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SOLID-STATE PRESSURE BONDING OF TITANIUM ALLOY 6Al-6V-2Sn

TECHNICAL REPORT

by

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DECEMBER 1964

MATERIALS ENGINEERING DIVISION

U. S. ARMY MATERIALS RESEARCH AGENCY

WATERTOWN, MASSACHUSETTS 02172

Rockets
Welded joints -
pressure welding

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ABSTRACT

High-strength titanium assemblies for Army weapon systems have been fabricated using solid-state bonding and controlled plastic deformation techniques to achieve union between individual components.

For this application coalescence is induced by heating the metal about the abutting interface area between units to a temperature slightly above that of the beta transus of the alloy. At this temperature, diffusion and grain growth occur across the interfaces of abutting components producing the desired solid-state bond. During post-weld cooling of the bonded area through the two-phase alpha-beta region of the alloy, plastic deformation is initiated and completed at the weld area. This action refines any grains that recrystallized during the heating cycle and disperses any oxide inclusions which may have been trapped within the bond area. The final microstructure developed at the bond is typical of a wrought material and exhibits a definite grain-flow pattern throughout.

It is indicated that alpha-beta titanium can be pressure-bonded to a strength and toughness approximately equal to the base material.

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INTRODUCTION

Since 1953, the U. S. Army Materials Research Agency (AMRA) has been developing titanium alloys and fabrication processes for critically designed weapon systems. One alloy (titanium 6Al-6V-2Sn-Fe-Cu)[1-3] was selected for weldability studies because of its excellent response to forging and thermal processing. A limited fusion welding study of this alloy has been conducted and reported.[4] Normally such titanium alloys joined by fusion welding develop cast weld-metal structures, high-temperature transformation products, and heat-affected zone patterns that cannot be substantially altered by post-weld heat treatments. These metallurgical characteristics impair the mechanical properties of the weldment.

To improve the metallurgical and mechanical properties of titanium alpha-beta alloy weldments, studies were initiated to determine the feasibility of joining such alloys by the solid-state pressure-bonding process. Since weldments fabricated by this technique do not require a liquid phase for uniting the components, the process eliminates the presence of a cast microstructure in the final weldment. Plastic deformation of the joint area refines any coarse grains which may have been formed during the initial bonding phase of processing.

In order to carry out the feasibility studies, the effects of bonding time, temperature, and subsequent plastic deformation on the metallurgical and mechanical properties of the final solid-state joint had to be determined.

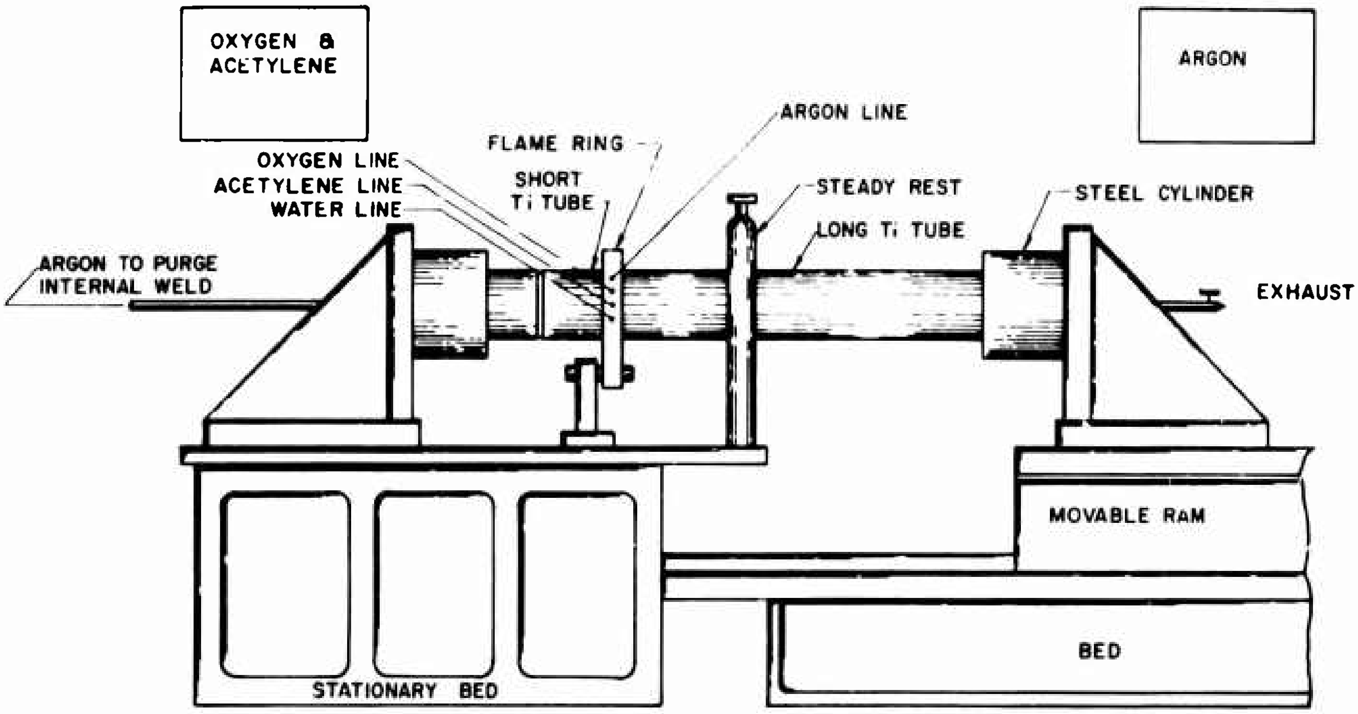
To facilitate the work required by this solid-state bonding study, a hydraulic gymnasticator used for gun-recoil testing was adapted and equipped with an oxyacetylene heating ring, steady rests, dial indicators, and argon valves which provided internal and external gas shielding of the component being welded (Figures 1a and 1b).

PROCEDURE

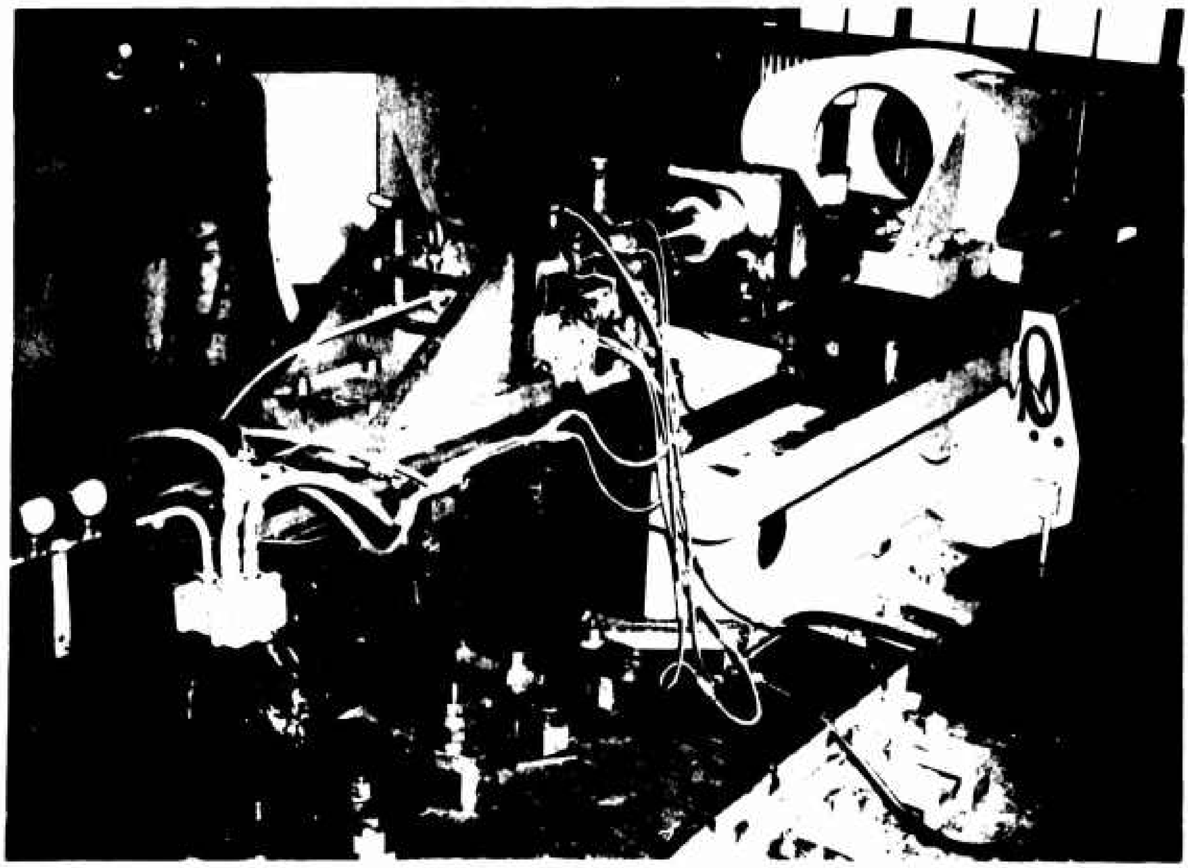
Titanium 6Al-6V-2Sn alloy tubes (3 feet long, 4-1/2 inch diameter) having wall thicknesses of approximately 5/16 inch were prepared for the pressure-welding study. A 32-1/2-degree bevel was machined about the outside diameter at one end of each tube (Figure 2). The tubes were then degreased and wiped clean with acetone prior to pressure-welding, and positioned in the horizontal hydraulic press (with beveled ends butted) to within 0.005-inch diametrical mismatch. The interior of the tubes received a continuous argon purge to prevent contamination and/or oxidation of the surfaces being joined.

TUBE ALIGNMENT

The ends of each tube were placed in pre-fitted closed-end cylindrical holding fixtures which in turn were attached to respective stationary and movable platens. The pre-fit cylinders insured alignment and provided an even force distribution along the longitudinal axis of the weld tubes. A



a.



b.

Figure 1a and b. PRESSURE WELDING MACHINE
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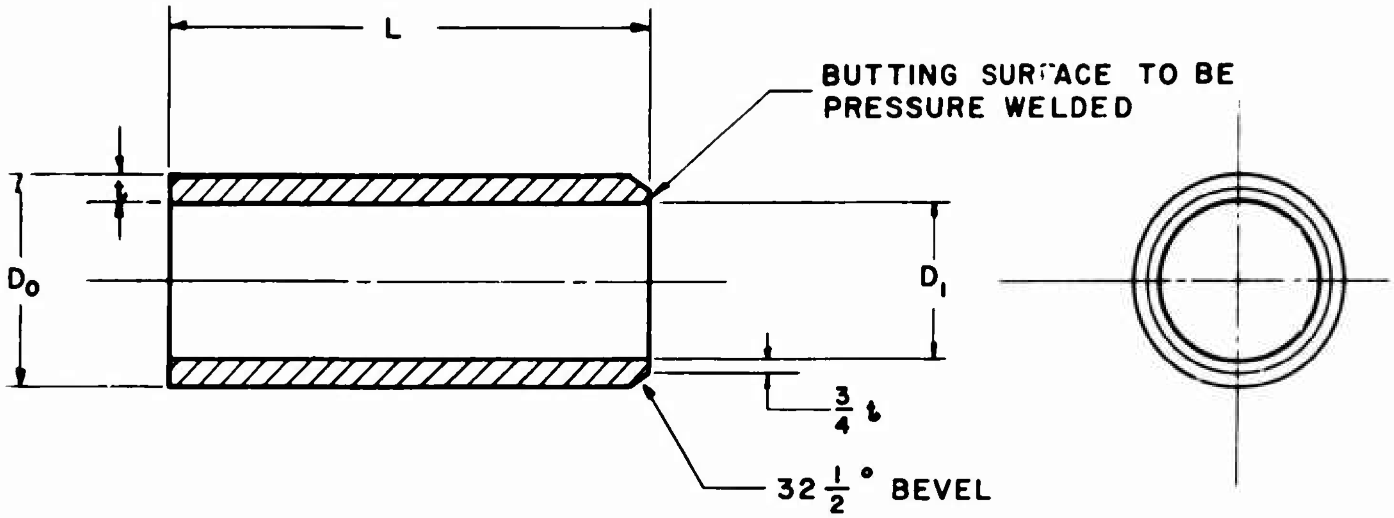


Figure 2. CYLINDER SECTION PRIOR TO PRESSURE WELDING

steady-rest was located as close to the flame ring as possible to add stability and insure tube alignment. Two dial indicators, measuring displacement in 0.001-inch increments, were placed at right angles to the longitudinal axis on the top and side of both tubes. The indicators were moved horizontally and parallel to the tube center line in the area being welded to determine concentricity.

Heating

Following alignment, a water-cooled oxyacetylene split-flame ring was located in position at the abutting surfaces. The ring was attached to a motor and cam assembly which caused oscillatory motion. This oscillation allowed a flame overlap on the tube surface, thus eliminating hot spots and uneven heat distribution. In addition, the ring was equipped with argon valves to provide a protective atmosphere about the outside surface of the weld when the flame was extinguished.

Pressure Weld Cycle

After the aligned cylinders had been purged with inert gas, a hydraulic ram force of from 10 to 20 tons was applied at the tube ends. (The load applied depended upon the area of the abutting surfaces.) This force insured an intimate contact at butting surfaces of the components, thus protecting the surface area of the weld joint from the effects of high-temperature oxidation and contamination.

Under a stress of 10,000 psi a 20-second heating cycle was required to elevate the temperature at the abutting interfaces of the titanium components to that of the plastic region of the alloy. Plastic upset of this region was continued until a 5/32-inch reduction in the over-all length of the weldment was observed. Following the 5/32-inch upset, the heat source was removed, and plastic deformation of the solid-state bond was continued until a total decrease of 5/16-inch was produced in the over-all length of the weldment. The weldment was then cooled to approximately 500 F in an argon atmosphere before the applied load was released and the weldment removed.

RESULTS AND DISCUSSION

Mechanical Testing

To evaluate the joint efficiencies developed by pressure welding, a comparison of the mechanical properties of the bonded area and the unwelded base metal was made. After pressure welding, the titanium 6Al-6V-2Sn alloy cylinder was postheated (1620 F for 1-1/2 hours and water quenched, followed by 1200 F for 4 hours and air cooled). Tensile specimens of 0.252-inch diameter and Charpy V-notch specimens were machined from the pressure-welded area in a direction parallel to the longitudinal axis of the tube (Figure 3). Results are shown in Table I.

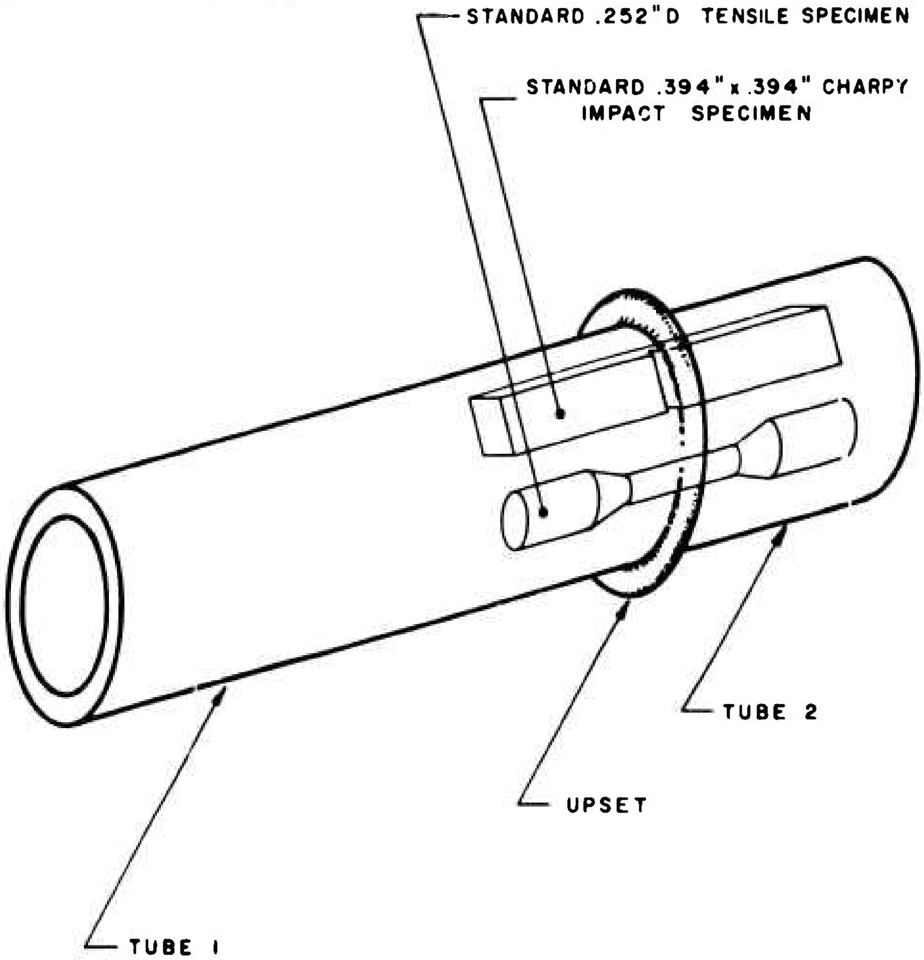


Figure 3. TYPICAL SPECIMEN LOCATION ON PRESSURE-WELDED TUBE

At the 160,000 psi yield strength level, initial tensile testing at room temperature gave 0.1 percent yield and tensile joint efficiencies from the pressure weld equal to 95 percent and 100 percent of those of the unwelded base metal. Ductility as measured by elongation and reduction of area values over a one-inch gage length were approximately 46 percent and 43 percent of those of the heat-treated base metal.* Charpy V-notch impact testing at -40 F and at room temperature showed the pressure-weld area to be approximately 95 percent that of the unwelded base-metal toughness.

*Most deformation occurred at the weld area over approximately a one-quarter-inch length; therefore actual elongation is much greater than that measured over a standard one-inch-gage length.

Table I. MECHANICAL PROPERTIES OF TITANIUM 6Al-6V-2Sn BASE METAL AND PRESSURE-WELDED TEST SPECIMENS HEAT-TREATED AFTER JOINING OPERATION

Identification Number	Yield Strength (ksi)		Tensile Strength (ksi)	Elon. (%)	R.A. (%)	Charpy V-Notch Impact Energy (ft-lb)	
	0.1%	0.2%				R.T.	-40 F
18 HT B1	159.0	159.0	166.2	10.0	20.5	4.4	4.4
B2	160.5	165.5	170.4	14.0	26.8	5.0	4.4
18 A1	152.0	157.0	169.8	6.0	11.8	4.2	4.2
18 A2	154.0	159.0	170.8	5.0	8.8	4.7	4.2

B Specimens - Heat-Treated Base Metal
A Specimens - Heat-Treated After Pressure Welding
Heat Treatment: 1620 F - 1-1/2 hr - Water Quench
1200 F - 4 hr - Air Cooled

Table II presents data generated during testing of additional pressure-welded 6Al-6V-2Sn alloy units heat-treated to the various strength levels shown. Pressure welds heat-treated to yield strength levels of 176,000 psi to 180,000 psi at 0.1 percent offset developed elongation values ranging from 43 percent to 60 percent those of the heat-treated base metal. Welds at the 182,000 psi to 185,000 psi yield strength level developed elongation values equal to 20 percent and 37 percent those developed in the base metal. Reduction of area values show the same decreasing trend with increasing yield strength. Below the 180,000 psi yield strength level, reduction of area values ranged from 35 percent to 55 percent those of the heat-treated base metal. Above the 180,000 psi yield strength level, reduction of area values were approximately 20 percent to 33 percent those of the heat-treated base metal.

Three heat-treated pressure-welded cylinders were machined and subjected to a simple axial compression load test. The test results are as follows:

Tube No.	Length (in.)	O.D. (in.)	Wall Thickness (in.)	Ram Force (lb)	Stress at Failure (ksi)
A	6.0	4.50	0.085	202,500	170
B	5.0	4.66	0.087	194,000	155
C	6.0	4.7	0.086	201,600	173

Mechanical properties of base material were: 160 to 170 ksi yield strength at 0.1%; 180 to 190 ksi tensile strength; 10 to 15% reduction of area; 4 to 6% elongation; 4 to 6 ft-lb Charpy V-notch impact energy at -40 F.

Table II. MECHANICAL PROPERTIES OF TITANIUM 6Al-6V-2Sn BASE METAL AND PRESSURE-WELDED MATERIAL IN THE ANNEALED AND HEAT-TREATED CONDITIONS

Material	0.1% Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)	R.A. (%)	Charpy V-Notch Impact Energy* (ft-lb)
BASE - Annealed	152	162	12.5	28.9	2.4
	153	161	20.3	39.8	2.7
	151	161	18.8	38.8	2.6
	152	164	15.8	36.8	2.4
	151	162	17.2	39.8	
	147	158	17.2	40.8†	
Heat Treated	185	190	7.8	19.9	1.0
	183	191	9.4	18.9	1.0
	185	193	9.4	18.9	1.3
	182	190	10.9	22.4	1.4
	183	191	9.4	18.9	
	183	191	7.8	16.9	
WELD - Annealed	151	162	4.7	8.0	2.0
	151	159	3.1	3.5	1.0
	151	161	6.3	8.0	2.0
	152	160	6.3	8.0	2.0
	150	162	7.8	9.5	
	149	156	3.1	3.5	
Heat Treated	182	184	1.5	2.5	1.3
	185	191	3.1	3.5	1.0
	183	189	3.1	5.0	1.0
	176	183	4.7	9.5	1.1
	180	187	4.7	10.5	
	179	187	4.7	6.0	

*Series B Specimens Tested -40 F
†Broke in Outer Third

Annealed	1300 F for 4 hours; air cooled
Heat Treated	1100 F for 4 hours; air cooled
	1600 F for 1 hour; water quenched

All welds in these three cylinders were considered metallurgically sound as checked by metallographic techniques. Considerable grain flow and refinement was noted, indicating that the major portion of the upsetting during welding was performed below the beta transus temperature. Figure 4 shows the microstructure obtained throughout the pressure-welded area and base metal of the specimen.

The cylinder failures exhibited a diamond-shaped buckle pattern.*

*The purpose of subjecting thin-walled welded cylinders to an axial compressive load was to study the mode of failure of a cylinder which contained a circumferential weld through its center portion. If the weld area had exhibited inferior properties to that of the base metal, a failure would have occurred in the weld zone rather than a uniform buckling throughout the entire length of the cylinder.

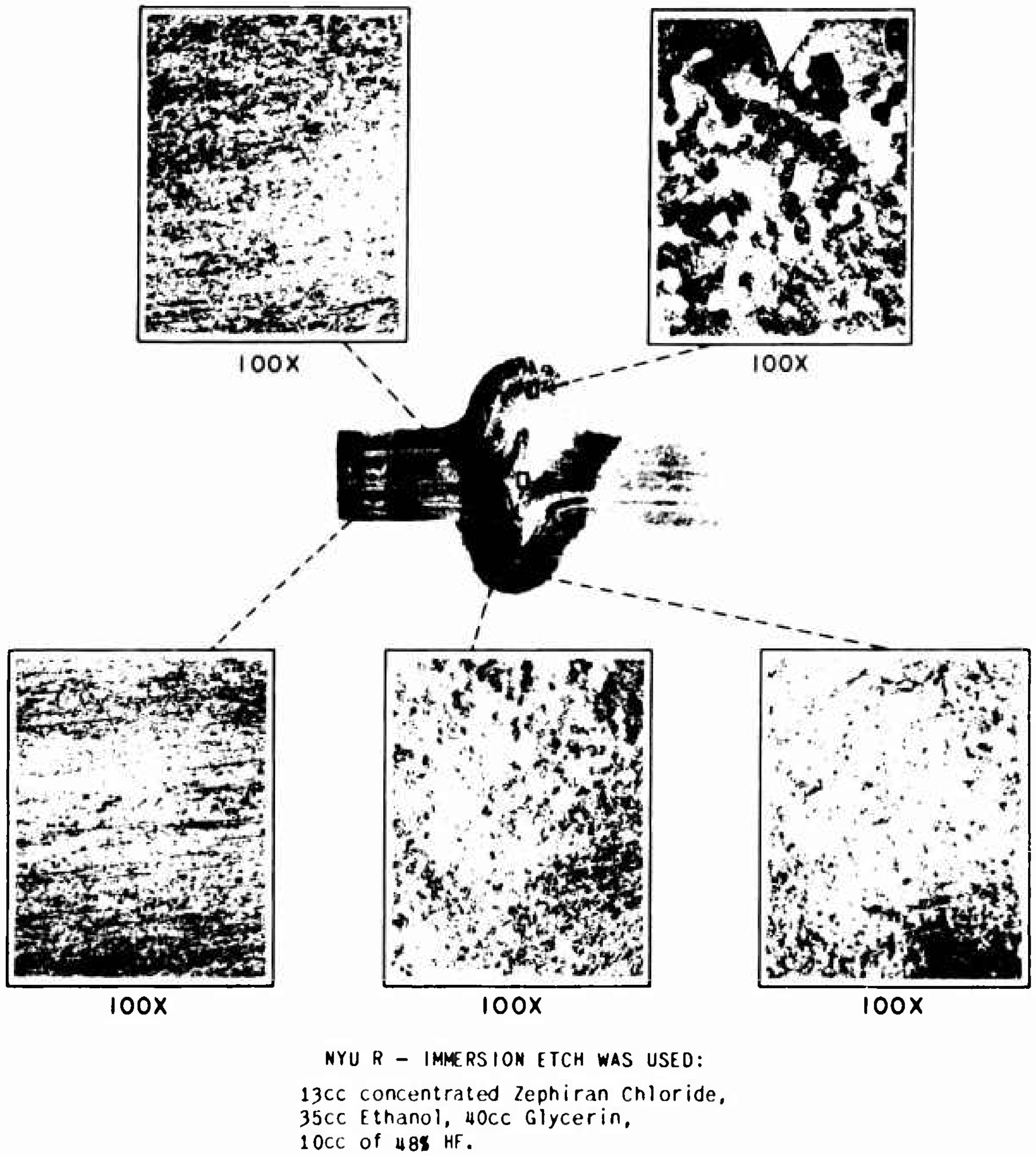
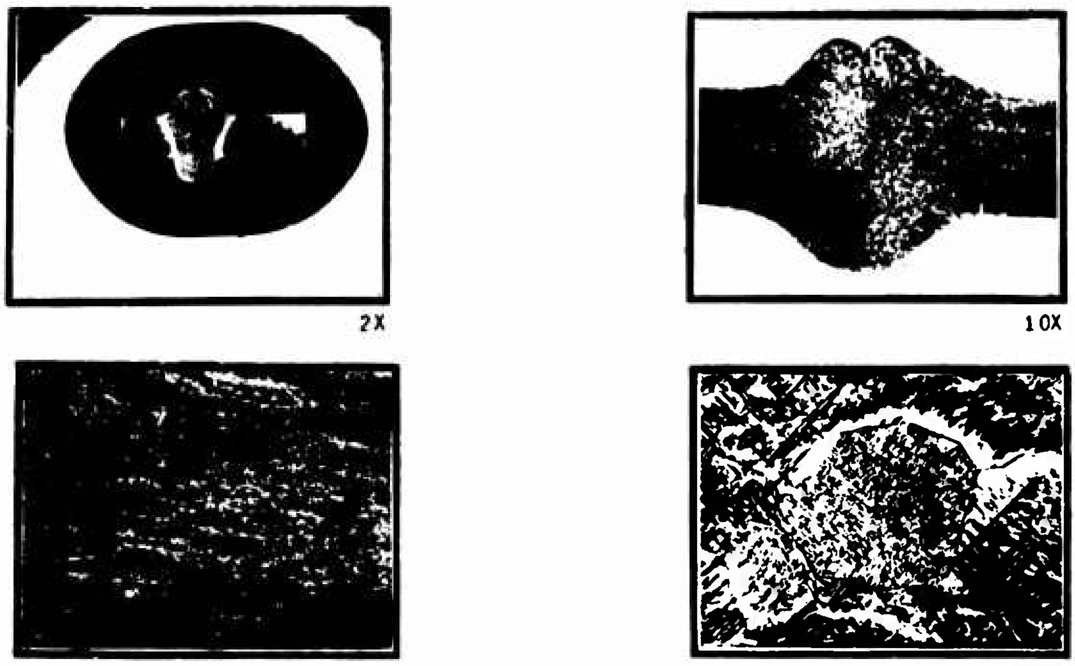


Figure 4. PRESSURE WELD SHOWING VARIOUS STRUCTURES (6Al-6V-2Sn Ti ALLOY)

Metallographic Examination

Post-weld microstructures in the weld-joint area of a pressure-welded Ti-6Al-6V-2Sn titanium component are presented in Figure 5. The acicular matrix of the pressure-bonded metal presented in the lower right-hand section occurs in alpha-beta type alloys that are heated in excess of the beta-transus temperature and that have insufficient plastic deformation of the material below the beta-transus temperature.



UPSET BELOW BETA TRANSUS   UPSET ABOVE BETA TRANSUS

Figure 5. MICROSTRUCTURE OF PRESSURE-WELDED TITANIUM ALLOY

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Figure 5 also presents the post-weld microstructure of the identical pressure-welded base material. However, the acicular matrix has been transformed and refined by controlling the degree of plastic deformation occurring below the beta transus temperature. In this weld-joint area the material was plastically deformed at temperatures below the beta transus, and the refined microstructure yielded good mechanical properties.

Effect of Joint Designs

Three joint designs were evaluated for pressure-weld studies as shown in Figure 6. The self-aligning joint design required more preparation prior to welding and it is believed that, on a production basis, it would be susceptible to retention of surface contamination and thus prove detrimental to high weld efficiency.

The following table compares the three types of joints with base metal properties on a percent basis. For example, the yield strength of the pressure-welded area using a flat joint design was 15 percent lower than the base metal yield strength. Base metal properties, taken as 100%, were: 160 to 170 ksi yield strength at 0.1%; 180 to 190 ksi tensile strength; and 4 to 6% elongation.

Type of Joint Design	Percent of Base Metal		
	Y.S.	T.S.	Ductility Based on Percent Elongation
Bevel	85.5	87.1	83.3
Flat	85.0	86.6	79.2
Self-Aligning	77	83.5	79.2

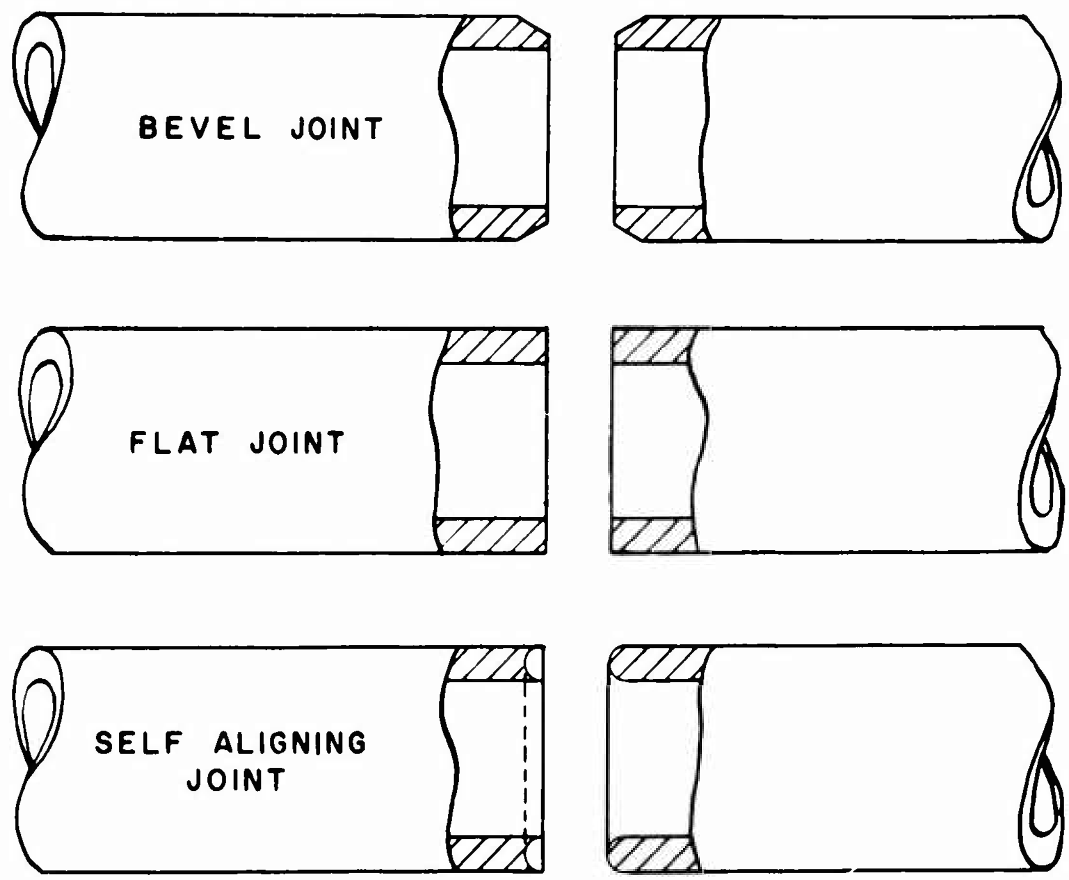

Figure 6. THREE JOINT DESIGNS EVALUATED FOR PRESSURE-WELD STUDIES

No significant difference existed in weld efficiency for the various butt joints investigated.

Hardness Survey

Rockwell C hardness readings were obtained at 1/16-inch intervals across the surface of the weld area. Readings averaged 36 to 38 Rockwell C at the center of the weld. Hardness values of the base metal averaged 43 to 44 Rockwell C. (See Figure 7 for hardness locations.)

CONCLUSIONS

1. Pressure bonding of titanium alloys affords an excellent method of joining high-strength structural components since it eliminates the undesirable fusion (as-cast) and heat-affected zones normally associated with fusion-welding operations. The pressure-bonded weldment consists entirely of a wrought structure which is not as susceptible to contamination or porosity as normal fusion weldments.

2. The toughness and strength of the pressure-bonded weldment closely approximates that of the base material.

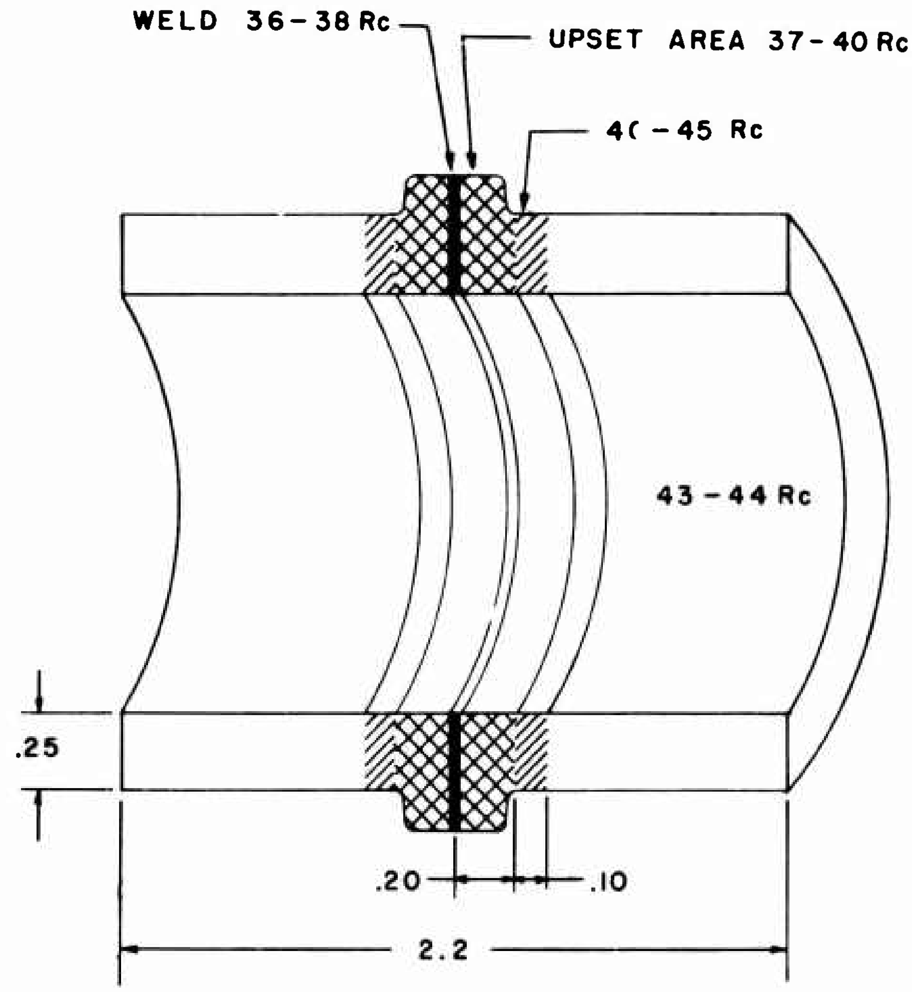

Figure 7. CROSS SECTION OF PRESSURE-WELDED CYLINDER SHOWING HARDNESS IN WELD AREA

GENERAL REMARKS

Optimum ductility was not realized in this initial investigation. However, it is probable that the weld ductility can be increased to that of the base metal level when processing refinements are introduced into the bonding process. These refinements include controlled induction heating incorporating a totally inert environment, thus eliminating contamination over the entire weldment.

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High-strength titanium assemblies for Army weapon systems have been fabricated using solid-state bonding and controlled plastic deformation techniques to achieve union between individual components.

For this application coalescence is induced by heating the metal about the abutting interface area between units to a temperature slightly above that of the beta transus of the alloy. At this temperature, diffusion and grain growth occur across the interfaces of abutting components producing the desired solid-state bond. During post-weld cooling of the bonded area through the two-phase alpha-beta region of the alloy, plastic deformation is initiated and completed at the weld area. This action refines any grains that recrystallized during the heating cycle and disperses any oxide inclusions which may have been trapped within the bond area. The final microstructure developed at the bond is typical of a wrought material and exhibits a definite grain-flow pattern throughout.

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