition.

Material Condition	Effective Strain (in/in)	0.2% YS (ksi)	UTS (ksi)	Total Elong. (%)	R. A. (%)
Undeformed	0	122.4	135.1	16.8	52.7
Cold Rolled	0.220	146.2	152.7	8.2	39.7
Shock Loaded (317 kbar)	0.220	132.8	143.3	6.4	39.0
Explosively Formed	0.028	123.6	137.8	12.0	53.8
	0.071	117.7	142.3	12.3	54.5
	0.105	111.1	139.1	13.0	53.4
	0.167	118.6	141.6	10.8	55.6

Table 2. Room Temperature Tensile Properties of Solution Treated, Deformed, and Aged (900°F, 8 hr.) Beta III Titanium.

Deformation Method	Effective Strain (in/in)	0.22 YS (ksi)	UTS (ksi)	Total Elong. (%)	R.A. (%)
Undeformed	0	201.8	209.7	4.4	13.2
Cold Rolled	0.220	200.4	214.0	3.5	6.3
Shock Loaded (317 kbar)	0.220	221.8	222.2	1.7	1.7
Undeformed	0	194.1	207.4	8.9	12.4
Cold Rolled	0.220	187.0	248.3	5.9	13.2
Explosively Formed	0.220	184.7	196.1	3.6	6.7

9. Explosive Compaction of Nickel Base Superalloy Powders

Faculty Advisor: H. Otto

Graduate Student: T. McClelland

The precipitation characteristics of nickel base superalloys are being studied. Explosively compacted Udimet 700 powders have shown that compacting at ambient temperatures results in the formation of spall cracks and sound billets are hard to obtain. Therefore, hot explosive compaction techniques are being studied. The hot compaction procedure is currently under construction. Essentially, the superalloy powder is canned in an evacuated steel container. This container is heated to a predetermined temperature. The hot container is transferred from the furnace to a guide tube in the blast area. A pin holds the container in the tube which extends about 3 feet above the powder container to fall on a micro-switch at the bottom, the closing of which detonates the system.

At the present time the heat loss during the transfer operation is being studied. The heat at the end of the transfer plus the adiabatic heat generated during detonation will be the compaction temperature. Optimum compacting temperatures will be determined.

Another alteration is to use a dual explosive charge to give a more uniform compaction rather than letting the detonation front sweep down the tube lengthwise. Essentially an explosive lens approach will be used with dynamite as the internal explosive and Detasheet as the external charge. This approach should eliminate radial cracking as experience in the previous approach.

10. Dynamic Strain Measurements on Explosively Autofrettaged Thick Walled Cylinders

Faculty Advisor: E. Wittrock

Graduate Student: B. Patel

A Program was conducted to develop a technique for measuring the dynamic strain on the outside wall of explosively autofrettaged thick walled tubes using strain gages. The strain gages and the method used to attach them to the tube were identical to those used on the boreout specimens reported on previously.

The technique used to autofrettage the tubes was the radial piston method wherein a stainless steel tube or radial piston filled with explosive is inserted along the axis of the thick walled tube. Water between the tube and the piston is used as the energy transfer medium. This method was chosen since data was available from specimens previously fired in this manner.

Initially, considerable difficulty was encountered in that the soldered joints (integral with the strain gages) and the lead wires were loosened by the shock wave reflecting from the outside wall of the tube resulting in loss of signal from the gages. This problem was solved by reducing the amount of solder used to fasten the lead wires and by using tape under the lead wires in such a way that the wires were not subject to direct motion of the tube wall. Also, it was found helpful to tape the point where the lead wires were soldered to the strain gage as tightly as possible.

Of the eight shots fired, two were considered to be successful. In the first of these, two strain gages were mounted on the tube (one gage at the center and one at the end of the tube opposite the ignition end). A measure of the accuracy of the strain as measured by the strain gages is to compare the average value read by the gages with the average residual strain measured at the same location by a micrometer. Results of this test are as follows:

Residual Strain Readings on Tube 17-1

Gage Location	Average Residual Strain (%)	
	Strain Gage	Micrometer
Center	0.34	0.3
Bottom	0.66	0.5

The agreement for the center gage is good. The discrepancy for the bottom gage cannot be explained at this time, especially since the strain gage reading is high, indicating that the adhesive (epoxy) between the tube and the strain gage remained intact. Also, visual inspection of these gages revealed no other source of error. The second test (Tube 18-1) was conducted with one strain gage mounted on the end of the tube opposite the ignition end as above. In this test, static readings were taken from the strain gage before and after the test to compare with the micrometer readings. (Dynamic readings were not obtained on this tube due to a faulty trigger.) Results of this test are as follows:

Residual Strain Readings on Tube 18-1

% Strain Strain Gage	% Strain Micrometer
0.4	0.45

The agreement between these two readings is good and shows that the strain gage was still reading correctly after the test. Continuous monitoring of this strain gage (for over one month after the test) showed no significant change in the reading.

Thus, a reliable method has been developed for taking dynamic strain measurements during the time that the thick walled tube is being explosively autofrettaged. Further work, resulting in refined strain gage techniques and in a complete and comprehensive data sample, would permit correlation with the mathematical model previously developed for this process.

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