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Friction Welding of Titanium Alloys

Titanium alloys are readily friction (inertia) welded and the weldments obtained can, in most instances, be used in the as-welded condition

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ABSTRACT. To determine the consistency of joint quality and the sensitivity of friction (inertia) welding in highly stressed gas turbine components, an extensive evaluation was made of the tensile, impact, and fatigue properties of welded Ti-6Al-4V and Ti-6Al-2Sn-4Zr-2Mo. Properties were consistently good within a 10% range of parameter variation, as long as the upset exceeded a minimum level. Statistical analysis showed that properties depended on the choice of parameters even when adequate upset was achieved. Therefore, degree of upset cannot be the sole criterion of acceptable properties.

Considerable tensile and fatigue testing showed that properties in reproducibly welded joints were consistent in level and scatter with the base metal. Additional evaluation assessing the inertia weldability of other titanium alloys also established that several alloys have slightly decreased but acceptable properties in the as-welded condition. Properties approximating base metal are usually achieved by welding followed by a 1000° (2 hr) stress relief.

Inertia welded titanium joints were

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found to contain a narrow, highly worked heat-affected zone with an alpha prime structure at its center. Test specimen failures were consistently in the base metal.

While ultrasonic inspection was found to be the only meaningful method of nondestructive testing, it could not detect slight residual contamination in low upset joints, indicating the necessity for

close process control.

Introduction

An extensive investigation was undertaken to determine the properties of inertia welded titanium alloys used in highly stressed gas turbine components such as the disc and spacer assembly shown in Fig. 1. Historical-

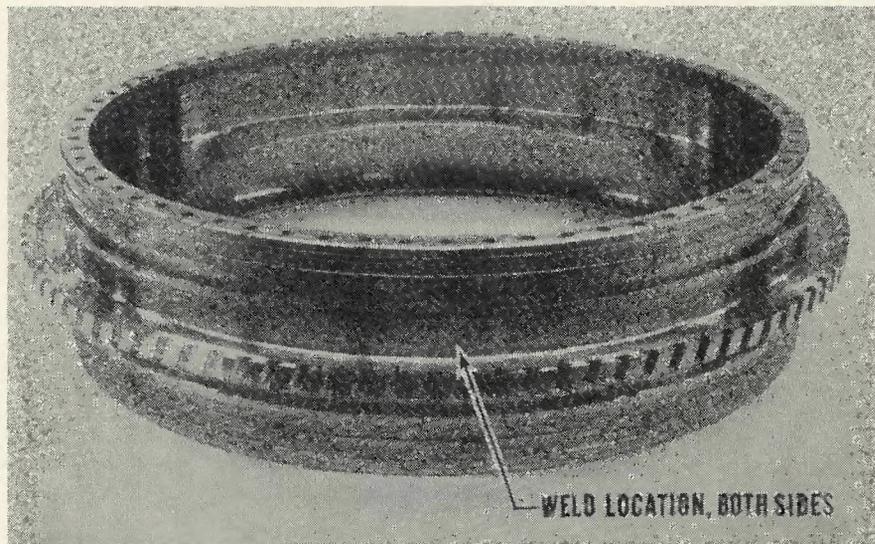


Fig. 1—Typical AMS 4928 titanium structure fabricated by friction (inertia) welding

Table 1—Statistical Program For Determining Sensitivity of Inertia Weld Properties in Ti-6Al-4V to Small Process Changes

Factors Considered	Levels	
	Minus (—)	Plus (+)
A. Concentricity	0.005 in.	0.015 in.
B. Speed (1130 rpm)	10% reduction	10% increase
C. Squareness	0.005 in.	0.015 in.
D. Thrust load (4550 psi)	10% reduction	10% increase
E. Surface roughness	63 rms max	250 rms min

Program Design^a

		A+		A—	
		B+	B—	B+	B—
C+	D+	E+	(15)		(4)
		E—		(1)	(13)
	D—	E+		(12)	(16)
		E—	(9)		(14)
C—	D+	E+		(11)	(10)
		E—	(8)		(2)
	D—	E+	(5)		(6)
		E—		(3)	(7)

^a Random testing sequence shown in ().

ly, such components are machined from one-piece closed die forgings, a technique which entails considerable machining and raw material waste. The use of three separate sections—a flat pancake forging and two rolled rings inertia welded together—was conceived as a potential cost reduction. Furthermore the use of weldments for this type of component opens design options for other structures which cannot be feasibly made from one piece.

Prior to this program no welds of any type were accepted as sufficiently reliable for this application. Of particular criticality in such acceptance is the mechanical fatigue strength of welded structures since this property is sensitive to localized weld defects. Metal fatigue in rotating gas turbine components is of two types: high frequency, low strain vibrations encountered during normal extended operation, and low frequency, high strain forces encountered during the starting and shut-down of the engine.

Prior experience with various types of welding indicated that uncommon consistency and reliability had to be achieved to meet the demanding design requirements for this part. As a simple process independent of operator skill, inertia welding was chosen because it appeared to be capable of giving the quality of welds which would consistently meet base metal properties throughout the weld zone. As a solid state process, it is conceptually similar to the forging process by which the base metal is formed, contrasting favorably with other processes which leave a cast structure in the weld zone.

It was apparent from preliminary

studies that upset is the most measurable output of an inertia weld, together with the weld time and the condition of the flash. Moreover, it also is apparent that upset can be achieved by widely different combinations of speed, thrust, and flywheel inertia. The experimental investigation sought the following goals: (a) evaluate the sensitivity of weld properties to small changes in process; (b) determine the consistency of properties throughout the weld; (c) characterize the design properties of inertia welds in several alloys; (d) determine the relationship between upset and properties and (e) establish criteria for process specifications, controls, and inspection.

The fundamental investigatory work was done utilizing titanium 6Al-4V (Ti-6-4) and titanium 6Al-2Sn-4Zr-2Mo (Ti-6-2-4-2). Once the basic trends and process controls were established, properties of inertia welds were determined for titanium 8Al-1V-Mo (Ti-81-1), titanium 6Al-6V-2Sn (Ti-6-6-2), and titanium 6Al-2Sn-4Zr-6Mo (Ti-6-2-4-6).

Statistical Analysis

A planned statistical experiment determined the extent to which certain parameters affected weld properties in Ti-6-4 as shown in Table 1. A full statistical matrix was not used because of cost limitations. Joints were made between 23-in. diameter cylindrical rings having a nominal wall thickness of $\frac{3}{16}$ in. The range of variables considered were those which could be anticipated as within the normal manufacturing process capabilities.

The variables evaluated were: (a) thrust—the force per unit area constantly applied to the joint during the

welding cycle; (b) speed—the rotary velocity of the moving workpiece at the moment of thrust application and resultant contact which initiates the weld cycle; (c) concentricity—the offset or deviation between the axis of one part with respect to the axis of the other part; (d) squareness—the extent to which the plane of one faying surface was out of parallel from its mate, measured at the mean circumference; (e) surface finish—the measured roughness of the faying surfaces.

The flywheel inertia was not used as one of the variables in this investigation since it is relatively easy to hold this parameter at a constant value. The mean welding parameters were chosen on the basis of prior experience as those which gave a smooth flash (material extruded during welding), a notch-free joint, and approximately 0.150 in. upset. These parameters were a speed of 1130 rpm, a thrust of 4550 psi, and a flywheel inertia ($WK^2 = \text{weight times radius of gyration}$) of 1160 pound (feet).²

In the statistical analysis program, the tensile properties—ultimate and 0.2% yield strength, reduction in area and elongation—were measured from each of the 16 test rings. Nine smooth tensile and nine impact specimens were taken from each ring. The analysis of the test data sought to determine the main effect of each variable together with some of the interactions (combined effects of different variables).

Reproducibility Analysis

After the statistical program evaluation was completed, a number of rings of both Ti-6-4 and Ti-6-2-4-2 were welded to determine the reproducibility in upset and properties in rings welded at identical parameters. In addition to tensile and impact properties, both high and low cycle fatigue strengths were determined. An evaluation was made of the effects and criticality of small defects which might be present in the faying surface due to mishandling of the machined parts prior to welding. Two sets of rings were welded with machined-in flaws (drilled holes and slots) from 0.010 to 0.100 in. deep in the center and edges of the faying surface.

Properties of Other Alloys

Upon completion of the statistical and reproducibility analyses, other alloys were tested on a more limited basis. In assessing inertia welds in other alloys, varying joint geometries were used, usually relating to the actual part under consideration. Typical-

ly these were thin wall cylindrical structures with a ratio of diameter to wall thickness ranging from 12:1 to 60:1.

Welding Procedure

Inertia welding was performed on a commercially available machine rated at 4800 rpm, 170,000 lb thrust, and 1200 lb-ft² flywheel moment of inertia. Special controls and instrumentation were utilized to monitor the rotary speed and thrust during the weld cycle. Flywheel moment of inertia was determined by calculation from its dimensions and material density (steel). The output measurements were upset—the change in axial dimension of the welded parts compared to their original length—and weld time. Mechanical properties were determined by cutting specimens from the weldment.

Preweld and Postweld Processing

Prior to welding, parts were cleaned using commercial acid-etch processes and then fixtured in the inertia welding machine by simple tooling constructed of low alloy steel. After welding and dimensional inspection, the joined parts were subjected to the postweld heat treatment or stress relief.

In both the statistical and reproducibility programs described above, the rings were inertia welded in the fully heat treated condition and subsequently stress relieved at 1000° F/2 hr/AC; as-welded properties were determined on a limited basis.

In the supplementary work on the inertia weldability of various other titanium alloys, differing combinations of postweld heat treatments and stress reliefs were evaluated as described below.

Nondestructive testing was undertaken after removal of the weld flash by machining. Test specimens were machined from the weldment at planned regular intervals. Up to 60% of the circumferential joint area was cut into test specimens in some instances.

Inspection and Testing

The nondestructive test methods used in evaluating joints included fluorescent penetrant, radiography, eddy current and ultrasonic techniques. Other methods being developed for detecting segregation in titanium alloys were also considered but not extensively used. Ultrasonic techniques have been found especially effective for titanium assemblies.³ Both delta scan and longitudinal pulse-echo methods were utilized; the former using a 1/2-in. diameter 5-MHz

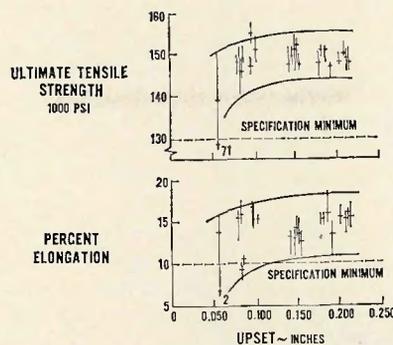


Fig. 2—Tensile properties of inertia welded Ti-6Al-4V at varying upsets (204 tests from 21 welded rings)

transducer located axially, and a 1/4-in. diameter focused receiving transducer located radially; the latter using a 1-in. focal length, 5-MHz transducer located axially.

From each weldment, a number of test bars were machined, all with the weld zone located at the center of the gage length. Smooth ($K_t=1$) 1-in. gage length tensile specimens were tested at room temperature. Tapered round 1/8 in. diameter low-cycle fatigue specimens were tested on a Sonntag 30 cps load-controlled machine where the sample is subjected to axial preload and alternating tensile-compressive stress. Typically, fatigue test bars were preloaded at a stress equal to the alternating stress. Fatigue life is determined by total fracture failure.

High frequency fatigue testing was conducted at room temperature using a flat polished Krouse-type specimen (0.100-in. thick, hour glass shape 0.450-in. wide gage section) subject to cyclic reverse bending. Specimens were excited at their natural frequency (750 cps) in an air stream and run to failure or terminated upon reaching 10^7 cycles. Stress levels reported were based on dynamic strain gage calibrations; failure was determined by a drop in natural frequency. The joint geometry dictated the use of a substandard test piece which may have resulted in less than optimum fatigue strengths. On a comparative basis, however, this limitation is not critical.

Considerable impact testing was un-

dertaken to assess the fracture mode on a comparative basis from ring to ring and within a single joint. Non-standard specimens cut directly from the welded ring sections were used; absorbed fracture energy was not measured.

Experimental Results

Inertia welding of titanium was readily accomplished over a wide range of parameters. Relatively low thrust is required because of the low hot yield strength of titanium alloys. All joints had uniform flash which varied according to the upset level. The interfacial notch formed by the flash on the opposing parts was well beyond the cylindrical surface of the part due to the choice of flywheel WK², the primary influence.

When mean parameters were used, the typical weld time (from moment of contact to cessation of motion) ranged from 1.2 to 1.5 seconds, indicating the completion of the weld during a relatively few revolutions. Such short times are characteristic of titanium alloy welds, as contrasted with 3 to 5 seconds for similar sized joints in steel and nickel alloys.

Statistical Analysis

Tensile properties (Fig. 2) from the statistically planned parameter program were analyzed mathematically to establish significant relationships. The analysis showed that neither ultimate tensile nor 0.2% yield strength was significantly affected by any of the variables. However, elongation proved to be more sensitive:

(a) Elongation was decreased slightly (from 15% to 14%) by low speed; poor concentricity had a similar effect. While statistically significant to a 95% confidence level, these parametric effects are minor from an engineering standpoint.

(b) High thrust yielded 15.5% average elongation whereas low thrust averaged 13%.

(c) At low thrust only, low speed yielded 12.7% elongation whereas high speeds were associated with 15% elongation. This indicates an interaction where speed is more important at lower thrust levels; at higher thrust levels, the effect of speed is nominal as stated in (a) above.

While the decrease in elongation under certain parametric conditions might not seem great considering variations encountered even in closely specified material from different sources, the change could be indicative of a concomitant decrease in critical fatigue life which was not measured in the statistical program. From a gas turbine design standpoint, a propor-

Table 2—Average Tensile Properties For Inertia Welded Ti-6Al-4V At Different Ranges of Upset

Property	—Upset level, inches—		
	0.058-0.105	0.125-0.175	0.182-0.219
UTS, ksi	149	150	149
0.2% Y.S., ksi	140	139	140
Elongation, %	14	13	15
RA, %	38	39	36

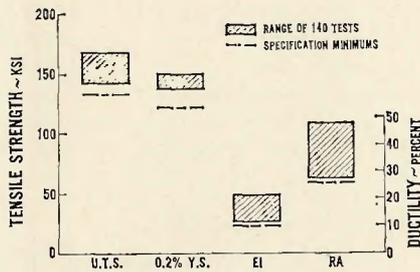


Fig. 3—Tensile properties from nine reproducibly inertia welded joints in Ti-6Al-2Sn-4Zr-2Mo

tionate shift downward in the fatigue properties scatter band would be of concern.

Surface finish was not found to be a significant factor affecting properties or upset, although slightly longer weld cycle times (1.0 vs. 0.97 sec) were associated with smoother finishes. This may be attributable to slightly different rates of frictional energy absorption at initial contact.

Concentricity and squareness did not significantly affect any of the properties within the narrow range of the investigation. However, conceptually at least, larger degrees of eccentricity could effectively alter the joint contact area in thin-wall joints, while extreme lack of squareness could vary the local upset from the average value.

Significance of Upset

To determine the interrelation of upset with properties, the rings welded in the statistical program were considered together with additional rings welded at the nominal mean parameters. The test results were averaged for three different upset ranges and compared in Table 2. There are no significant differences for the average of any of the tensile properties. However, when the distribution of 204 test bar results for ultimate tensile strength and elongation from 21 rings (16 from the statistical program, 5 from the reproducibility program) are plotted as a function of upset (Fig. 2), a more significant effect can be observed.

It is evident that there is a general correlation between upset and properties; at low upset levels consistency is less and some low properties will be encountered. It is also apparent that these tensile properties do not change appreciably with increasing upset at the higher levels.

One tensile test specimen of all those tested failed at a low stress in a brittle fashion. This bar had been machined from a test ring with 0.58 in. upset; the other eight bars from the same ring failed normally at higher levels. Of the 210 impact specimens

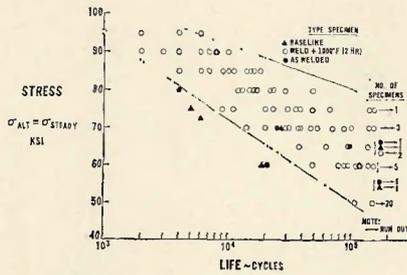


Fig. 4—Sonntag low-cycle fatigue properties for inertia welded Ti-6Al-2Sn-4Zr-2Mo

tested, three evidenced a relatively planar fracture surface; these were associated with rings having upsets of 0.58 and 0.86 in.

Upset is primarily determined by the total energy input to the weld. However, upset is also found to be dependent on the balance between the parameters; e.g., high inertia and low speed will give a different upset from the inverse combination even though the energy is the same. The statistical analysis showed that at any upset level properties will vary according to the parameters chosen. It is conjectural whether unacceptable properties would occur in higher upset titanium welds at parameter combinations more varied than the 10% range evaluated in this program. However, in some materials other than titanium, melting can be induced by high speeds and low thrust; an unsound joint results even though adequate "upset" has been achieved.

Therefore, upset per se is not a fully reliable indicator of weld properties. In critical applications, once satisfactory welding parameters have been developed, they should be monitored and closely controlled. Reproducible upset in identical area joints can be used to assess process control.

Reproducibility

Tensile and fatigue properties were measured for fifteen rings (ten Ti-6-2-4-2 and five Ti-6-4) or three slightly different dimensions which were welded at parameters producing 0.150 in. upset; these were nominally the mean parameters of the statistical program.

The reproducibility of tensile properties is shown in Fig. 3 where the full range of 140 tests from 9 welded Ti-6-2-4-2 rings is presented. (These rings were stress relieved at 1000° F for 2 hours after welding; the tenth ring was tested as-welded.) The data for Ti-6-4 welds are not presented but exhibited similar distribution. The tensile property scatter is consistent with that expected from a series of specimens taken from forgings of the same number of lots and indicates that high

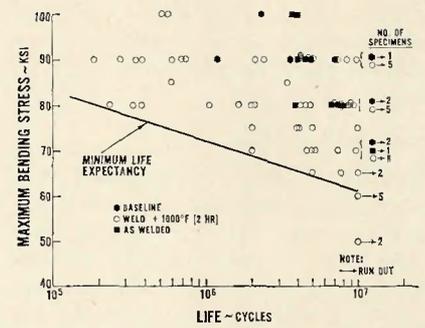


Fig. 5—Reverse bending high frequency strength for inertia welded Ti-6Al-2Sn-4Zr-2Mo

consistency of properties can be expected from inertia welds throughout the full circumference of the joint.

In joining a number of large diameter rings at identical machine parameters, it was found that very close reproducibility of upset also could be achieved, provided closely machined details were used. Although from a cost standpoint it is undesirable to require precision machined details, varying area affects the distribution of energy and thrust within the joint and therefore the resultant upset. In critical applications requiring close upset or parameter control, identical details must be mandated.

Although empirical relationships between change in upset and the various welding parameters were determined, a detailed presentation is beyond the scope of this paper. For one joint design a nominal 10% increase in parameters led to the following changes in upset:

- Speed: +0.057 in.
- Area: -0.036 in.
- Thrust: +0.015 in.

It is evident that speed and area are the stronger variables and therefore should be the more closely controlled.

Low cycle Sonntag fatigue properties of Ti-6-2-4-2 inertia welds from the reproducibility program are shown in Fig. 4. This important property is substantially above minimums for the base metal when the weld is stress relieved. Limited testing of base metal and as-welded joints indicates that the stress relieved welds may be slightly superior although the number of tests made is not conclusive. In any case, it can be concluded that as-welded properties are satisfactory. Location of the failure in the test bars could not be determined due to damage incurred subsequent to failure in this type of test.

The high cycle fatigue strength determined by reverse bending is shown in Fig. 5 to also be at a consistently high level exceeding the normal requirements of the Ti-6-2-4-2 alloy.

The great scatter in the data is attributable to the nature of the test and the limitations of the specimen design. When compared to a limited number of base metal tests, the welded and stress-relieved material appears to have somewhat lowered properties.

By contrast, testing of the as-welded material appeared to indicate that superior strength results for this condition. The stress distribution in the gage section of the specimen was measured and found relatively uniform, thereby subjecting the weld and adjacent base metal on either side to approximately the same stress. Since etching of failed specimens showed that in all conditions failure occurred in the base metal away from the weld zone, it may not be prudent to draw strong inferences from the apparent comparisons.

Inspection and Process Control

The nondestructive inspection techniques previously described were used to inspect rings after welding, stress relief and flash removal. Eddy currents, X-ray and fluorescent penetrant were not effective in distinguishing between any of the rings; the inspection results were typical of those from single piece forgings. Ultrasonic inspection was successful in locating the joint; a circumferential traverse of the weld zone showed some areas had more "noise" or random response than others.

These areas were no more prevalent in rings of any particular upset level, nor did test bars machined from them have inferior tensile or impact properties. There was no correlation with the few specimens from low upset rings which had inferior properties and the ultrasonic inspection of the areas from which they came. Consequently, this varying response was attributed to benign structural differences in the weld zone and was not an indicator of quality.

Since nondestructive testing of the weld zone was not effective in discriminating between low and high quality joints, it was necessary to establish process specifications and tolerance limits. Primarily this entailed fixing upset level and welding parameters for each joint geometry. Even when close reproducibility of parameters and upset may not be necessary for acceptable properties, close process control is desirable since in this way malfunctions of the machine controls, off-specification material, and out-of-tolerance details will become evident through deviant upset.

One set of proposed tolerances together with their estimated effect on upset is shown in Table 3. More

Table 3—Tolerances For Inertia Welding Parameters For a Joint in Ti-6Al-4V With an Estimated Effect on Upset

Parameter	Mean value	Proposed tolerance		Estimated effect on upset, inches
		Absolute	%	
Speed, rpm	1500	± 10	± ¾	± 0.006
Thrust, lb	50,000	± 1000	± 2	± 0.003
WK ² , lb-ft ²	1150	—	—	—
Concentricity	—	0.015 in. FIR	—	± 0.002
Squareness	—	0.015 in. FIR	—	± 0.002
Area, sq. in.	14	—	± 3	± 0.012
Diameter, in.	22	± 0.003	—	—

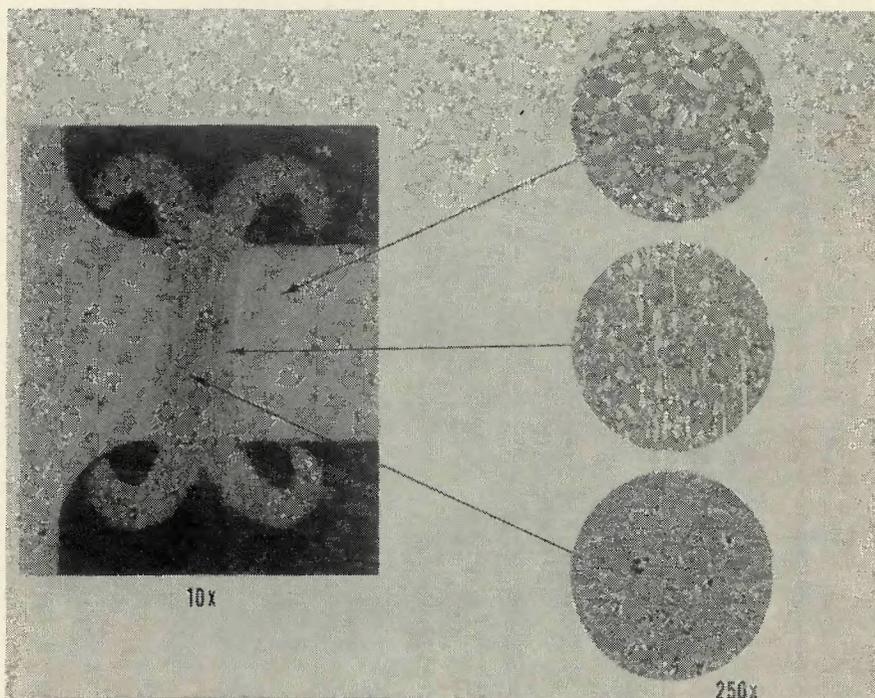


Fig. 6—Typical microstructure of an inertia weld in Ti-8Al-1V-1Mo cylinder wall

stringent upset reproducibility than that indicated can be achieved if necessary for manufacturing considerations. Very close upset control will entail a trade-off between the cost of fixturing and detail preparation compared to efficient material utilization and postweld fabrication.

Purposeful Defects

After welding two 0.150-in. upset rings containing purposeful defects, ultrasonic inspection indicated the presence of localized areas of discontinuity within the joint corresponding to the location of defects which had been 0.100-in. deep. Eddy currents and radiographic inspection were not effective in indicating any discontinuity in these areas. There was no non-destructive testing response from regions where the next largest defects (0.050-in. deep) had been. Fluorescent penetrant indicated where the deeper residual defects had been at the edge of the faying surface. As described below, metallographic examination showed that the defects de-

tected ultrasonically contained expelled material usually found in the flash.

Test specimens were taken from the two rings in regions adjacent to but not containing the residual defects. Properties were consistent in level and scatter with those from rings which had unblemished faying surfaces. Consequently, it was decided that the presence of residual defects did not have a deleterious effect on the rest of the weld.

It was concluded that ultrasonic techniques were the most meaningful nondestructive testing techniques. Defects in thin wall joints to a depth about equal to half the total upset will probably be obliterated. Since there is a low probability of encountering defects exceeding half anticipated upsets, very careful handling of the details is unnecessary.

It should be considered, however, that the upset levels required to achieve satisfactory properties in normal joints, and to remove residual defects, probably are greater with increased wall thicknesses.

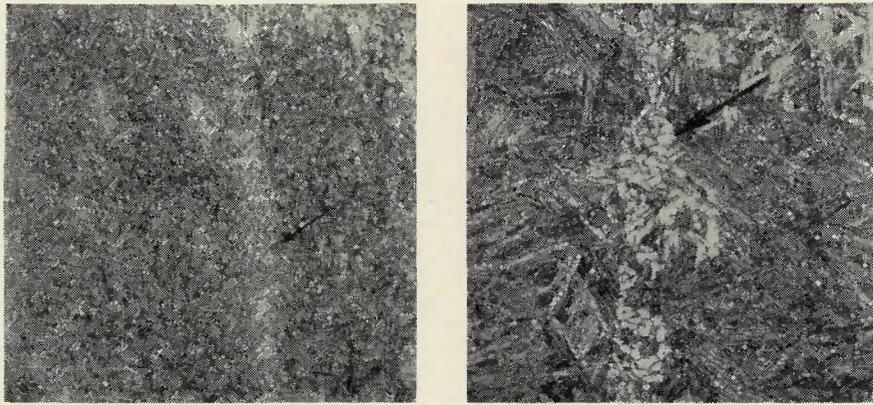


Fig. 7—Etch sensitive area at weld interface in low upset Ti-6Al-4V inertia weld prepared with Kroll's etch; right—same area after heating at 1850° F/10 min. in argon showing interstitially stabilized alpha (reduced 35% in reproduction)

Table 4—Comparative Room Temperature Properties of Stress Relieved Weld Zone and Base Metal in Ti-6Al-2Sn-4Zr-2Mo

Specimen	DPH	UTS, ksi	0.2% YS, ksi	Elongation, %
Weld zone	420	186	177	5.9
Base metal	360	148	135	8.8

Table 5—Average Tensile Properties of Inertia Welded Titanium Alloys

Alloy	Condition	UTS, ksi	0.2% YS, ksi	Elongation, %	RA, %
Ti-8Al-1V-1Mo (rolled ring)	Baseline ^a	140	125	12	22
	As welded	147	135	8	18
	Weld + SR ^b	150	137	10	21
Ti-6Al-2Sn-4Zr-2Mo (rolled ring)	Baseline ^c	164	148	13	44
	As welded	189	166	11	32
	Weld + SR	166	151	14	41
Ti-6Al-6V-2Sn (bar)	Baseline ^d	181	176	17	51
	As welded	184	177	10	25
	Weld + SR	186	181	13	44
	Weld + FHT ^d	180	174	14	47
Ti-6Al-2Sn-4Zr-6Mo (rolled ring)	Baseline ^e	184	170	12	47
	Weld + FHT ^e	193	175	6	17
Ti-6Al-4V (bar)	Baseline ^f	145	134	15	33
	As welded	138	123	13	32
	Weld + SR	139	125	15	33
	Weld + FHT ^f	145	132	17	39

Note: All inertia welds made in fully heat treated condition
^a 1700°F(1 hr)WQ + 1100°F(8 hr)AC; ^b 1000°F(2 hr)AC; ^c 1790°F(1 hr)AC + 1100°F(8 hr)AC;
^d 1600°F(1½ hr)WQ + 1100°F(4 hr)AC; ^e 1675°F(2 hr)AC + 1100°F(8 hr)AC; ^f 1700°F(1 hr)WQ + 1300°F(2 hr)AC

Microstructural Analysis

Inertia welded titanium joints, as shown in Fig. 6, are characterized by a highly worked, fine-grained weld zone. The alpha prime martensitic structure in the center of the weld indicates this area was quenched and that the welding temperature was probably above the beta transus (1830° F). The flashing contains a structure similar to the weld center but with the addition of a very thin alphacase (oxidized layer). Titanium alloy inertia welds do not contain any evidence of melting in the joint or flash, over a wide range of parameters. Titanium joints can be made at faying surface speeds (circumference

multiplied by the rotary speed) from 400 to 7000 feet per minute, unlike other materials which exhibit melting in the joint region when a critical velocity is exceeded. The microstructure and width of the weld zone (0.125 in.) were not strongly influenced by the range of parameters within the statistical evaluation program. The notch formed by the flashing is largely determined by the choice of flywheel inertia and was therefore acceptable in this work, regardless of other parameters.

Extensive metallographic examination was conducted on two rings which had low upsets (0.059 and 0.080 in.) and which had yielded test

bars with poor tensile and impact properties. It was found that in some joint specimens, the center of the weld region exhibited a sensitivity to Kroll's etch (Fig. 7) whereas specimens taken from higher upset rings never exhibited this structure. To evaluate this anomalous response, etch sensitive specimens were annealed for short periods near the beta-transus. After heat treating at 1850° F for ten minutes and quenching, the center of the joint contained primary alpha phase, whereas the rest of the weld and base metal had a transformed beta structure, as in Fig. 7. This behavior of the etch sensitive areas indicated that they contained alpha stabilizing elements, presumably oxygen and nitrogen, as a result of inadequate expulsion of the weld flash from the joint. Inasmuch as only some of the specimens cut from the low upset rings contained this contamination, it was characterized as sporadic. Since titanium which is high in interstitial oxygen and nitrogen can be expected to have lower ductility than comparable base metal, the presence of sporadic contamination was concluded to be the cause of some regions of inferior properties in low upset joints. Examination of impact and tensile specimen fracture surfaces from low strength specimens indicated etch sensitive areas, thus supporting the conclusion.

Areas containing residual purposeful defects found by ultrasonic inspection after inertia welding were examined metallographically. These regions were void-free, but the original defect area was completely filled with material which exhibited strong etch sensitivity and alpha-stabilized heat treatment response. It was surmised that, during welding, oxidized flashing is forced into the defect region. This area can be expected to have inferior properties and to be a potential source of failure in weldments. Significantly, the contamination was confined to the defect area and was not detected metallographically in other areas of the joint. This observation correlated with the good properties obtained from specimens cut from the joint adjacent to the defects.

To characterize the properties of the weld zone itself in a 0.150-in. upset inertia weld, tensile specimens were removed from the plane of the joint so that the specimen was comprised totally of weld zone material. The comparative results for a Ti-6-2-4-2 stress relieved inertia weld and base metal are shown in Table 4. As expected from the microstructural examination, the weld metal has a higher strength and lower ductility than

the base metal. Scanning electron microscopic examination of the failed specimens indicated that the fracture surface was similar for both types of specimens. All areas examined exhibited dimples, indicating a ductile failure mode.

Properties of Different Alloys

Several alloys were inertia welded to determine their properties and the necessity for postweld stress relief or heat treatment. All alloys were welded in the fully heat treated condition; weld properties were compared to baseline specimens machined from the same forging or barstock.

As previously indicated, the inertia weld zone has a higher strength and lower ductility than the surrounding base metal. In weld-containing tensile specimens (1-in. gage length by 0.250-in. dia) the $1/8$ -in. wide heat-affected zone alters the effective gage length, leading to lower apparent elongation and higher yield strength. In Table 5 a number of alloys in the as-welded and as-welded plus stress relieved condition have properties substantially exceeding those of the base metal even though all welded specimens failed outside the weld zone. Similar behavior of lesser magnitude has been observed with some fusion weld-containing titanium specimens, suggesting part of the effect is simply mechanical. However, it is conceivable that inertia welding induced structural changes (cold working) in the adjacent base metal even though none have been observed metallographically.

The average values of tensile properties for various inertia welded titanium alloys are presented in Table 5. Generally, full heat treatment after welding was considered undesirable since it leads to distortion incompatible with the parts being constructed; therefore data for this condition are limited.

Ti-8Al-1V-1Mo

This alloy exhibited the characteristic behavior of most alloys: decreased elongation in the as-welded condition which is partially recovered in the stress relieved condition. All elongations are above the minimum specification level for this material.

Creep testing at 40 ksi and 850° F indicated that stress relief was necessary to meet the specification for "time to 0.1% creep." Metallographically, there was no structural difference between the as-welded and stress relieved weld zone. Low cycle fatigue testing showed acceptable properties in the as-welded condition although slightly decreased compared to the base metal.

Ti-6Al-2Sn-4Zr-2Mo

This material was extensively evaluated in the reproducibility determination reported above and behaved similarly to other alloys. In this instance the base metal properties are achieved through stress relief of the weld, obviating the need for an evaluation of full postweld heat treatment. The relative fatigue properties were previously described. The substantial increase in strength in the as-welded condition is unexpected but verified by the extensive testing.

Ti-6Al-6V-2Sn

This alloy exhibited only small changes in ultimate and yield strength under varying postweld conditions but showed strong changes in ductility and reduction in area. The ductilities that are achieved through stress relief and full heat treatment are seen to be essentially the same. Although both are still below the base metal, they are well above the specification minimum of 6%.

Ti-6Al-2Sn-4Zr-6Mo

Since this alloy, unlike the others evaluated, is strongly responsive to heat treatment and cooling rate, it was anticipated that the weld would have very high strength and low ductility.⁵ Therefore, evaluation was only made of the weld in the fully heat treated condition. While the resultant elongation and reduction in area are substantially less than the base metal, they are within the specification minimums and therefore usable. Low and high frequency fatigue testing verified that the base metal and heat treated weld specimen had similar life expectancy.

Ti-6-4

This alloy was fully discussed above in both the statistical and reproducibility programs. In other work, a comparative evaluation of the properties under various postweld treatments shows it to be the least sensitive of all the alloys investigated, exhibiting fully acceptable properties in the as-welded condition. Unlike the generally comparable Ti-6-2-4-2 alloy, this material does not exhibit the marked as-welded strength increase. Tensile properties were also tested at 850° and 1000° F and found comparable to the base metal; 800° F creep rupture strength was insensitive to postweld condition and also was comparable to the parent metal.

Conclusions

1. Titanium alloys are readily inertia welded. Within the range of parameters investigated, properties of

joints are acceptable provided sufficient upset is achieved. However, some properties, particularly tensile elongation, can vary within the acceptable range depending on the choice of parameters which yield a given upset.

2. Upset is useful as a check on the consistency of the process but is not by itself an infallible indicator of successful weld properties. Once the minimum upset to reach full properties is achieved, there is no trend of increasing average properties at greater upsets.

3. Inertia welds without adequate upset can have regions of sporadic contamination yielding inferior local properties compared to the rest of the weld.

4. Close and consistent control of the inertia welding parameters can reproduce both upset and properties. Speed and joint area are the most critical parameters which affect upset.

5. Most titanium alloy inertia weldments can be used in the as-welded condition, although somewhat better tensile elongation and fatigue lives will be achieved by postweld stress relief or reheat treatment. The ability to use as-welded joints permits joining finish machined details or service repair.

6. Ultrasonic inspection is the most effective method of inspecting inertia welds, but it cannot detect slight interfacial contamination that may result from inadequate upset. Other than destructive tests on weldments, the most meaningful checks on the process are the consistency of upset and flash and careful monitoring of the machine performance.

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