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Microstructure and Mechanical Properties of Electroslag Welds in Ti-6Al-4V Alloy

Investigation points to large prior beta grain size and lamellar alpha + beta microstructure as causes of ductility losses

BY S. J. CHEN AND J. H. DEVLETIAN

ABSTRACT. The structure and mechanical properties of consumable guide electroslag welds in 50-mm-thick Ti-6Al-4V plate are evaluated. In this alloy, the tensile strength and hardness values of the welds match the base metal values. But the tensile elongation and CVN toughness values of the welds are substantially lower than the base metal values. These ductility losses in the welds are correlated to the large prior beta grain size and the coarse lamellar alpha + beta microstructure produced by the high heat input that is characteristic of the electroslag welding process.

Introduction

The alpha + beta Ti-6Al-4V alloy has been widely used for various structures in the aerospace and marine industries. This alloy has excellent corrosion resistance and a good combination of strength and toughness. However, the application of thick-section titanium plates has been limited by the high cost of welding titanium by inefficient joining processes. For example, due to its unique physical properties, titanium cannot be welded by conventional GMAW, FCAW or SAW processes.

Consumable guide electroslag welding (ESW) has long been recognized as the most cost-effective method to weld thick-section steel and stainless steel plates. And for the first time outside the Soviet Union, the consumable guide ESW process has been successfully applied to joining thick-section titanium alloy plates (Refs. 1, 2). Complete joint penetration welds can now be made on thick titanium plates in a single pass at a travel speed in excess of 25 mm/min (1 in./min).

The mechanical properties of alpha + beta titanium alloys, such as Ti-6Al-4V, strongly depend on their interstitial element content, prior beta grain size and microstructure (Refs. 3–7). Although a great deal of work has been published in the Soviet literature (Refs. 8–11), the effect of high heat input welding processes such as ESW on the structure and mechanical properties of thick-section Ti-6Al-4V alloy has not been fully studied.

Since ESW of titanium alloys is new in the U.S.A., the microstructures and mechanical properties of welds made by this process need to be evaluated. Thus, the objective of this paper is to present an assessment of metallurgical structures and mechanical properties of welds made by consumable guide ESW on alpha + beta Ti-6Al-4V alloy.

KEY WORDS

Microstructure
Mechanical Properties
Electroslag Welds
Ti-6Al-4V Alloy
Ductility Losses
Beta Grain Size
Lamellar Alpha/Beta
Tensile Strength
ESW
Fracture Fractograph

Experimental Procedure

Materials used in this investigation included: 1) 50-mm (2-in.) thick plate of Ti-6Al-4V alloy, which was received in the beta-annealed condition, and 2) filler metal closely matching the composition of the plate as shown in Table 1. The interstitial

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Table 1—Chemical Compositions (wt-%) of 50-mm-Thick Titanium Alloy Plate and Matching Filler Metal

	Al	V	O	N	H
Ti-6Al-4V, 50-mm-thick plate	6.32	4.15	0.215	0.021	0.004
Ti-6Al-4V, 3.2-mm-diameter filler metal wire	5.95	4.15	0.143	0.008	0.001

Table 2—Optimized Welding Conditions for Consumable Guide ESW of 50-mm-Thick Ti-6Al-4V Alloy

Power supply	AC constant voltage
Voltage	28–30 V
Current	1000–1100 A
Filler metal	Single 3.2-mm-diameter wire
Consumable guide tube	12.7 × 38 × 610 mm
Flux	High-purity CaF_2
Root opening	32 mm
Deposition rate	11.1 kg/h
Shielding gas	Argon over slag

element levels of the Ti-6Al-4V filler metal were lower than the Ti-6Al-4V plate. The consumable guide tubes were machined and joined together by GTA welding from a 12.7-mm (½-in.) Ti-6Al-4V plate with similar chemistry as the 50-mm (2-in.) thick base metal plate. Therefore, in consideration of weld metal chemistry, the consumable guide tube was counted as the base metal.

Due to the reactivity of titanium, the interstitial element contamination during ESW was always a concern. In this study, the welds were protected by using high-purity CaF_2 flux (99.99999% pure) and argon shielding gas over the molten slag, as shown in Fig. 1. The optimum conditions for consumable guide ESW of these titanium plates were those developed in Ref. 1 and are given in Table 2. For comparison, Ti-6Al-4V welds were made with both reagent grade CaF_2 flux (99.9% pure) and the high-purity CaF_2 flux to see the effect of flux purity on the resulting microstructures and properties. Approximately 0.5-mm (0.02-in.) thick specimens were extracted from specific locations within the weld, heat-affected zone (HAZ) and base metal from the midsection of each weld for chemical analyses.

Mechanical property tests included tension, CVN (Charpy V-notch) toughness and microhardness testing. Transverse-to-weld tension specimens having a 12.7-mm (0.5-in.) diameter were machined per MIL-STD-418 to assess the weld joint properties. Tension tests were carried out at a cross head speed of 0.041 mm/s (0.10 in./min). Since the weld width was as wide as the 50 mm (2 in.) gauge length of the transverse-to-weld tensile specimens, the values of % elongation (%EL) and % reduction of area (%RA) were actually property measurements of the weld metal itself.

Metallographic specimens were prepared by polishing and etching in a solution containing 200 mL H_2O, 30 g oxalic acid, 2 mL HF, and 5 g $Fe(NO_3)_3 \cdot 9H_2O$. This etchant was used to reveal the grain structure of the weld, while Kroll's reagent was used to reveal the general microstructure. In addition, fractographic studies of tension and CVN toughness specimens were carried out by scanning electron microscopy (SEM).

CVN toughness specimens were also extracted from the weld metal and HAZ. After the welded specimens were macroetched to reveal grain structure, the location of each CVN toughness specimen could then be accurately machined out of the weld, as shown in Fig. 2. Macroetching also permitted precise placement of the notch (using a broaching technique) at different locations in the weld metal and HAZ. The specimens were then machined to final dimensions according to ASTM Specification E23. The CVN toughness Specimens were tested at three different temperatures: 0°, 25° and 100°C (32°, 77° and 212°F).

Specimens for the microhardness test were taken from the same location as were the specimens for the transverse-to-weld microstructural studies. Microhardness readings were taken with a Knoop indenter using a 500-g (1.1-lb) load. Measurements were made 1 mm (0.04 in.) apart starting from the weld center to the base metal. Five measurements were taken at each location across the weld along the mid-thickness plane of the 50-mm (2-in.) thick base metal plate.

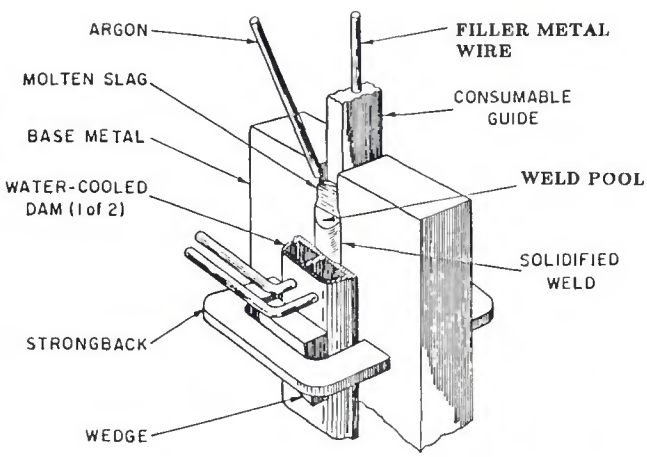

Fig. 1—Schematic view of the consumable guide ESW process for 50-mm-thick titanium plates using a single filler metal wire fed through a plate guide.

Results

Two sets of experimental conditions were utilized to assess the structure and mechanical properties of electroslag welds made in 50-mm (2-in.) thick plates using the optimum welding conditions given in Table 2. These experimental conditions included:

1) ESW Ti-6Al-4V plates with high-purity CaF_2 flux.

2) ESW Ti-6Al-4V plates with reagent grade CaF_2 flux. The structure/property relationships were developed for each of the experimental conditions above.

The transverse-to-weld macrostructures of both welds were identical, the typical macrostructure of the Ti-6Al-4V weld using reagent grade CaF_2 flux is shown in Fig. 3. From this, it was evident that the weld was symmetric with respect to the weld axis. Upon traversing the weld from the weld center into the base metal, the unique manifestations of the prior beta grain macrostructure could be classified by the three different zones in each weld: 1) columnar grain weld metal, 2)

HAZ and 3) the unaffected base metal (BM). Although the weld center macrostructure in Fig. 3 appeared to be equiaxed in the plane of the photograph, the entire weld metal structure in three dimensions was actually fully columnar.

Since the microstructures of the electroslag welds using high-purity and reagent grade CaF_2 fluxes were virtually identical, the microstructural profile of only the Ti-6Al-4V weld using reagent grade CaF_2 flux is illustrated in Fig. 4. The weld metal microstructures contained grain boundary alpha, lamellar alpha + beta structure, and Widmanstätten alpha + beta colonies in the grain center. The HAZ microstructures contained grain boundary alpha, lamellar alpha + beta structure, and basket-weaved Widmanstätten alpha + beta structure in the grain center. The base metal had the typical Widmanstätten alpha + beta colony structure with grain boundary alpha. The notable difference was that the alpha plate thickness was finest in the HAZ, medium in the weld metal and thickest in the BM—Fig. 4.

The amount of interstitial elements emanating from the flux, filler metal and base metal additively contributed to the resulting interstitial element content of the weld metal. Thus, the purity levels of the filler metal and flux were closely monitored. The weld metal of the Ti-6Al-4V weld made with high-purity CaF_2 flux always developed lower interstitial element contents than the weld metal made with reagent grade CaF_2 flux—Fig. 5.

The transverse-to-weld tension specimens for both welds failed in the weld metal, primarily because of geometric effects. Virtually all of the gauge length of the transverse tension specimen contained weld metal only. The tensile and yield strengths of the weld metal for both welds were always slightly greater than the base metal values as shown in Fig. 6. However, the reduction in area (%RA) and percent elongation (%EL) for the weld metal of both welds were around 50% lower than the values for the base metals. Also, the weld metal of Ti-6Al-4V using reagent grade CaF_2 flux exhibited slightly lower %RA and %EL values than the weld metal using high-purity CaF_2 flux—Fig. 6.

Transverse microhardness profiles of Ti-6Al-4V welds using reagent grade CaF_2 flux revealed that the hardness values were highest in the weld metal, medium in the HAZ and lowest in the base metal, as shown in Fig. 7A. However, from Fig. 7B the hardness profile across the Ti-6Al-4V weld using high-purity CaF_2 flux showed that the hardness values were the same in the weld metal and the HAZ, but lower in the BM.

The CVN toughness values at 0°, 25°, and 100°C (32°, 77° and 212°F) across the welds exhibited the same trend, so only the 0°C values are compared in Fig. 8. In general, the weld metal for both Ti-6Al-4V electroslag welds always had lower CVN toughness values than did the BM and HAZ. The CVN toughness values across the Ti-6AL-4V weld using high-purity CaF_2 flux were slightly higher than the corresponding values of the Ti-6Al-4V weld using reagent grade CaF_2 flux.

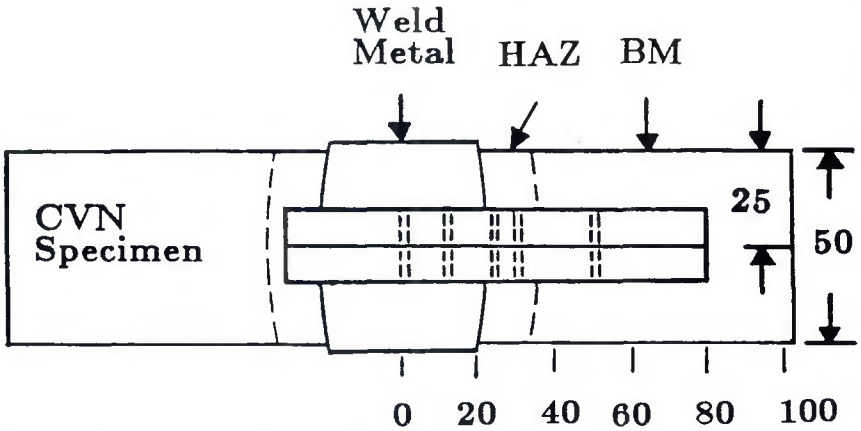

Fig. 2 — Specimen location for CVN toughness blanks taken from electroslag welds. The blanks were etched and notched in the appropriate location (dotted lines), and then machined to final dimensions. (All units in mm.)

Since the fractographs of broken CVN toughness specimens of both welds were similar, only the fractographs of the weld using reagent grade CaF_2 flux are shown in Fig. 9. Fractographs in Fig. 9A showed that the fracture surface of weld metal specimens exhibited a transgranular appearance, while the fracture surfaces of the HAZ and BM specimens revealed a more granular appearance due to substantial crack branching. At higher magnifications, all the fracture morphologies displayed an almost entirely ductile dimple fracture mixed with small regions of quasi-cleavage fracture as shown in Fig. 9B. The occasional occurrence of quasi-cleavage fracture was a result of the crack passing through the prior beta grain boundary alpha phase.

Discussion

The large prior beta grain size of the weld metal macrostructure shown in Fig. 3 is due to the very high heat input (75 kJ/mm) used to make these welds. The symmetry in macrostructure about the weld axis occurs because of the symmetric placement of the base metal plates and cooling shoes, which are the major heat sinks in the ESW process. Since the thermal diffusivity values for Ti alloys are rel-

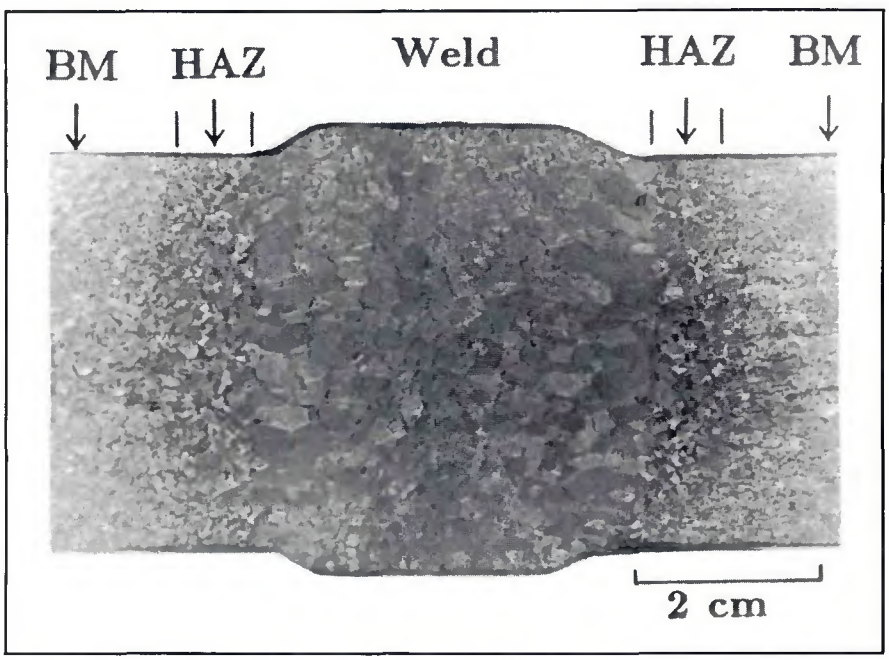

Fig. 3 — Transverse-to-weld section macrostructure of Ti-6Al-4V electroslag weld made with reagent grade CaF_2 flux.

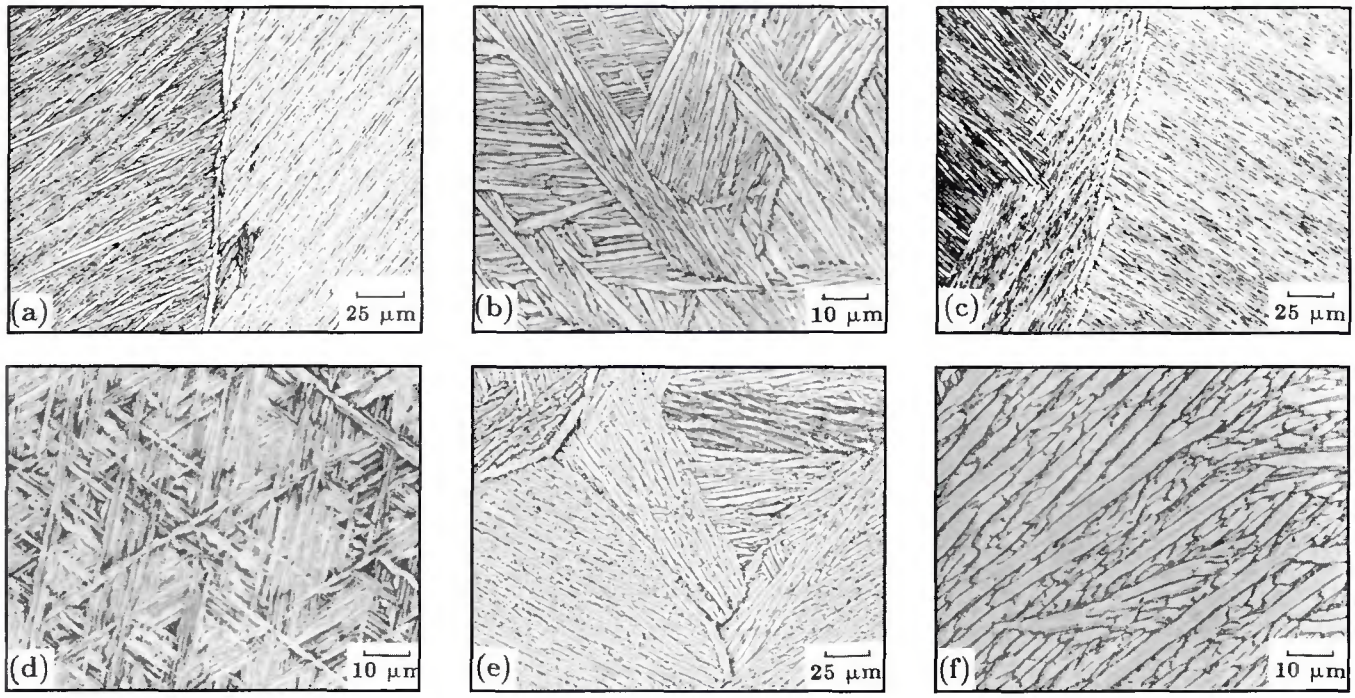

Fig. 4 — Microstructure of Ti-6Al-4V weld made with reagent grade CaF_2 flux. A, B — Weld metal; C, D — HAZ; E, F — unaffected base metal.

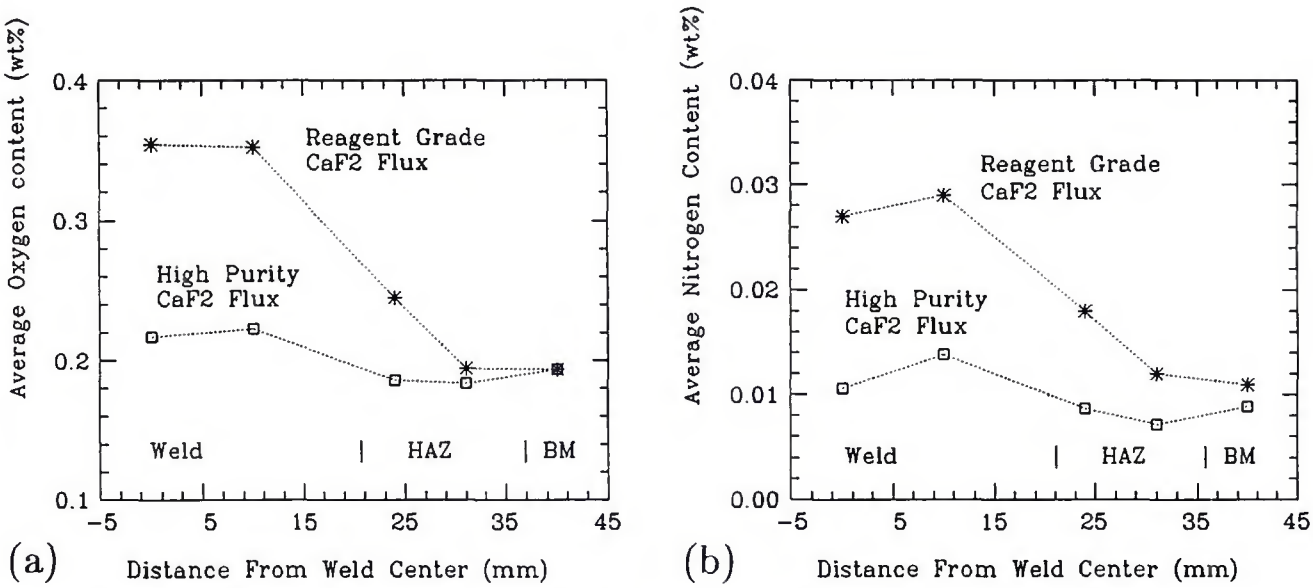

Fig. 5 — Interstitial element profile across Ti-6Al-4V electroslag welds. A — Oxygen; B — nitrogen.

atively low compared to steel, aluminum and other structural metals, the HAZ is relatively large.

Unlike weld metal made with the GTAW process, where martensite is commonly observed in the microstructures of Ti-6Al-4V alloy (Ref. 12), no martensite was observed in any of the electroslag welds. This is due to the substantially slower cooling rate resulting from the high heat input used for the ESW process.

The beta-to-alpha transformation in Ti alloys has been well documented (Refs. 12–17). The weld metal had coarse microstructures similar to that of a small casting except that the prior beta grains of the HAZ continued to grow into the weld metal by epitaxial growth. The threefold increase in grain width in the weld metal (compared to the coarse-grained HAZ) was a result of competitive grain growth. Upon cooling from ESW, the substructure within the large beta grains has been shown by Damkroger, *et al.* (Ref. 13), to develop in three distinct steps:

1) The alpha phase first grew heterogeneously from the prior beta grain boundary and advanced by a planar interface.

2) The planar interface was disrupted due to the undercooling and the lamellar-type alpha plates continuing to grow into the prior beta grain with the retained beta phase between them.

3) At the grain center, some new nuclei formed due to further undercooling and subsequently grew and interlocked with each other to form the Widmanstätten-type alpha + beta colony structure.

In the HAZ, the first two steps were similar, only the microconstituents were finer than those in the weld metal. During the last step in the HAZ, the basket-weave Widmanstätten structure developed because many new nuclei formed and grew

due to the higher undercooling produced by the relatively fast cooling rate in the HAZ.

In the Ti-6Al-4V weld made with the high-purity CaF_2 flux, the weld metal contained approximately the same interstitial element content as did the base metal—Fig. 5. This meant the weld was well protected from interstitial element contamination during the ESW using the procedures described earlier. The Ti-6Al-4V weld using reagent grade CaF_2 flux contained 100% more oxygen and 200% more nitrogen than did the base metal—Fig. 5. This showed that the use of reagent grade CaF_2 flux was inadequate to protect the molten metal from interstitial element contamination.

Increasing prior beta grain size will decrease both tensile strength and ductility (Ref. 18). Also, raising the interstitial element content, particularly oxygen, is known to increase the tensile strength while decreasing tensile ductility (Refs. 19, 20). Also, reducing the alpha plate thickness will increase both tensile strength and ductility (Refs. 4, 5, 21). The tensile strength values of the weld metal of both high-purity and reagent grade CaF_2 flux electroslag welds were slightly higher than the base metal values as shown in Fig. 6. This is a combined result of larger prior beta grain size, higher interstitial element content and finer alpha plate thickness in the weld metal compared to the base metal.

The values of %RA and %El of both Ti-6Al-4V weld metal specimens in Fig. 6 were approximately 50% lower than the corresponding values of the base metal, in spite of the fact that the weld metal (made with high-purity CaF_2 flux) had the same levels of interstitial element content as the base metal—Fig. 5. It is important to note that %RA and %El values obtained from transverse-to-weld tensile specimens of electroslag welds are actually weld metal properties because the weld metal width covered the entire 50-mm (2-in.) gauge length. All-weld-metal specimens were also tested, and the results were similar to those transverse tensile results given in Fig. 6. Thus, the large prior beta grain width of 3–5 mm (0.12–0.20-in.) in the weld metal was responsible for the lower tensile ductility than that developed in the base metal. Also, the weld metal values of %RA and %El for the Ti-6Al-4V welds made with reagent grade CaF_2 flux were slightly lower than those for the Ti-6Al-4V weld made with high-purity CaF_2 flux—Figs. 5, 6. This shows that interstitial element contamination can further decrease tensile ductility of the weld metal.

It is well established that the microhardness values of titanium alloys increase with increasing interstitial element content and decreasing alpha plate thickness (Ref. 20). In the weld made with reagent grade CaF_2 flux, the weld metal possessed both higher interstitial element content and finer alpha plate thickness than did the BM. The HAZ of this weld possessed a finer alpha plate

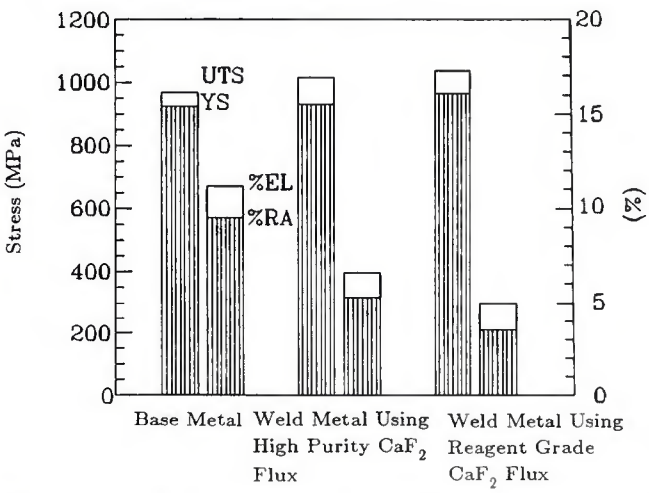

Fig. 6—Comparison of tensile properties of the weld metal with the base metal in Ti-6Al-4V welds made by ESW process.

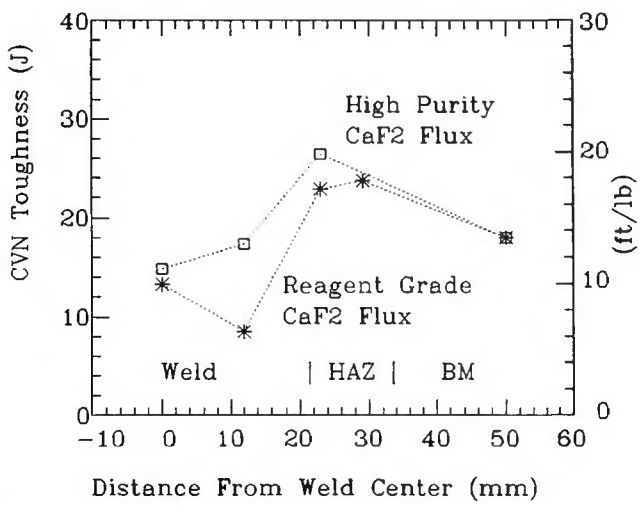

Fig. 8—CVN toughness profiles at 0°C (32°F) across Ti-6Al-4V electroslag welds.

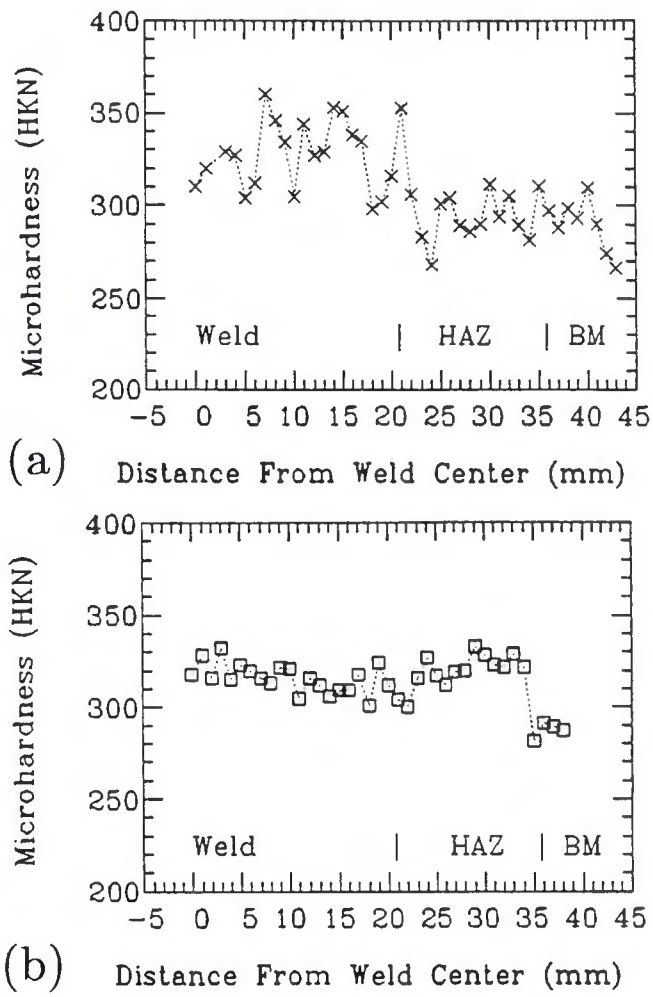

Fig. 7—Transverse microhardness profiles across Ti-6Al-4V electroslag welds made with: A—Reagent grade CaF_2 flux; B—high-purity CaF_2 flux.

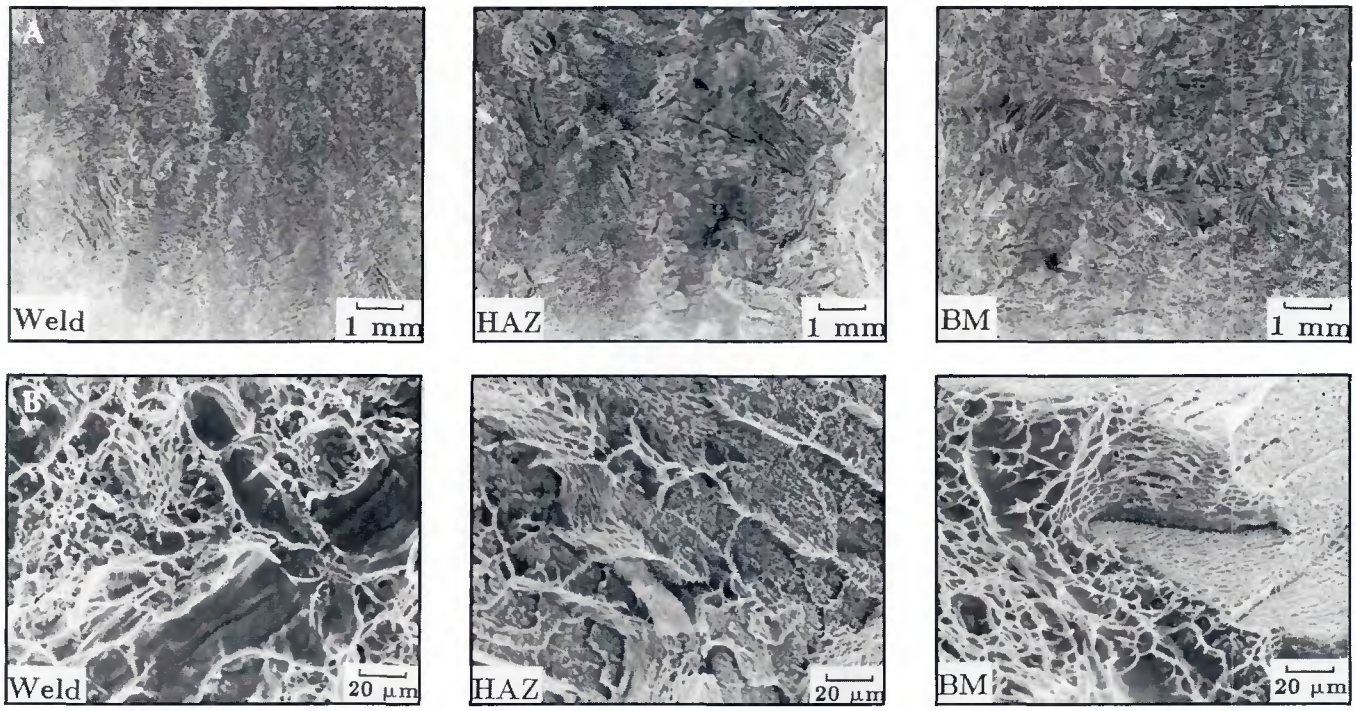

Fig. 9 — Fractographs of broken CVN toughness specimens taken in the weld metal, HAZ and BM of electroslag welds made on Ti-6Al-4V using reagent grade CaF_2 flux. A — Low magnification; B — high magnification.

thickness than did the BM. Therefore, the microhardness values were highest in the weld metal, medium in the HAZ and lowest in the BM, as shown in Fig. 5. In welds made with high-purity CaF_2 flux, the interstitial element contents were uniform (Fig. 5); therefore, the microhardness values are only affected by the alpha plate thickness. The microhardness values across the weld are similar in the weld and HAZ, but lower in the BM as shown in Fig. 7B. This is because the alpha plate thickness is greater in the BM than in either the weld metal or the HAZ — Fig. 4.

The 0°C (32°F) CVN toughness profiles in Fig. 8 show a decreasing trend in toughness from BM toward the weld center. Conversely, the prior beta grain size increases from around 0.5 mm (0.02in.) in the BM to 3–5 mm (0.12–0.2-in.) in the weld center, as shown in Fig. 3. The interstitial element content across the Ti-6Al-4V weld made with high-purity CaF_2 flux was uniform — Fig. 6. These results strongly indicate that the CVN toughness loss in the weld metal is mainly caused by the large prior beta grain size produced by the high-heat-input ESW process. By comparing the CVN toughness curves of the welds made with high-purity vs. reagent purity CaF_2 fluxes, the weld made with high-purity CaF_2 flux had only slightly higher CVN toughness values (Fig. 9), in spite of its lower interstitial element content — Fig. 5. Therefore, the effect of interstitial element content on the loss of CVN toughness values in the weld metal is secondary compared to the prior beta grain size effect.

The CVN toughness values for the HAZ of both welds were slightly higher than the corresponding BM values. This might be explained by the finer alpha + beta microstructure in the HAZ than the BM (Fig 4), because the finer microstructure has a greater alpha/beta interphase area to absorb more energy when a crack propagates through them.

In the base metal and HAZ of both welds, the crack front branched along the prior beta grain boundaries and the inter-Widmanstätten colony boundaries as shown in Fig. 9B. When branching occurred, the crack required more energy to propagate so the CVN toughness value increased compared to fracturing without branching. In the weld metal, it was not the grain boundary alpha film surrounding the coarse prior beta grain causing the loss of CVN toughness because, if it were, the weld metal would fracture intergranularly rather than transgranularly as shown in Fig. 9A. It is proposed that the coarse prior beta grain size and the large area of lamellar alpha + beta microstructure (Fig. 4A) provide the path for the crack to propagate long distances without branching. This is the reason why the weld metal fractured transgranularly and had lower CVN toughness values than did the HAZ and BM.

In summary, the mechanical properties of the weld metal and HAZ were directly related to interstitial element content, prior beta grain size and microstructure. The large prior beta grain size and the lamellar alpha + beta structure associated with it have the most detrimental effect on the toughness of Ti-6Al-4V electroslag welds.

Conclusions

From the consumable guide ESW of 50-mm (2-in.) thick plates of Ti-6Al-4V alloy, the following are concluded:

1) Due to the high heat input of the ESW process, the weld metal and HAZ possess large prior beta grain sizes. The weld metal and HAZ microstructures are similar to that of the beta-annealed and slow-cooled base metal microstructure.

2) The losses of tensile ductility and CVN toughness in the weld metal are mainly caused by the coarse prior beta grain size and secondarily by the interstitial element contamination.

3) The large area of lamellar alpha + beta structure within the coarse prior beta grains is responsible for the transgranular fracture occurring in the weld metal. Because of the smaller prior beta grain size and the finer alpha/beta colony structure, the HAZ and BM exhibit a more granular fracture due to increased crack branching.

Acknowledgments

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Interpretive Report on the Mechanical Properties of Brazed Joints
By M. M. Schwartz

This report summarizes the mechanical properties, brazing procedures and testing of materials, such as aluminum, beryllium, copper, steel, nickel, superalloys, reactive metals, ceramics and graphite. Over 120 references are included in this interpretive report.

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WRC Bulletin 341
February 1989

A Preliminary Evaluation of the Elevated Temperature Behavior of a Bolted Flanged Connection
By J. H. Bickford, K. Hayashi, A. T. Chang and J. R. Winter

This Bulletin consists of four Sections that present a preliminary evaluation of the current knowledge of the elevated temperature behavior of a bolted flanged connection.

Section I—Introduction and Overview, by J. H. Bickford; Section II—Historical Review of a Problem Heat Exchanger, by J. R. Winter; Section III—Development of a Simple Finite Element Model of an Elevated Temperature Bolted Flanged Joint, by K. Hayashi and A. T. Chang; and Section IV—Discussion of the ABACUS Finite Element Analysis Results Relative to In-the-Field Observations and Classical Analysis, by J. R. Winter.

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