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Electron Beam Weldability of Advanced Titanium Alloys

Variations in solution heat treatment and aging parameters result in significant mechanical property changes, implying that a wide range of strength-fracture toughness combinations may be achievable

BY R. W. MESSLER, JR.

ABSTRACT. The weldability of Ti-10V-2Fe-3Al (Ti-10-2-3), Ti-6Al-2Zr-2Sn-2Mo-2Cr-0.25Si (Ti-6-2-2-2-2), Ti-4.5Al-5.0Mo-1.5Cr (Corona 5) and Ti-15V-Cr-3Al-3Sn (Ti-15-3-3-3) plate-gage alloys was evaluated. In each case, two different postweld aging heat treatments were evaluated. One was intended to develop yield strength equivalent to Ti-6Al-4V (Ti-6-4) [i.e., 135-140 ksi (931-965 MPa)] with significantly higher fracture toughness, while the other was intended to develop higher strength with comparable fracture toughness [i.e., 40-50 ksi $\sqrt{\text{in.}}$ (44-55 MPa $\sqrt{\text{m}}$)].

Ultimate and yield tensile strengths, tensile elongation, area reduction, modulus of elasticity, and fracture toughness of weldments were determined and compared to corresponding values for base metal specimens subjected to the same heat treatments.

Introduction

Weldability is an important consideration in evaluating alloys for potential airframe structural applications. In conventionally fabricated airframe structures (i.e., machined, forged, hot formed, or cast), welding has traditionally offered a low-cost (i.e., low labor intensity) means of joining details to create structurally efficient assemblies. In parts not intended to be joined by welding, weldability provides the option for repairing discrepantly machined or defective parts (e.g., porous castings, cracked formed parts, etc.).

Good weldability of titanium alloys is especially desirable because, in addition to the traditional advantages above, welding has been identified[1] as a widely available process for improving material usage. Also, it is useful for achieving structural optimization when combined with rapidly emerging advanced titanium processing technologies such as superplastic forming with or without diffusion bonding, hot isostatic pressing of metal powders, and isothermal forging and rolling. By welding titanium alloy details fabricated by these advanced processes, overall part size (i.e., plan area) can be increased beyond existing facility limits (e.g., HIP autoclave capacity). In addition, material procurement leadtimes can often be shortened or circumvented by increasing existing facility through-put or providing alternate approaches for fabricating the required structure.

Emerging advanced titanium alloys have been developed with either or both of two major objectives in mind:

- Higher strength and fracture toughness for improved structural efficiency and damage tolerance
- Improved fabricability by either conventional (e.g., cold forming) or advanced (e.g., superplastic or isothermal forming) processing techniques

Weldability of these alloys is essential if full structural advantage is to be taken of the improved properties or if parts fabricated by the advanced processing technologies are to be economically and efficiently joined into structurally optimized hybrid assemblies.

A program was initiated to evaluate the weldability of four advanced titanium alloys:

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Table 1—Chemical Composition of Titanium Alloys

	Element, wt/%											
Titanium alloy	Al	Zr	Sn	Mo	Cr	V	Fe	Si	C	O	N	H
Ti-10-2-3	3.2					9.2	2.1		0.01	0.10	0.016	0.0036
Ti-6-2-2-2-2	6.0	2.0	1.9	2.1	2.0			0.25	0.002	0.12	0.008	0.0098
Corona 5	4.3			4.9	2.0		0.15		0.03	0.16	0.008	0.004
Ti-15-3-3-3	3.1		2.9		2.7	15.2	0.14		0.018	0.11	0.017	0.010

Table 2—Heat Treatment Parameters for Titanium Alloys

	Heat treatment no.1						Heat treatment no.2					
	Solution H.T.			Aging			Solution H.T.			Aging		
Titanium alloy	Temp, °F	Time, hr	Cool.	Temp, °F	Time, hr	Cool.	Temp, °F	Time, hr	Cool.	Temp, °F	Time, hr	Cool.
Ti-10-2-3	1350	1	FAN	1075	8	AIR	1400	1	FAN	950	8	AIR
Ti-6-2-2-2-2	1725	1	AIR	1000	8	AIR	1750	1	AIR	1000	8	AIR
Corona 5	1525	4	AIR	1050	8	AIR	1525	4	AIR	1300	6	AIR
Ti-15-3-3-3	1400	1	AIR	950	16	AIR	1400	1	AIR	1000	8	AIR

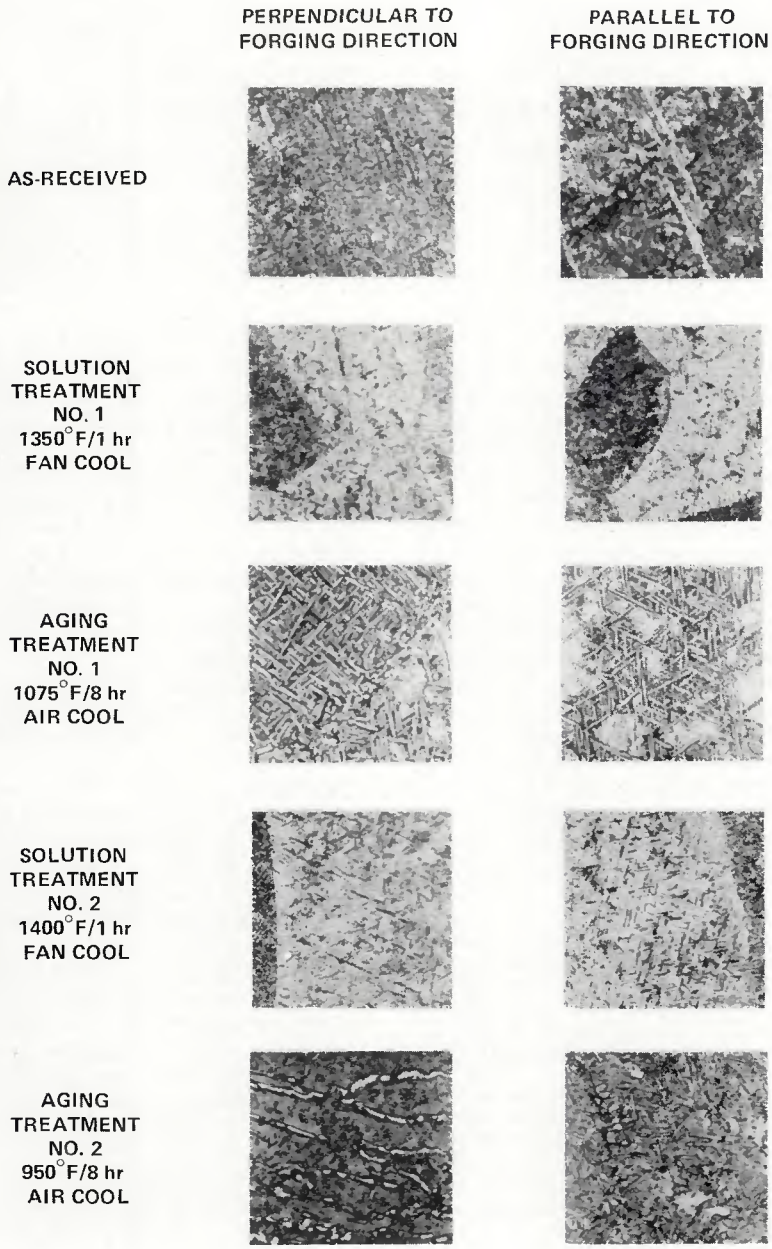

Fig. 1—Microstructure of Ti-10-2-3. ×100 (reduced 16% on reproduction)

- Ti-10V-2Fe-3Al (Ti-10-2-3)
- Ti-6Al-2Zr-2Sn-2Mo-2Cr-0.25Si (Ti-6-2-2-2-2)
- Ti-4.5Al-5.0Mo-1.5Cr (Corona 5)
- Ti-15V-3Cr-3Al-3Sn (Ti-15-3-3-3)

Material product forms were either plate (in the case of Ti-6-2-2-2-2, Corona 5, and Ti-15-3-3-3) or forged billet (in the case of Ti-10-2-3) with thicknesses averaging ⅝ to 1 in. (15.9 to 25.4 mm). Electron beam (EB) welding was selected as the preferred process for evaluating weldability on the basis of its single-pass welding capability, low heat input, retention of base metal properties, and inherent suitability for building up details into larger components.

Discussion

Material Characterization

Chemical analyses of the Ti-10-2-3, Ti-6-2-2-2-2, Corona 5, and Ti-15-3-3-3 alloys included in the EB weldability study are given in Table 1.

The near beta Ti-10-2-3 alloy is capable of developing high-strength [170-180 ksi (1172-1241 MPa), tensile yield] and moderate toughness [50 ksi $\sqrt{\text{in.}}$ (55 MPa $\sqrt{\text{m}}$)] or moderate strength [140-150 ksi (965-1034 MPa), tensile yield] and high toughness [75-85 ksi $\sqrt{\text{in.}}$ (82-94 MPa $\sqrt{\text{m}}$)]. Its low beta transus and low flow strength make the alloy extremely attractive for isothermal or hot die forging of near net or net shapes. The inherent deep hardenability of the beta alloys, in general, combined with the high strength and high toughness of Ti-10-2-3, in particular, make the alloy

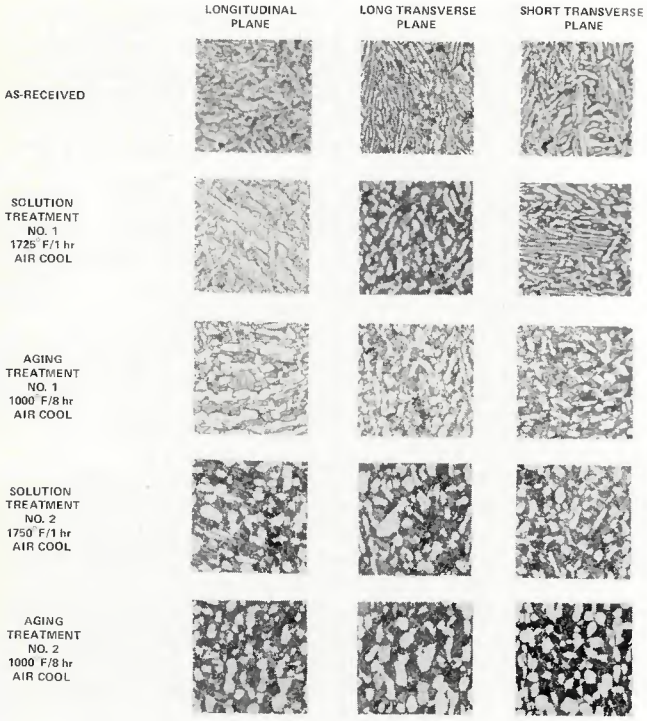

Fig. 2 (left)—Microstructure of Ti-6-2-2-2-2. ×100 (reduced 52% on reproduction)

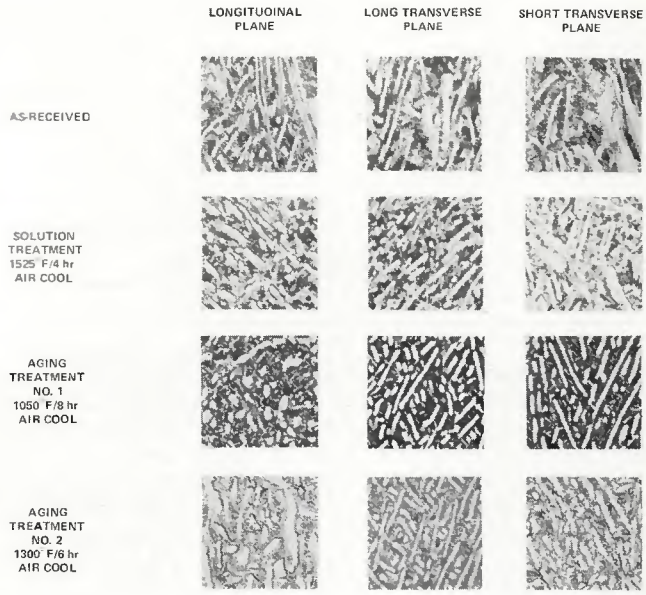

Fig. 3—Microstructure of Corona 5. ×100 (reduced 52% on reproduction)

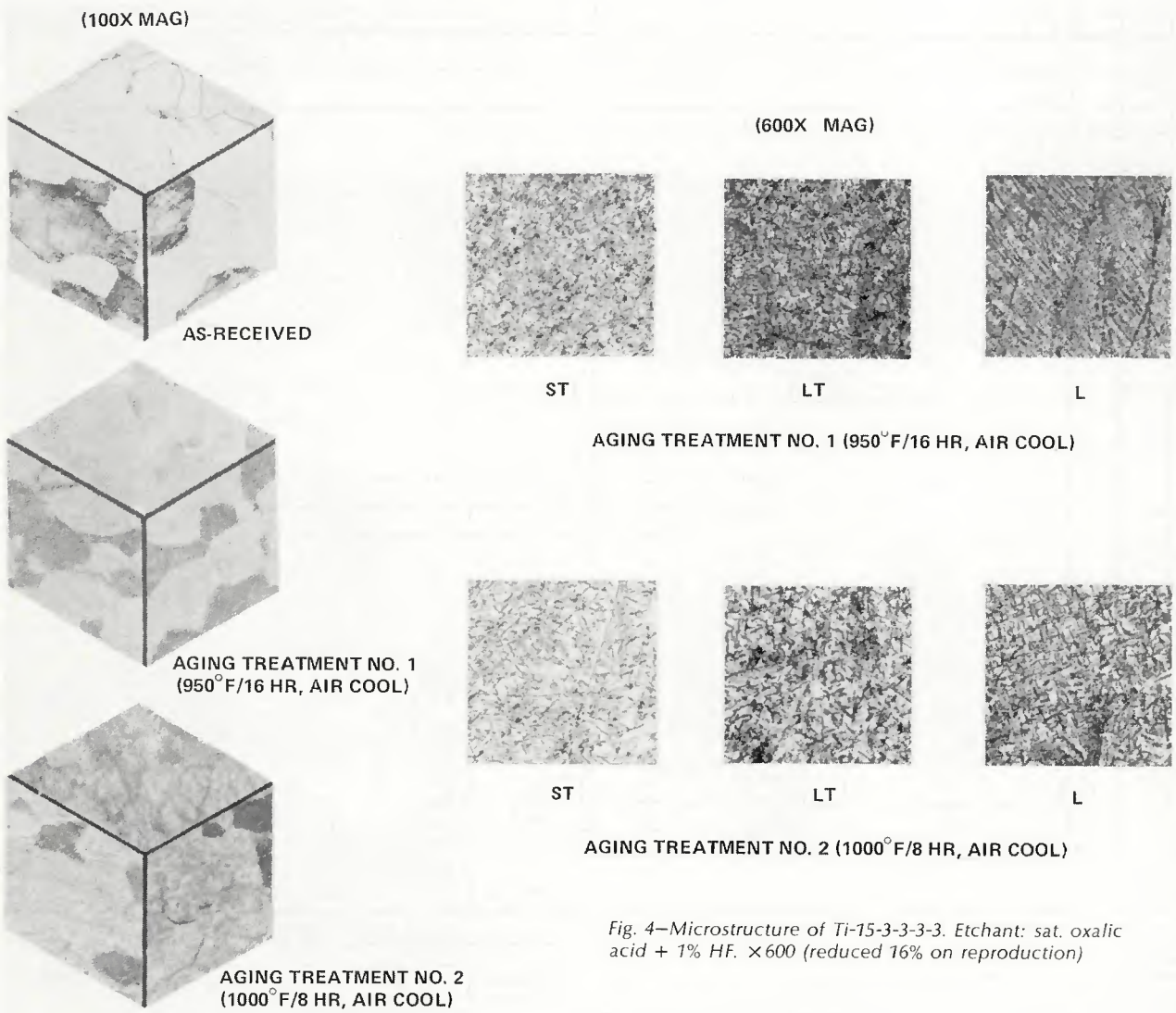

Fig. 4—Microstructure of Ti-15-3-3-3-3. Etchant: sat. oxalic acid + 1% HF. ×600 (reduced 16% on reproduction)

Table 3—Final EB Welding Parameters

Parameter	Titanium alloy				
	Ti-6-4	Ti-10-2-3	Ti-6-2-2-2-2	Corona 5	Ti-15-3-3-3
Beam current, MA	325	300	300	325	715
Beam voltage, kV.	45	45	45	45	30
Travel speed, ikm	35	40	40	35	30
Energy input, kJ/in.	25.0	20.4	20.4	25.0	10.5
Gun-to-work distance, in.	8	8	8	8	8
Focus adjustment	4.98	4.98	4.98	4.93	–
Focus meter reading	4.35	4.35	4.35	4.30	3.85
Focus delta	−5	−5	−5	−10	
Sharp focus	4.40	4.40	4.40	4.40	4.40
Material thickness, in.	1.0	0.75	0.625	1.00	0.25

extremely attractive for highly loaded, heavy section, critical components. The material employed in this study was a section of a rough upset forging from Wyman-Gordon, exhibiting considerable variation in grain size. EB welding was performed on ¾ in. (19.1 mm) thick plate extracted from the billet.

The high-strength, high-toughness, alpha-beta Ti-6-2-2-2-2 alloy was obtained from Reactive Metals, Inc. (RMI) as a section of 0.625 in. (15.9 mm) thick hot-rolled plate. This alloy was designed to have the deep hardenability more characteristic of beta alloys together with the high modulus and low density of the alpha-beta alloys. In fact, Ti-6-2-2-2-2 has an unusually high tensile modulus and low density and is thus extremely attractive for stiffness- or weight-critical structures.

Corona 5 or Ti-4.5Al-5.0Mo-1.5Cr is an intermediate strength [140-150 ksi (965-1034 MPa), tensile yield] alpha-beta alloy developed jointly by Colt-Crucible, Rockwell International, and the Navy (CO-RO-NA) to have exceptionally high fracture toughness [80-100 ksi $\sqrt{\text{in.}}$ (88-110 MPa $\sqrt{\text{m}}$)]. The alloy has demonstrated excellent superplasticity.[2] In this study, 1.0 in. (25.4 mm) thick plate was extracted from the mid-thickness of a 3.25 in. (32.5 mm) thick plate processed by Colt-Crucible Research Center.

The all beta alloy, Ti-15-3-3-3, was developed as a continously (strip) producible, cold-formable titanium sheet material. Strength can be varied through heat treatment over a wide range [120 to 180 ksi (827-1241 MPa) tensile yield]. In this program, 0.25 in. (6.4 mm) thick plate or sheet was evaluated.

Heat Treatment

The two heat treatments selected for evaluation with each titanium alloy are outlined in Table 2. One treatment was intended to develop yield strength comparable to that for annealed Ti-6-4 [i.e., 135 to 140 ksi (931 to 965 MPa)] with significantly higher fracture toughness. The second treatment was intended to develop high yield strength with fracture toughness comparable to annealed Ti-6-4 [i.e., 40 to 50 ksi $\sqrt{\text{in.}}$ (44 to 55 MPa $\sqrt{\text{m}}$)]. In the case of Ti-6-2-2-2-2, only one aging

Table 4—Mechanical Properties of Advanced Titanium Alloys

Titanium alloy	Heat treat no.	Type of specimen	Test type[a]	Number of specimens	Average tensile properties					Fracture toughness
					F_{tu}, ksi	F_{ty}, ksi	Elong, %	RA, %	E, Msi	ksi $\sqrt{\text{in.}}$
Ti-10-2-3	1	BASE METAL	LT	1	143.9	138.6	16.0	51.3	15.15	–
	1	WELD	TT	3	138.1	134.2	10.0	40.8	15.54	–
	2	BASE METAL	LT	2	185.8	175.5	5.0	7.9	15.41	–
	2	WELD	TT	3	182.2	171.5	5.5[b]	9.9	15.62	–
	2	BASE METAL	FT	2	–	–	–	–	–	52.5
	2	WELD	FT	1	–	–	–	–	–	55.7
Ti-6-2-2-2-2	1	BASE METAL	LT	3	182.4	167.2	13.3	34.9	17.16	–
	1	BASE METAL	FT	2	–	–	–	–	–	44.0
	1	WELD	TT	3	180.3	165.5	12.8	35.7	16.92	–
	1	WELD	FT	2	–	–	–	–	–	[c]
	2	BASE METAL	LT	3	179.8	164.5	13.7	34.4	16.64	–
	2	BASE METAL	FT	2	–	–	–	–	–	47.0
	2	WELD	TT	3	178.1	163.7	10.0	29.9	16.81	–
	2	WELD	FT	2	–	–	–	–	–	[c]
Corona 5	1	BASE METAL	LT	3	174.9	168.8	10.0	22.1	17.32	–
	1	BASE METAL	FT	1	–	–	–	–	–	43.7
	1	WELD	TT	3	174.1	165.6	10.0	25.9	17.05	–
	1	WELD	FT	2	–	–	–	–	–	26.4
	1	BASE METAL	TT	1	164.2	159.7	15.0	51.0	15.91	–
	1	WELD	LT	1	186.9	182.9	3.0	3.2	16.17	–
	2	BASE METAL	LT	3	147.5	145.8	14.7	40.2	16.77	–
	2	BASE METAL	FT	2	–	–	–	–	–	61.4
	2	BASE METAL	TT	1	141.2	136.4	18.0	45.3	16.29	–
	2	WELD	TT	3	149.6	144.6	15.3	49.9	16.29	–
	2	WELD	FT	2	–	–	–	–	–	60.8[d]
	2	WELD	LT	1	152.9	148.6	8.0	23.4	17.06	–
Ti-15-3-3-3	1	BASE METAL	LT	3	179.4	168.4	8.5	–	15.9	–
	1	WELD	TT	2	170.4	158.8	9.0	–	15. 8	–
	2	BASE METAL	LT	3	154.6	142.2	12.5	–	14.5	–
	2	WELD	TT	2	148.6	136.4	12.0	–	15.7	–

[a]For base metal specimens, "LT" and "TT" designate loading in the grain and perpendicular directions, respectively, while "FT" designates compact tension specimens. For welded specimens, "LT" and "TT" designate longitudinal and transverse welds, respectively, while "FT" designates compact tension specimens.
[b]Specimen broke at the gage mark.
[c]All specimens failed during pre-cracking, indicating very high notch sensitivity.
[d]Invalid test; apparent K_{Ic} value obtained (80 ksi $\sqrt{\text{in.}}$) should be rechecked using larger test specimens.

temperature was evaluated to produce a 160-170 ksi (1103-1172 MPa) yield strength, but the solution treatment temperature was varied slightly to assess the sensitivity of these small variations on subsequent aging response.

All blanks designated for the weldability study were EB welded in the as-solution-heat-treated condition. Aging heat treatments were performed on test specimens machined to final dimensions. Microstructures of the various titanium alloys in various stages of processing (i.e., as-received, solution treated and aged) are shown in Figs. 1 through 4.

EB Weldability

EB weld parameters and general material weldability were established by making a series of bead-on-plate welds on each alloy/gage combination. Starting parameters in each case were the same as those for comparable gages of Ti-6-4. Final EB welding parameters were refined using square butt joint welds of each alloy/gage combination. All welds were made without filler metal addition. Resulting parameters are summarized in Table 3. Parameters for a comparable thickness plate of Ti-6-4 are shown for comparison.

Experimental butt joint welds produced using these parameters were inspected radiographically and ultrasonically, as well as with fluorescent dye penetrant, and were found to be free from rejectable defects. The overall weldability of all of the alloys was comparable to that for Ti-6-4. The weldability of Corona 5 was indistinguishable from Ti-6-4 and, in fact, was welded to Ti-6-4 with no difficulty. For Ti-15-3-3-3, welding beam power had to be increased slightly (compared to Ti-6-4 of comparable thickness) to achieve penetration and proper weld profile and bead contour.

Mechanical Properties Evaluation

Mechanical properties of Ti-10-2-3, Ti-6-2-2-2-2, Corona 5, and Ti-15-3-3-3 weldments and base metal specimens are listed in Table 4 and are plotted in Figs. 5 through 7. Tensile tests of the base metal were conducted with loading both parallel (longitudinal tensile) and perpendicular (transverse tensile) to the grain (rolling) direction. Tensile tests of the weldments were also conducted with loading both transverse (transverse weld tensile) and parallel (longitudinal weld tensile) to the weld. Fracture toughness was evaluated using a pre-cracked compact tension specimen. In welded specimens, the specimen notch was located in the center of the weld fusion zone, and crack growth was intended to occur along the weld centerline.

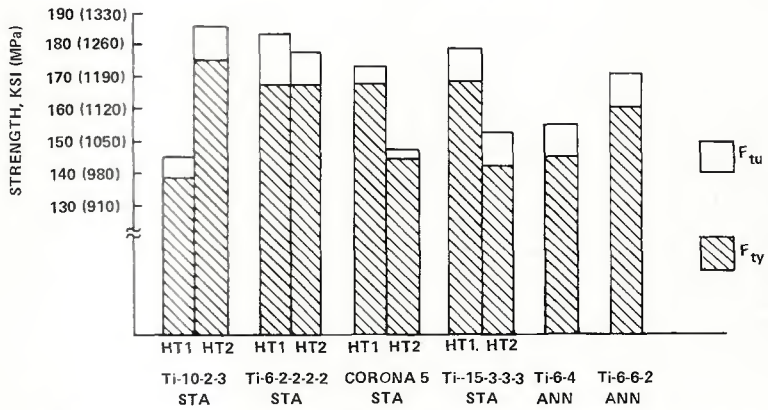

Fig. 5—Tensile properties of advanced titanium alloys in STA condition compared to conventional annealed airframe alloys

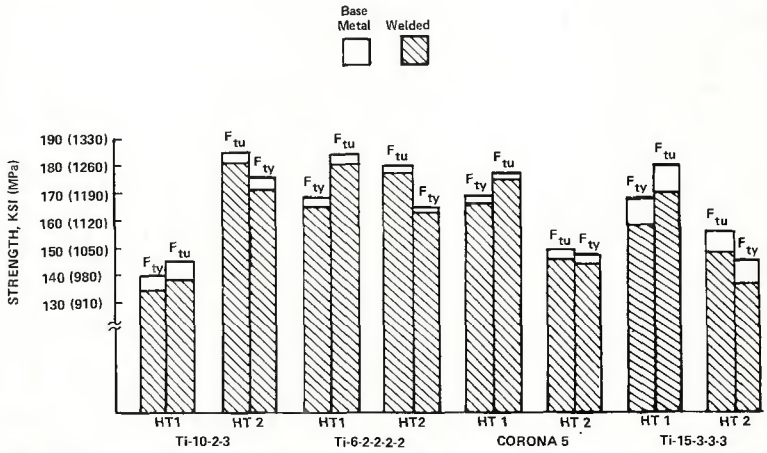

Fig. 6—Welded properties vs. base metal properties for advanced titanium alloys

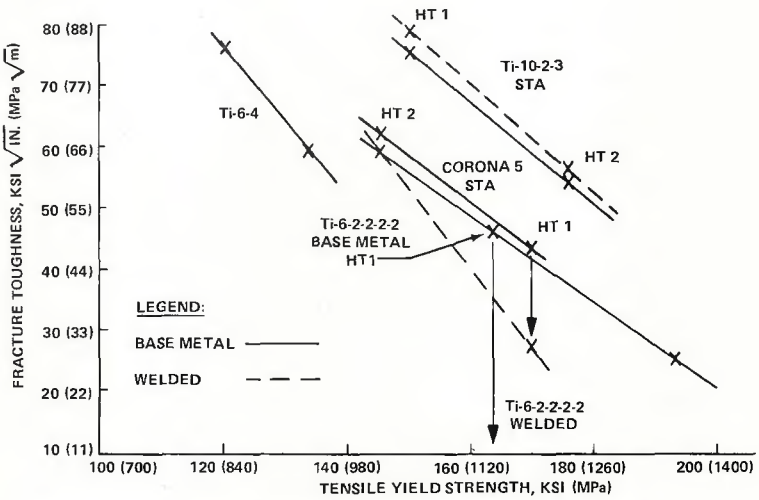

Fig. 7—Fracture toughness-tensile yield strength relationships

Tensile yield and ultimate strength in the weldments was generally 95 to 100% of the base metal; joint tensile efficiency was thus very high. Comparisons between the tensile ultimate and yield strengths for the alloys evaluated are shown for the base metal in Fig. 5 and for the weldments to the base metal in Fig. 6. Conventional Ti-6-4 and Ti-6-6-2 are shown for comparison. Base metal and weld metal fracture toughness are shown as a function of tensile yield strength in Fig. 7.

Ti-10-2-3 alloy heat-treated to the

170 ksi (1172 MPa) F_{ty} (yield strength) level exhibited fracture toughness in excess of 50 ksi $\sqrt{\text{in.}}$ (55 MPa $\sqrt{\text{m}}$) in both base metal and welds. At the lower [135 to 140 ksi (931 to 965 MPa)] F_{ty} range, fracture toughness test results exceeded limits for small compact tension specimens used [75 ksi $\sqrt{\text{in.}}$ (82 MPa $\sqrt{\text{m}}$) max]; accordingly, these tests cannot be considered valid. Insufficient material was available for fabricating larger specimens.

In an intermediate F_{ty} range [145 to 150 ksi (1000 to 1034 MPa)], fracture toughness of Corona 5 base metal and welds exceeded 60 ksi $\sqrt{\text{in.}}$ (66 MPa $\sqrt{\text{m}}$) and was thus comparable to that of Ti-6-4 alloy at the 130 ksi (896 MPa) F_{ty} level. At a higher F_{ty} level [165 to 170 ksi (1133 to 1172 MPa)], the fracture toughness was approximately 43 ksi $\sqrt{\text{in.}}$ (47 MPa $\sqrt{\text{m}}$) for the base metal and only 26 ksi $\sqrt{\text{in.}}$ (29 MPa $\sqrt{\text{m}}$) for welds.

Fracture toughness for the Ti-6-2-2-2-2 alloy heat-treated to 160 to 170 ksi (1103 to 1172 MPa) F_{ty} was in the range of 43 to 47 ksi $\sqrt{\text{in.}}$ (47 to 52 MPa $\sqrt{\text{m}}$) for the base metal. Fracture toughness of welds appeared to be exceptionally low since all welded specimens failed on pre-cracking.

Conclusions

1. The Ti-10-2-3, Ti-6-2-2-2-2, Corona 5, and Ti-15-3-3-3 titanium alloys can be EB welded using parameters similar to those for Ti-6-4 alloy of comparable thicknesses.

2. Mechanical properties of Ti-10-2-3, Corona 5, and Ti-15-3-3-3 welds are generally comparable to those of the base metal.

3. Although Ti-6-2-2-2-2 welds have tensile properties comparable to those of the base metal, they have very high notch sensitivity and very poor toughness.

4. Variations in solution heat treatment and aging parameters resulted in significant changes in mechanical properties. This implies that a wide range of strength-fracture toughness combinations may be achievable.

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November 1980

An Annotated Bibliography on the Significance, Origin and Nature of Discontinuities in Welds, 1975–1980

by C. D. Lundin and S. J. Pawel

The literature search from which this annotated bibliography is derived is a part of the continuing effort in The Welding Engineering Group at The University of Tennessee. The Subcommittee on Significance of Weld Discontinuities of the Fabrication Division of the Pressure Vessel Research Committee has provided the impetus for continued research in the area of discontinuities in welds and has provided grant monies to undertake research in the area. This bibliography updates the references and bibliography published in Welding Research Council Bulletin 222, *Significance of Weld Discontinuities—A Review of Current Literature*, December 1976; therefore, the time period covered is 1975 to 1980. WRC Bulletin 222 and this additional annotated bibliography provide researchers with a starting point for studies of the origin, nature and significance of discontinuities in welds with the hope of encouraging further studies in this important area of weldment behavior.

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