Microstructure — Property Control With Postweld Heat Treatment of Ti-6Al-6V-2Sn

By proper selection of postweld heat treatments, considerable ductility and fracture toughness can be achieved

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ABSTRACT. A major limitation in the use of Ti-6Al-6V-2Sn as a structural alloy is its poor weldability. After conventional postweld heat treatment, the weld has very low ductility. However, proper postweld heat treatment will develop good ductility and fracture toughness in welded Ti-662. It is important to develop the correct microstructure, since mechanical properties depend upon the morphology of the alpha phase. Superior tensile ductility and fracture toughness was achieved with a duplex alpha-plate structure produced by a triplex heat treatment of automatic GTA welded 0.125 in. sheet. Matching filler metal gave better properties than Ti-6Al-4V filler.

Introduction

The high fracture toughness, ductility, and strength-to-weight ratio of titanium alloys has established them as essential materials in the development of present and future aerospace systems. At present, Ti-6Al-4V (Ti-64) is used for most applications where welded components are required. Other high strength alpha-beta alloys have greater fracture toughness and ductility when heat treated to the same strength level as Ti-64, but have been limited in use because of poor weldability (Refs. 1,2). As-welded sheet of Ti-6Al-6V-2Sn (Ti-662) has lower fracture toughness than the base metal and virtually no ductility. One approach for improving this situation was the development of a dual filler metal welding technique (Ref. 3). While this allows more ductility in the fusion zone by control of its chemical composition, it does not change the properties in the heat-affected zone where they seem to be lowest.

Recently, investigations (Refs. 4,5) have increased the understanding of microstructure-mechanical property correlations in titanium alloys. The present effort was made to produce microstructures known to have good ductility, in both the heat-affected zone (HAZ) and fusion zone (FZ), by controlled heat treatments after welding. Previous work has established the success of this approach (Ref. 6) with synthesized HAZ microstructures.

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Experimental Procedure

Strips of Ti-662 sheet, 0.125 in. thick, 18 in. in length and 2½ in. wide, were machined to provide a single 45 deg Vee groove with a 0.040 in. root face weld joint. Two-inch square sheet pieces were used for run-on and run-off tabs. Sheets were degreased in acetone before and after wire brushing in the area about 1 in. in width along the machined joint. An arc-voltage controlled, automatic GTA welding head in conjunction with an ac-dc 400 A power supply was used to weld these sheets. Argon shielding gas having a dew point of –40 F was used for torch, trailing, and back-up shieldings.

Both Ti-662 and Ti-64 filler metal, 0.062 in. diam, were used for each postweld heat treatment condition investigated. Chemical analyses of the filler metals and base metal are shown in Table 1, along with standard specifications for the filler metals. The welding schedules, listed in Table 2, gave complete joint penetration single pass welds essentially free of contamination and gas porosity. This was substantiated by x-radiography of each weld.

Blanks for tensile and subsize Charpy specimens were cut from the welded sheet and heat treated before final machining. The three postweld heat treatment thermal cycles were the same as those used in the work with synthesized HAZ microstructures (Ref. 6) and ranged from a simple solution treatment to a triplex thermal cycle procedure.

Heat Treatment I: 1600 F — 2h, FC
Heat Treatment II: 1350 F — 6h, FC; 1700 F — 3h, FC; 1350 F — 3h, FC
Heat Treatment III: 1500 F — 1 H, cool 250 F/h to 1200 F; 1200 F — 2h, AC; 1000 F — 2h, AC

The first heat treatment, (HT I) was selected as a variation of the conventional annealing procedures to coarsen the structure. The second, (HT II), was a result of extensive heat treatment studies in earlier work (Ref. 6). Both these heat treatments were

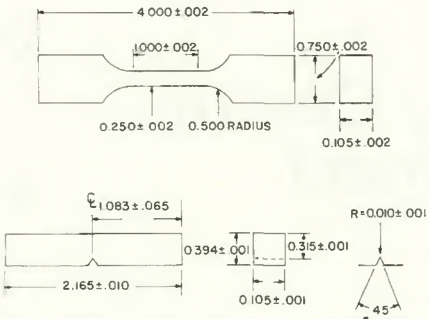

Fig. 1 — Tensile and fracture toughness specimen geometry


Fig. 2 — Overall view of the GTA welded Ti-6Al-6V-2Sn microstructure using matching filler metal (X35, reduced 54%)

Table 1 — Chemical Analysis and Standard Specifications for Welding Materials (Wt%)

Element	Base metal	Ti-64 filler metal Analysis	Ti-64 filler metal BMS-7-197	Ti-662 filler metal Analysis	Ti-662 filler metal AMS-4971
Titanium	Rem.	Rem.	Rem.	Rem.	Rem.
Aluminum	5.65	5.60	5.5-6.5	5.10	5.0-6.0
Vanadium	5.50	3.51	3.5-4.5	5.30	5.0-6.0
Iron	0.42	0.18	0.25 max	0.92	0.35-1.0
Copper	0.47	0.02	—	0.50	0.35-1.0
Tin	1.85	—	—	1.95	1.50-2.50
Hydrogen	0.0056	0.0073	0.0125 max	0.0065	0.015 max
Oxygen	0.200	0.188	0.175 max	0.168	0.20 max
Nitrogen	0.012	0.015	0.03 max	0.014	0.04 max
Carbon	0.036	0.029	—	0.029	—

Table 2 — Welding Schedules for Ti-662 Sheets

Arc voltage, V	Welding current, A	Welding speed, in./min	Welding speed, cm/min	Deposit rate, in./min	Deposit rate, cm/min
9	200	5	12.7	33.5	85

done in a vacuum furnace with pressure in the 10^{-6} torr range. Heat treatment III was performed on samples encapsulated in a partial pressure of argon and was selected from a computer regression analysis of the best heat treatment to optimize mechanical properties on β -extruded Ti-662 (Ref. 8).

Test specimens were machined to final dimensions shown in Fig. 1 after postweld heat treatment. Fracture toughness was determined for the base metal, HAZ, and FZ in the as-welded and three postweld heat treated conditions with fatigue-pre-cracked slow bend Charpy specimens conforming to ASTM-E-399. The W/A values were obtained from slow bend, three point loading tests at a crosshead rate of 0.1 in./min, where W is the energy of fracture and A is the net cross-sectional area under the fatigue crack. Tensile elongation, yield strength, and ultimate strength were determined for each of the four conditions in the base metal, FZ, and across the weld zone (transverse to the weld direction). Tests were run in an Instron tensile machine at a strain rate of 0.05 in./in./min. Photomicrographs were taken on a standard metallograph at 500X magnification in most cases. Standard section, polishing, and etching procedures were followed.

Results and Discussion

Microstructures

An overall view of the as-welded Ti-662 microstructure with Ti-662 filler metal is given in Fig. 2. It shows how the prior β grain size increases continually from the base metal across the HAZ to the middle of the FZ (MFZ). The detailed microstructure produced by the thermal cycle of welding is examined more closely in Fig. 3 for each of the weld regions. The MHAZ (b), EFZ (c), and MFZ (e) are predominantly fine acicular α which contains approximately 20% to 30% hexagonal martensite, α' (Ref. 7), which formed by the transformation of β during the rapid cooling associated with welding. The retained β is estimated to be about 10% of the structure (Ref. 6). There is no noticeable grain boundary α in the as-welded microstructure.

Heat treatment I (HT I) holds the weldment 140 F below its β transus in the two-phase $\alpha + \beta$ region. The α plate structure in the grains is coarsened considerably from the as-welded condition and a continuous grain boundary α network is produced (Fig. 4). It is the same thickness as plates within the grains and necked in many regions. The reaction in the as-welded HAZ and FZ during this heat treatment is $\alpha' \rightarrow \alpha + \beta$. The larger α plates coarsen at the expense of the smaller plates, which go into solution. In addition, on cooling from 1600 F, some of the β phase transforms to a fine α structure.

The first stage of HT II was designed to create α nucleation sites by bringing out α in the retained β and from α', to facilitate α globularization in the grains as well as at grain boundaries during the 1700 F treatment. The second stage (of HT II) heats the weldment 40 F below its β transus (1740 F) in the two-phase $\alpha + \beta$ region. The exception to this is the fusion zone of the Ti-64 filler metal welds where the composition is more α stabilized, having a higher β transus. This is shown schematically in Fig. 5 where the equilibrium amount of each phase present at any temperature is determined by the lever law. Thus, the fusion zone of weldments produced with Ti-64 filler metal should have more α present at 1700 F than the Ti-662 weldments, although optical metallography does not reveal this (Fig. 6).

The final 1350 F anneal coarsens the α platelets formed on cooling from 1700 F and is responsible for the duplex structure. This duplex α plate structure is apparent for both the Ti-64 and Ti-662 filler metal material (Fig. 7). The relative differences in fusion zone α content are not as obvious, as would be expected after the 1350 F anneal, although the Ti-64 filler welds do appear to have more α and slightly larger plates in some FZ regions. The α plates within grains and at grain boundaries are

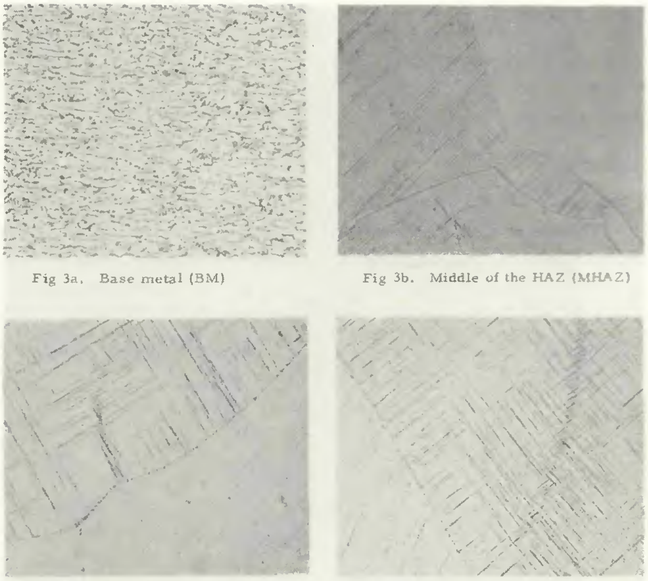

Fig 3a. Base metal (BM)
Fig 3b. Middle of the HAZ (MHAZ)
Fig 3c. Edge of the FZ (EFZ)
Fig 3d. Middle of the FZ (MFZ)

Fig. 3 — Microstructure of the GTA welded Ti-6Al-6V-2Sn using matching filler metal (all photos X500, reduced 54%)

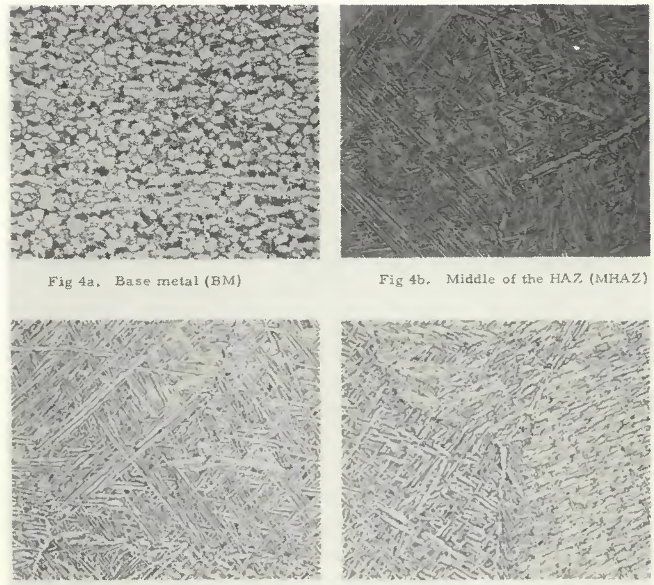

Fig 4a. Base metal (BM)
Fig 4b. Middle of the HAZ (MHAZ)
Fig 4c. Edge of the FZ (EFZ)
Fig 4d. Middle of the FZ (MFZ)

Fig. 4 — Microstructure of post weld heat treated (HT I) Ti-6Al-6V-2Sn weld using matching filler metal (all photos X500, reduced 54%)

considerably coarser than after HT I. Grain boundary α is necked down similar to the HT I case, although it is more obvious due to the greater plate thickness.

In the third heat treatment, (HT III), the alpha coarsening is achieved mainly during the first step, 1500 F. Since alpha coarsening is critically related to time at temperature, the alpha plate structure, Fig. 8, is considerably finer than after HT I or II. The grain boundary α network is continuous and thicker than the plates within the grains. There is little difference between the Ti-64 and matching filler metal FZ structure.

In summary, HT I and III produce a continuous grain boundary α network of similar thickness, while the plates within the grains are finer for HT III. The second heat treatment, (HT II), produces a coarser grain boundary network, necked in some cases, and a duplex α plate structure within the grains. The coarser plates are similar in size to the grain boundary network, while the finer background plates are the size of those produced by HT III.

Mechanical Properties

The results of the slow bend fracture toughness tests and tensile tests are presented in Tables 3 and 4. The correlation between W/A and K_Q for all the fracture toughness data is shown in Fig. 9. Since W/A and K_Q are obtained from the same test, each point represents corresponding W/A and K_Q values for the identical microstructure. Relative changes in each property with heat treatment correspond to the same microstructure change. While W/A continues to increase with α -plate thickness, K_Q

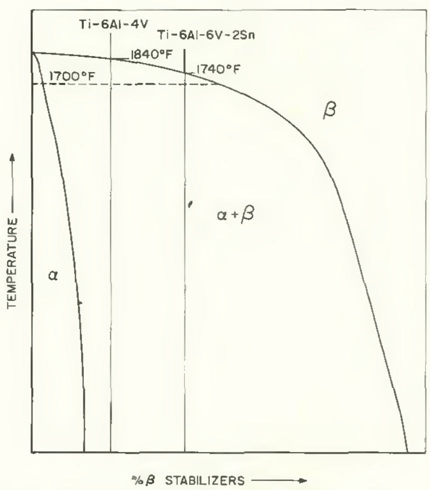

Fig. 5 — Schematic metastable phase diagram for Ti alloys

tends to level out. This plateau in K_Q was noted by Greenfield and Margolin (Ref. 9) for grain boundary alpha. The continued increase in W/A (crack propagation energy) with alpha thickness suggests that a large amount of energy is absorbed even after the crack has started to propagate.

Microstructures that will blunt a propagating crack tip are very important in the high toughness region. Synthesizing the correct microstructure will have a great effect on crack propagation energy. W/A is a more sensitive measure of toughness change for these two-phase materials because it better reflects the total microstructure encountered by the propagation of the crack during fracture. While HT I has substantially increased W/A from the as-welded condition, it is much less than HT II.

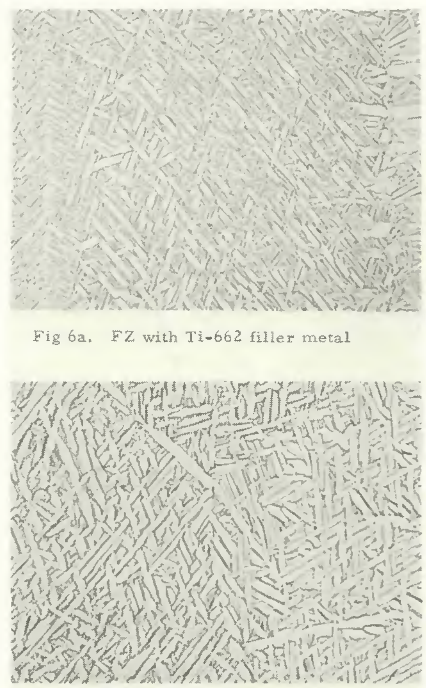

Fig 6a. FZ with Ti-662 filler metal
Fig 6b. FZ with Ti-64 filler metal

Fig. 6 — Microstructure of the Ti-6Al-6V-2Sn fusion zone (FZ) after heat treatment II B (1350 F — 6h, FC; 1700 F — 3h, FC) for matching filler metal and Ti-6Al-4V filler metal (X500, reduced 46%)

The ability of the matrix to retard crack propagation should be similar for these two cases, since their yield strengths are similar. The difference is due to the coarser alpha plate structure in the grains and at grain boundaries for the HT II condition (Figs. 4 and 7). The as-welded and HT III material has low fracture toughness because the matrix is too strong and the alpha plates are too thin to absorb

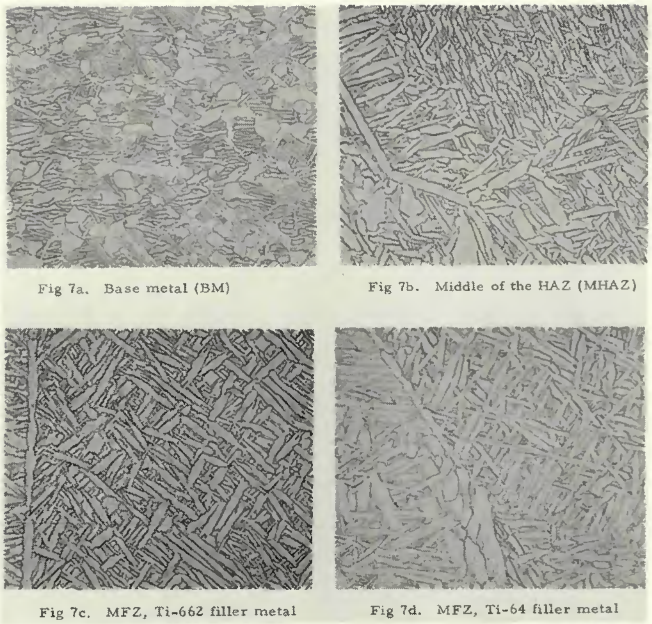

Fig. 7 — Microstructure of post weld heat treatment (HT II) Ti-6Al-6V-2Sn weld using matching filler metal and Ti-6Al-4V filler metal (all photos X500, reduced 54%)

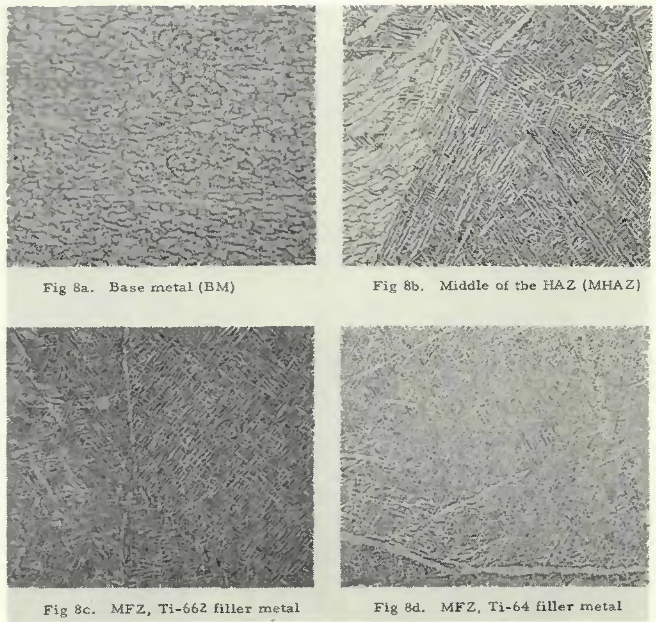

Fig. 8 — Microstructure of post weld heat treatment (HT III) Ti-6Al-6V-2Sn weld using matching filler metal and Ti-6Al-4V filler metal (all photos X500, reduced 54%)

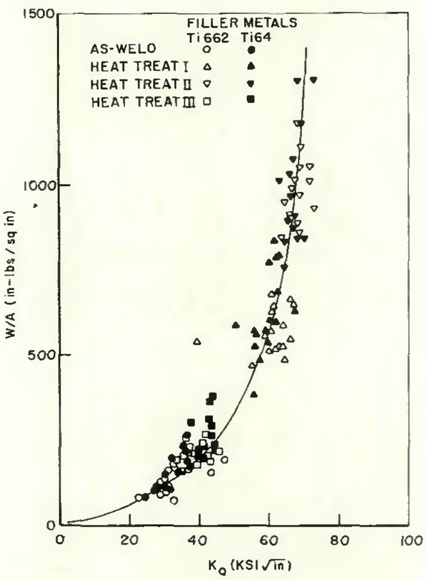

Fig. 9 — Correlation between W/A and K_Q of the welded Ti-6Al-6V-2SN fusion zone

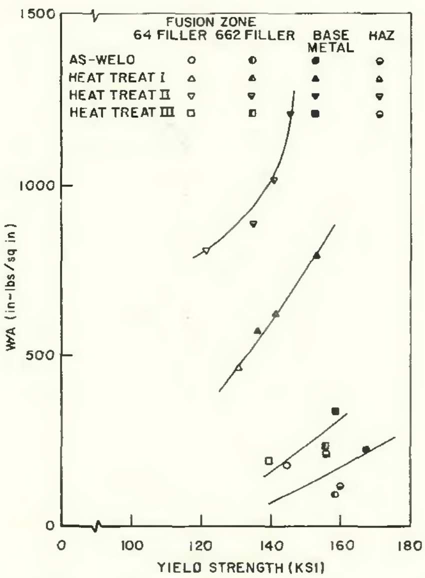

Fig. 10 — Effect of heat treatment on the toughness and strength of welded Ti-6Al-6V-2Sn

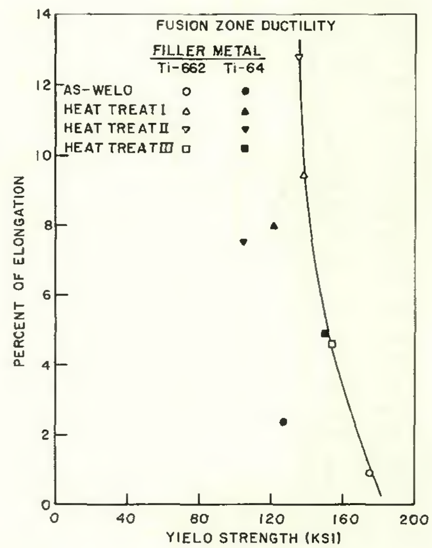

Fig. 11 — Effect of heat treatment on fusion zone ductility of welded Ti-6Al-6V-2Sn

energy and blunt an unstable crack tip. Once the fatigue crack becomes unstable the microstructure for materials in this region offers little resistance to its propagation.

The relationship between W/A and yield strength is shown in Fig. 10 for the as-welded and each postweld heat treated condition. The HAZ yield strengths were taken from the results of synthesized HAZ tests (Ref. 6). In each of the postweld heat treated conditions, fusion zones with matching filler metal have better properties, while the Ti-64 filler metal gives increased W/A at a lower yield strength in the as-welded fusion zone. For each heat treatment, the toughness and yield strength in the base metal is consistently better than that of the fusion zone. This is related to the difference in alpha phase morphology. It was further observed that base metal fracture toughness (W/A) was sensitive to rolling direction (not shown in the figure), which is believed due to the relative orientation between the crack front and grain texture.

The effect of each heat treatment on fusion zone ductility is presented graphically in Fig. 11. Along with Fig. 10, it indicates that HT II gives the best mechanical properties and those in the as-welded condition are the lowest. Heat treatment III, which was reported to be the optimum heat treatment for beta-treated extrusions, is the worst among the three heat treatments for a weld.

The fusion zones deposited with Ti-64 filler metal have lower fracture toughness, as well as yield strength, than that deposited with Ti-662 filler. This is consistent in all heat treatment conditions. It is well known that Ti-64 has better weldability than Ti-662. There is little noticeable difference in microstructures, although more alpha is expected. If anything, this should increase W/A. Therefore, the lower mechanical properties in the Ti-64 fusion zone are not explainable without further investigation.

Table 3 – Fracture Toughness Data

Property	Sample Condition	Base Metal ⊥ to RD	Base Metal ‖ to RD	Heat Affected Zone ⊥ to RD	Heat Affected Zone ‖ to RD	Fusion Zone (Ti-662 Filler) ⊥ to RD	Fusion Zone (Ti-662 Filler) ‖ to RD	Fusion Zone (Ti-64 Filler) ⊥ to RD	Fusion Zone (Ti-64 Filler) ‖ to RD
W/A $\frac{in.-lb}{in.^2}$	AW	229	178	116	125	96	87	181	171
	HT I	799	552	577	615	625	620	465	493
	HT II	1215	934	889	985	1020	1070	810	922
	HT III	340	206	214	222	242	227	196	201
K_Q (ksi in.)	AW	33.5	32.5	29.5	29.5	27.0	31.0	39.0	42.5
	HT I	61.5	62.0	60.0	63.5	57.5	62.5	56.5	60.5
	HT II	69.5	70.5	67.0	67.5	64.5	68.5	66.5	67.5
	HT III	41.5	36.0	41.5	41.0	41.0	40.5	37.0	38.5

⟷ Rolling Direction

Table 4 – Tensile Data

Property	Sample Condition	Base Metal ⊥ RD	Base Metal ‖ RD	Fusion Zone ⊥ RD(1)	Fusion Zone ‖ RD(2)	Transverse to Weld ⊥ RD(1)	Transverse to Weld ⊥ RD(2)	Transverse to Weld ‖ RD(1)	Transverse to Weld ‖ RD(2)
Y.S. (ksi)	AW	167	161	174	127	158	145	163	162
	HT I	153	152	138	121	141	130	145	145
	HT II	146	144	135	105	141	121	143	138
	HT III	158	154	154	150	156	140	159	159
UTS (ksi)	AW	175	168	182	170	172	171	175	175
	HT I	164	162	149	149	155	156	157	156
	HT II	159	160	143	140	153	148	154	148
	HT III	167	164	162	158	167	164	169	164
FS (ksi)	AW	230	202	184	174	192	173	176	176
	HT I	193	209	170	171	180	182	187	192
	HT II	185	201	173	166	197	186	182	189
	HT III	221	225	172	169	177	182	178	174
% Elong.	AW	16.2	15.2	0.9	2.4	7.1	3.4	3.3	4.6
	HT I	15.0	15.1	9.5	8.0	6.0	4.2	8.0	5.3
	HT II	13.8	16.6	12.8	7.5	8.3	4.4	7.3	6.5
	HT III	15.8	17.0	4.6	4.9	8.8	4.6	7.0	2.4

(1) Ti-662 Filler Metal

(2) Ti-64 Filler Metal

⟷ Rolling Direction

Conclusions

1. It is possible to weld Ti-6Al-6V-2Sn sheet with good ductility and fracture toughness by the use of proper postweld heat treatment.

2. Fracture toughness and ductility are related to the microstructure in the weld; the coarser the alpha plates, the better the mechanical properties.

3. Matching filler metal gives better mechanical properties than Ti-6Al-4V for each postweld heat treated condition. The reverse is observed in the as-welded condition.

4. A triplex heat treatment (HT II) gives superior mechanical properties with excellent ductility (12%).

5. W/A is a more sensitive measure of toughness for these two-phase alloys with coarse alpha plates.

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