Properties and Structure of Welded Joints in Ti-3Al-2.5V Hydraulic Tubing

Weldability of the alloy, as well as mechanical properties and microstructure are examined using EB and GTA welding

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ABSTRACT. Ti-3Al-2.5V hydraulic tubes were cold-worked 55 percent and annealed at 575, 600 and 625 C. Tube specimens were GTA and EB welded and the effect of welding on the tensile properties, mechanical anisotropy and structure was evaluated. GTA welded specimens were tensile tested at room temperature and 120 C and EB welded specimens at RT.

The weldability of Ti-3Al-2.5V is as good as for unalloyed titanium. GTA welded joints display lower yield and tensile strength than the base metal. This gives transformation zone failures. The elongation of GTA welded joints is less than that of the base metal. This is caused by deformation localized in the transformation zone. EB welded joints exhibit base metal failures. This shows that the tensile strength of the weld metal and the HAZ is higher than that of the base metal. The elongation of EB welded joints is less than that of the base metal, which is caused by deformation localized in the base metal. Knoop hardness yield loci of the base metal and the transformation zone can be used to predict where welded Ti-3Al-2.5V tubes will begin to deform plastically under different stress ratios and to estimate where failure will occur. EB welding gives a considerably finer primary β grain size than GTA welding. Upon cooling the β phase is transformed into α phase and hexagonal martensite.

Introduction

The combination of high ductility, high strength and structural stability at high temperature has made the $\alpha + \beta$ titanium alloy Ti-3Al-2.5V well suited for hydraulic tubing in modern aircraft. Brazing is the most frequently used method for joining couplings to tubes. In the early development of brazing alloy filler metals, ductility problems were encountered owing to the formation of brittle intermetallic compounds (Ref. 1). These ductility problems have been overcome to some extent by the development of filler metals of Ti-Zr-Be and Ti-Cu-Ni types (Ref. 2). However, more and more stringent requirements for ductility and strength of tube connections have caused increased interest in welding as a joining method in recent years.

No reports on Ti-3Al-2.5V welding can be found in the available literature. But, in general, low-alloy $\alpha + \beta$ titanium alloys are considered as being readily weldable if protected against absorption of oxygen and nitrogen from the ambient atmosphere. This makes the gas tungsten-arc (GTA) and the electron beam (EB) methods most suitable. The closely related alloy Ti-6Al-4V has been both GTA and EB welded with relatively good results (Refs. 3-5). GTA welding of sheet material gave a pronounced mechanical anisotropy (Ref. 3). When the weld was perpendicular to the rolling direction, the weld metal was as strong as the parent metal and there was plastic deformation of the latter even if the final failure was in the weld. However, when the welding and rolling directions were parallel, there was no deformation of the base metal before failure occurred in the weld with little overall elongation. In

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tests of EB welded, soft annealed plate and sheet material, all failures occurred in the base metal (Refs. 4-5).

The purpose of this work is to examine and compare the GTA and the EB welding processes and to clarify the weldability of the alloy Ti-3Al-2.5V. The program also contains an investigation of the effect of welding on the tensile properties, mechanical anisotropy and structure of Ti-3Al-2.5V hydraulic tubing.

Material

Ti-3Al-2.5V hydraulic tubes of standard production with 12.7 mm outer diam and 0.85 mm wall thickness were chosen for the experiments. The test material had the following chemical composition in weight percent: Al 3.0, V 2.5, Fe 0.086, C 0.018, H 0.0007, N 0.006, O 0.067, Ti bal.

In the final rolling operation the tubes were cold rolled 55 percent. Tubes for the welding trials, identified as A, B and C, were then final-annealed for one hour at three temperatures.

> Base metal of tube A was stress relieved at 575 C
> Base metal of tube B was partially recrystallized at 600 C
> Base metal of tube C was partially recrystallized at 625 C

The temperature range for partial recrystallization in Ti-3Al-2.5V is 575-660 C after 55 percent cold working.

Table 1 — Welding Data(a)

Welding method	Welding current A	Voltage V	Welding speed m/s	Heat input J/m	Welding chamber pressure Pa
GTA	18	8.5	1.6×10^{-3}	96×10^{-3}	1.0×10^{5}
EB	2.1×10^{-3}	100×10^{3}	40.0×10^{-3}	13×10^{-3}(a)	1.3×10^{-2}

(a) Includes welding 2.5 turns

Table 2 — Results of tensile testing at RT of tube B and of GTA and EB welded strip specimens in the as-welded condition, cut from the tube

Weld process	Specimen type	No. of tests	Test location	Yield(a) strength (b) N/mm²	Tensile strength (b) N/mm²	Elongation in 15 mm %	Failure location
—	tube	7	base metal	617 ± 11	756 ± 9	17.2 ± 0.5	—
GTAW	strip	19	weld joint	613 ± 15	726 ± 14	12.6 ± 0.9	Transformation zone
	strip	23	weld metal	—	792 ± 31	40 ± 7(c)	—
EBW	strip	4	weld joint	636 + 16	761 ± 8	14.0 ± 2.8	base metal

(a) 0.2% offset
(b) Average value and standard deviation
(c) Elongation of 20mm dia hole

Table 3 — Results of tensile testing at 120 C of tubes and of GTA welded specimens in the as-welded condition.

Specimen identity	Test(a) location	Yield(b) strength, average N/mm²	Tensile strength, average N/mm²	Elongation (%) in 15 mm	Elongation (%) in 50 mm	Elongation (%) of 2.0 mm diam hole	Failure location
Tube A	base metal	555	695	—	14.4	—	—
Tube A	weld joint	524	616	11.3	4.3	—	TZ(c)
Tube A	weld metal	—	667	—	—	54	—
Tube B	base metal	534	665	—	16.1	—	—
Tube B	weld joint	515	620	12.4	5.3	—	TZ
Tube B	weld metal	—	668	—	—	50	—
Tube C	base metal	504	620	—	16.9	—	—
Tube C	weld joint	490	598	16.7	8.9	—	TZ
Tube C	weld metal	—	652	—	—	53	—

(a) 3 specimens each of base metal, welded joint and weld metal from each tube
(b) 0.2% offset
(c) TZ = Transformation zone

GTA welding

GTA welding experiments were made in a closed welding chamber where the samples were manipulated from the outside. After evacuation to a pressure of 10^{-3} Pa (about 10^{-5} torr), the chamber was refilled to atmospheric pressure with argon containing not more than 0.01 % of impurities. During welding new argon gas was supplied at a rate of 10 dm³/min. A gas-cooled torch with a thoriated tungsten electrode of 1 mm dia and a gas cup with an inside diameter of 9 mm were placed on a fixed mounting in the welding chamber. The tube specimens were set up horizontally in a chuck, centered against a steady rest and rotated at constant speed during the welding operation. The joints were prepared by facing the tube ends. The welding was carried out in a square groove without root opening and without filler metal.

Preliminary trials were made to determine suitable welding data as given in Table 1. These trials also showed how to clean the tubes prior to welding. When the tubes were washed only with acetone, x-ray radiography after welding revealed occasional (some two or three) pores in the welds. By contrast, completely homogeneous welds were obtained when the tubes were pickled before welding in a solution of 35 % HNO_3 + 5 % HF + 60 % H_2O. Consequently, the experimental material for GTA welding was cleaned by the latter means prior to welding.

During welding the tubes were rotated 1 1/3 turns. In the overlap area the amperage was eased down from the nominal welding current to about 7A, after which the arc was extinguished.

Both top and root side of all the welds displayed a bright surface. This is characteristic of titanium welds which have been completely protected from oxygen and nitrogen. Like unalloyed titanium, Ti-3Al-2.5V has extremely good flow, which makes it possible to obtain completely smooth, flush welds without undercuts. The height of the root reinforcement was about 0.05 mm. The width of the weld was measured as about 3 mm on the top side and about 2 mm on the root side.

The welded tube specimens were examined for cracks and pores by means of dye penetrant tests and x-ray radiography. All specimens were found to be sound.

EB Welding

The EB welding was carried out with a Zeiss ES 1002 machine. This machine is of the high voltage high vacuum type, with maximum power of 3 kW at 150 kV accelerating voltage and 20 mA welding current.

Joint preparation, setup and rotation of the tubes were carried out in the same way as in the GTA welding. The welding data were determined by preliminary trials, Table 1. These trials also showed that homogeneous welds were obtained both after cleaning in acetone followed by rinsing in ethanol and after pickling in the same solution as used before GTA welding. Thus, the test material for EB welding was welded after being cleaned in acetone.

The electron beam was on for a period corresponding to 2-2.5 turns of welding. As a result of the high welding rate, 1 turn per second, the heat input of the second turn was added to the heat input of the first. For this reason, the heat input was multiplied by 2.5 as reported in Table 1.

The EB welds also exhibited a bright, smooth surface. The reinforcement on the top of the welds was negligible and the height of the root reinforcement was about 0.1 mm. The width of the weld was about 1 mm on the top side and about 0.4 mm on the root side. All welds were free from cracks or pores.

Tensile Testing

Tensile specimens were either full section tubes or 6 mm wide strips cut from the tubes. The tensile strength of the GTA weld metal was determined after drilling and reaming a hole of 2 mm dia in the weld metal. This was done in order to concentrate the stress in the weld metal. Apart from this, the welds were not given any kind of treatment prior to tensile testing.

The results of tensile testing at room temperature of base metal from tube B and of GTA and EB welded specimens from tube B are summarized in Table 2. The yield strength and the tensile strength of the GTA welded joints are lower than the yield and tensile strength of the base metal. On the other hand, the tensile strength of the GTA weld metal is higher than that of the base metal. Failure occurred in the transformation zone. This kind of failure shows that the transformation zone constitutes the weakest part of the as-welded specimen. The overall elongation of the GTA welded joints is less than that of the base metal, decreasing from 17 to about 13 percent. The decrease in elongation is caused by deformation localized in the transformation zone.

The failures in EB welded specimens were all obtained in the base metal far from the fusion boundary. The site of failure shows that the tensile strength of the weld metal and the HAZ is higher than that of the base metal for the partially recrystallized tube B. Also EB welded joints have less elongation than the base metal, decreasing from 17 to 14 percent. The decreased elongation is caused by deformation localized in the base metal.

The tensile properties of Ti-3Al-2.5V tubes at somewhat elevated temperatures are of special importance. Since GTA welding was the most critical welding method, GTA welded specimens as well as non-welded base metal tube specimens were subjected to tensile testing at 120 C. In these tests, the effect of the annealing temperature of the base metal on the mechanical properties was also studied. The results of the 120 C tensile testing are compiled in Table 3.

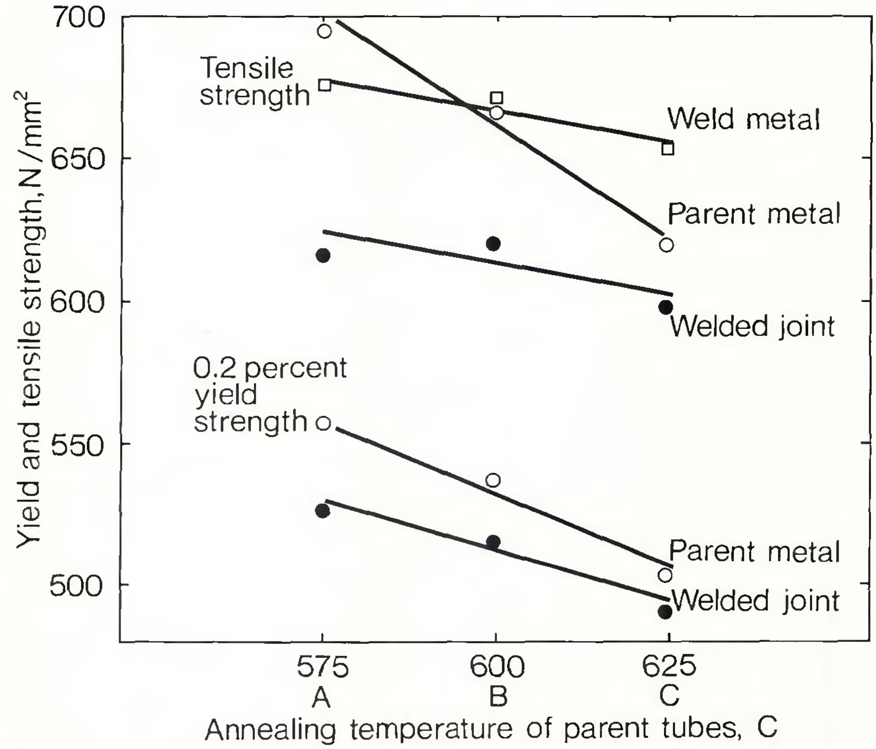

Fig. 1 — Yield and tensile strength of base metal at 120 C, GTA welded joint and weld metal as a function of annealing temperature of the tubes

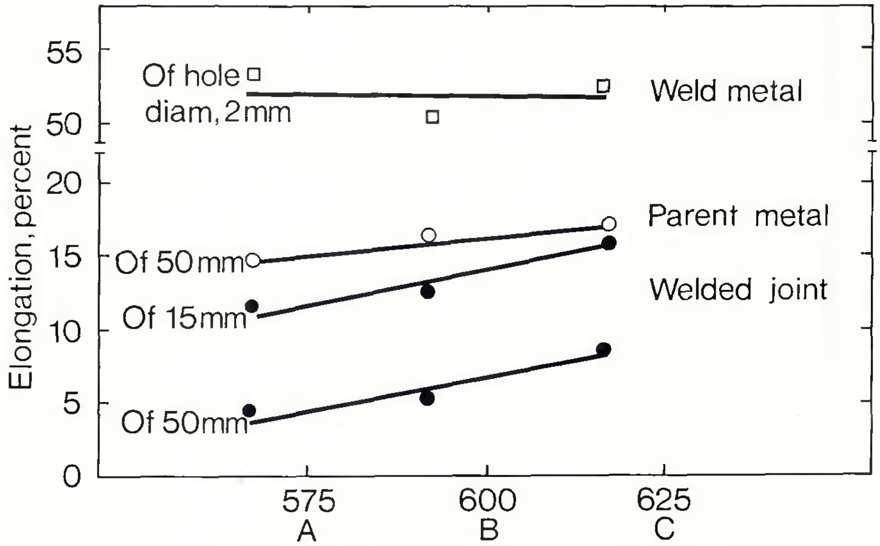

Fig. 2 — Elongation at 120 C of parent metal, GTA welded joint and weld metal as a function of annealing temperature of the tubes

In the welded specimens, all failures occurred in the transformation zone. The difference between the yield and tensile strength of the base metal and the yield and tensile strength of the welded joint decreases with increased annealing temperature of the base metal, Fig. 1. The tensile strength of the weld metal is higher than that of the base metal for the partially recrystallized tube C but lower for the stress relieved tube A. Also at 120 C the GTA welded joints have less overall elongation than the base metal. The elongation of welded specimens is dependent on the gage length and on the annealing temperature, Fig. 2. The effect of the gage length is such that the elongation increases with decreased gage length, which shows that the major part of the strain is concentrated in the transformation zone. The reason that the difference in elongation between the parent metal and the welded joint decreases with increased annealing temperature of the base metal is that the parent metal takes part in the total strain on a growing scale.

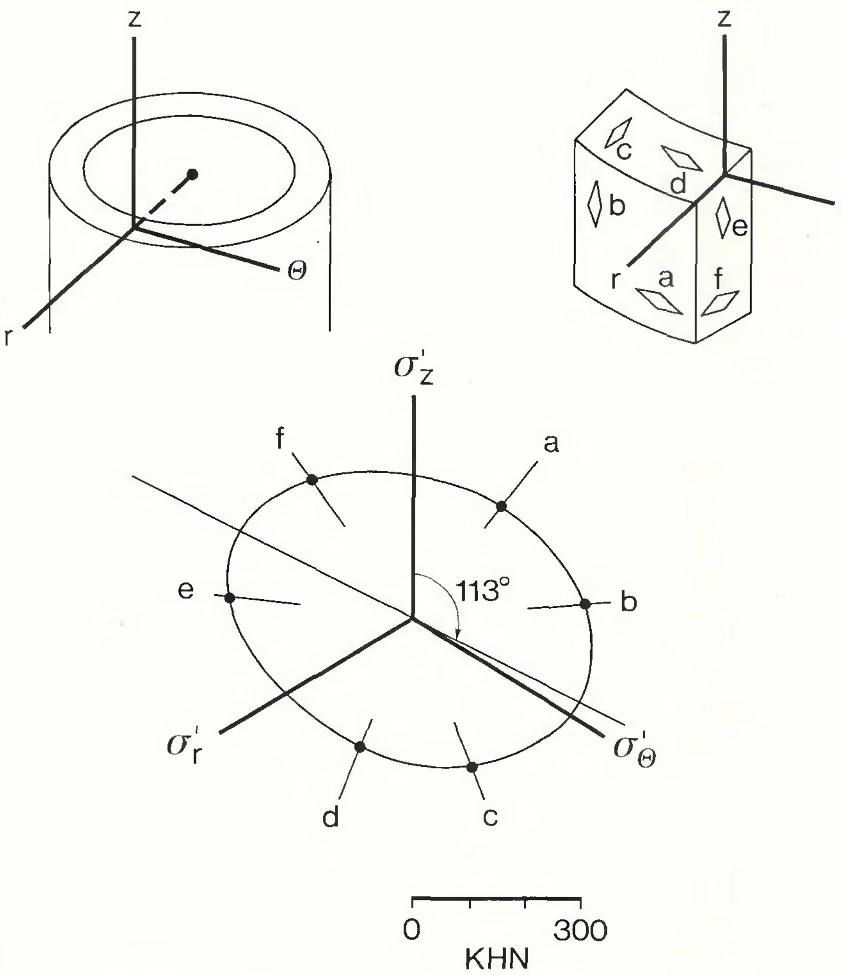

Fig. 3 — Definition of directions in tube material, orientation of the six Knoop hardness indentations and the yield locus of tube B

Mechanical Anisotropy

In Ti-3Al-2.5V tubes undergoing plastic deformation the basal poles of the hexagonal α phase crystal lattice have a tendency to align themselves parallel to the direction of maximum compressive strain. This results in a texture. On mechanical testing, the direction of the basal poles is hard and the directions perpendicular to the basal poles are weak. This mechanical anisotropy for textured material is displayed by distortion of the corresponding yield locus.

To investigate how hardness and mechanical anisotropy change in the transformation zone and in the low temperature heat affected zone during GTA and EB welding, the welding operation was simulated by heating 10 mm long specimens of tube B. The heat treatment was carried out in saltbaths both for 10 and for 30 seconds at temperatures between 700 C and 1300 C, after which the specimens were left to cool in air. The structures that were obtained show that the 10 sec duration simulates EB welding and the 30 sec duration, GTA welding.

The mechanical anisotropy was determined by Knoop hardness measurements, using the Wheeler and Ireland technique (Ref. 6). Here the Knoop hardness is measured with six

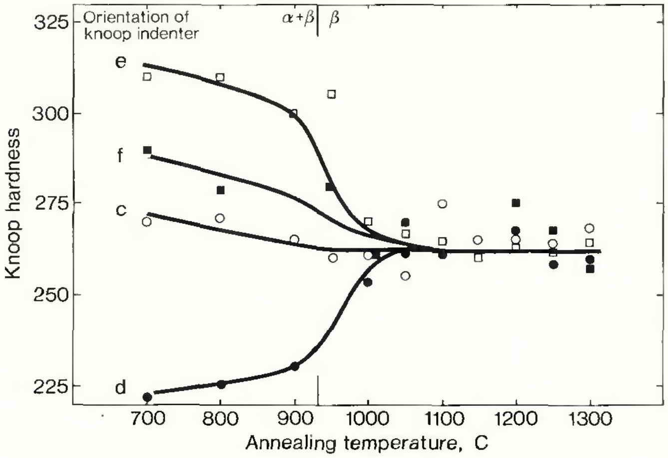

Fig. 4 — Tube B after simulated EB welding. Knoop hardness as a function of annealing temperature. Annealing time 10 sec

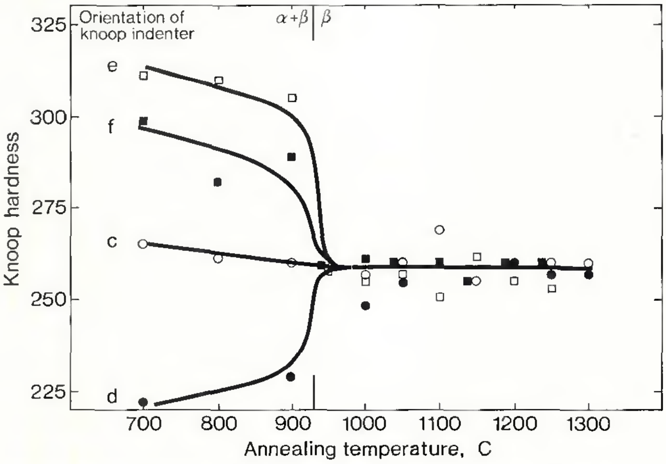

Fig. 5 — Parent tube B after simulated GTA welding. Knoop hardness as a function of annealing temperature. Annealing time 30 sec

separate orientations of the indenter and the hardness values are plotted in a deviator stress diagram for six separate stress ratios. The measurements were made with a 500 gram load on polished surfaces. Figure 3 defines directions in tube material, orientation of the six Knoop hardness indentations and the elliptical yield locus of parent tube B. The character of the anisotropy is described by the orientation of the major axis, which is 113 deg, and the degree of anisotropy is represented by the eccentricity of the yield locus, which is 0.64 for tube B. It should be noticed that the yield locus of an isotropic material is circular in accordance with the von Mises yield criterion.

Figures 4 and 5 show the Knoop hardness in each of two orientations on the transverse and the longitudinal section as a function of the annealing temperature of tube B after annealing within the range 700 C - 1300 C. The hardness in the c, e and f directions decreases and the hardness in the d direction increases with increased annealing temperature. These hardness changes mean that the mechanical anisotrophy decreases with increasing annealing temperature. After annealing in the β range, i.e. at temperatures above 930 C, the hardness after 30 sec is the same in all orientations, which shows that the material becomes isotropic as a result of the phase transformations, $\alpha + \beta \rightarrow \beta$ upon heating and $\beta \rightarrow \alpha + \beta$ upon cooling. A 10 sec anneal is too short for all the α phase to transform within the temperature range 930 C to about 1050 C, so that some mechanical anisotropy remains after cooling.

From these results the conclusion can be drawn that the transformation zone becomes mechanically isotropic in GTA welding and nearly isotropic in EB welding. In both GTA and EB welding the weld metal becomes isotropic. Further, the mechanical anisotropy of the low temperature heat affected zone can be expected to be less than the mechanical anisotropy of the base metal.

To confirm the result of these welding simulations, the Knoop hardness was measured in the f direction of GTA welded and EB welded tube B. As expected the hardness is lower in the weld metal and in the HAZ than in the base metal, Fig. 6, even though partial transformation to martensite occurred in these zones and this tends to raise the hardness.

The yield locus of the transformation zone in comparison with the yield locus of the base metal shows where plastic deformation first occurs in tensile testing, i.e. loading in the z direction of welded specimens. Based on data from Fig. 3 and Fig. 6, Fig. 7 illustrates that plastic deformation first occurs in the *transformation zone* in the case of *GTA welded specimens* and in the base metal in the case of *EB welded specimens*. The failure then occurs where the plastic deformation starts.

The yield strengths and the positions of failures obtained in tensile testing indicate that yield loci determined by Knoop hardness measurements can be used for a description of the yield behavior of welded Ti-3Al-2.5V under different stress ratios. The properties of Ti-3Al-2.5V hydraulic tubing in testing under internal pressure with the stress ratio $\sigma_\theta : \sigma_z$ = 2:1 is of great importance. The inter-

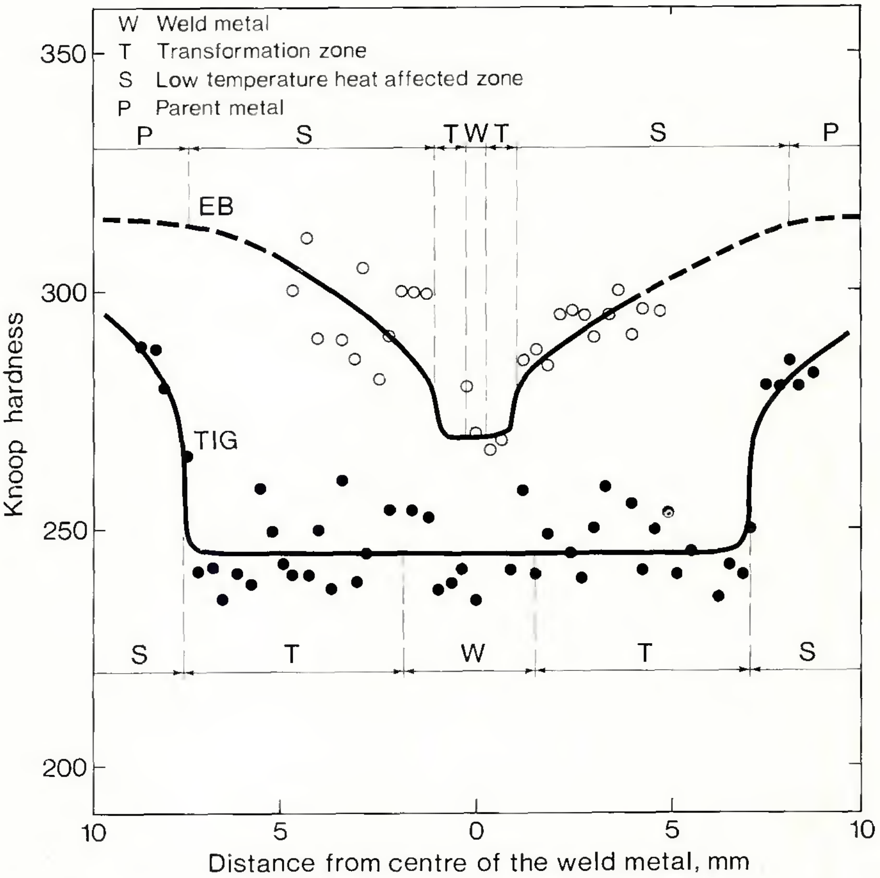

Fig. 6 — Parent tube B after GTA and EB welding. Knoop hardness in the f direction

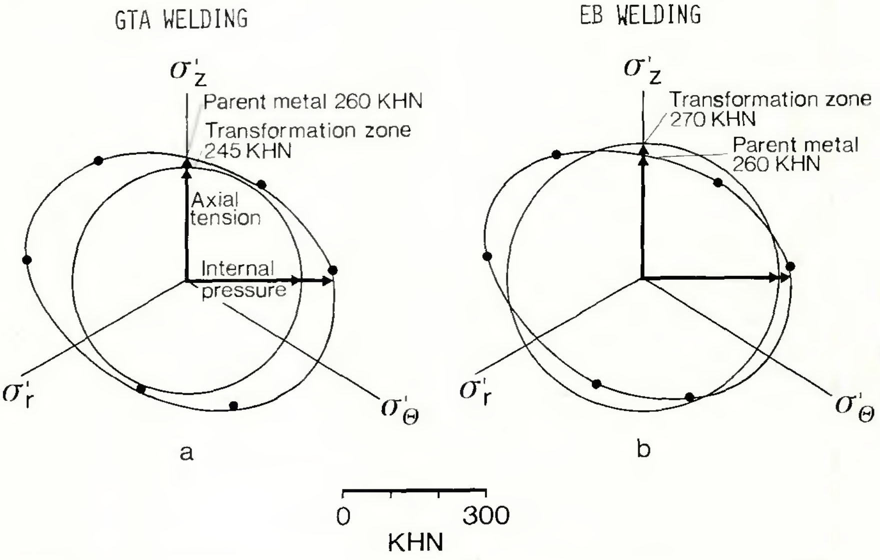

Fig. 7 — Yield loci of base metal and transformation zone after GTA and EB welding of tube B

pretation of Fig. 7 is that plastic deformation will begin and failure will occur in the *transformation zone* for both GTA and EB welded specimens in testing under internal pressure with a 2:1 stress ratio. Thus, the conclusion is that both GTA and EB welded specimens will have lower strength than the tube base metal in testing under internal pressure.

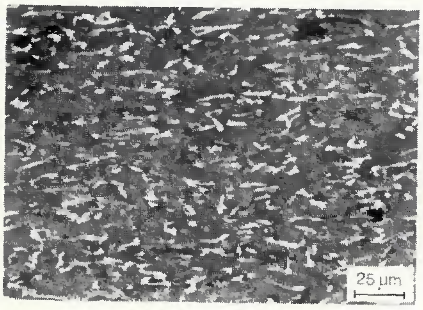

Fig. 8 — Longitudinal section of tube B. Recrystallized and deformed α grains, dark phase, with elongated β phase particles, bright phase, in α grain boundaries

Metallographic Structure

The structure was studied in tube B base metal and in welded specimens from tube B. The structure of the tube base metal is partially recrystallized, consisting of equiaxed recrystallized and elongated deformed α grains. In the α grain boundaries there are axially elongated β phase particles, as shown in Fig. 8.

The continuous cooling transformation diagram (CCT diagram) in Fig. 9 shows what phases are to be expected in the transformation zone (Ref. 7). After GTA welding, the weld metal has a structure of primary α phase in a matrix of fine and coarse needled hexagonal martensite, α″, Fig. 10. The structure appearance in the transformation zone near the fusion boundary closely matches the structure of the weld metal, so that it is difficult to distinguish the fusion boundary. The grain size in the transformation zone is coarse next to the weld metal, and decreases with increasing distance from the fusion boundary. The structure in the middle of the transformation zone can be seen from Fig. 11. Moreover, the volume part of α″ phase decreases with increasing distance from the weld metal, and next to the low temperature heat affected zone there is a clearly marked precipitation of α phase in the original β phase boundaries and within the grains, Fig. 12.

The structure of the EB welded joint is shown in Fig. 13. EB welding gives a considerably narrower HAZ than GTA welding. It may further be observed that the grain size in the transformation zone is smaller than after GTA welding, which is explained by the lower heat input associated with EB welding. The fusion boundary is more clearly marked, whereas the transformation border is more difficult to distinguish than after GTA welding.

Conclusions

The results of GTA and EB welding, tensile testing, Knoop hardness measurement and structure observations of Ti-3Al-2.5V hydraulic tubing can be summarized as follows:

1. The weldability of the α+β titanium alloy Ti-3Al-2.5V is as good as for unalloyed titanium, if the welding area is enclosed in a controlled protecting atmosphere for GTA welding and in vacuum for EB welding.
2. In tensile testing, GTA welded specimens exhibit transformation zone failures and EB welded specimens base metal failures.
3. GTA welded joints have lower yield strength and tensile strength and less elongation than the base metal. The decreased elongation is caused by deformation localized in the transformation zone. The site of failures in EB welded joints shows that the tensile strength of the weld metal and the HAZ is higher than that

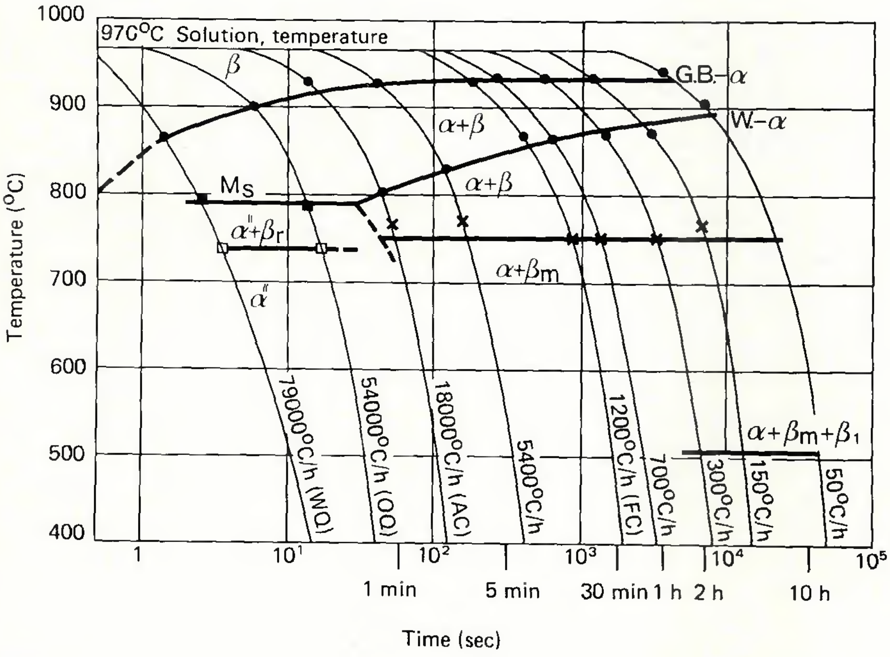

Fig. 9 — Ti-3Al-2.5V, continuous cooling diagram

Fig. 10 — Tube B after GTA welding. Longitudinal section of the weld metal. α phase and hexagonal martensite α″ phase

Fig. 11 — Tube B after GTA welding. Longitudinal section in the middle of the transformation zone. α phase and α″ phase

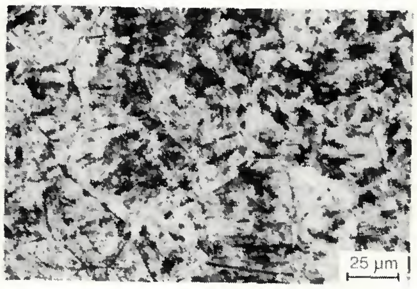

Fig. 12 — Tube B after GTA welding. Longitudinal section of the transformation zone next to the transformation border. α phase and α″ phase

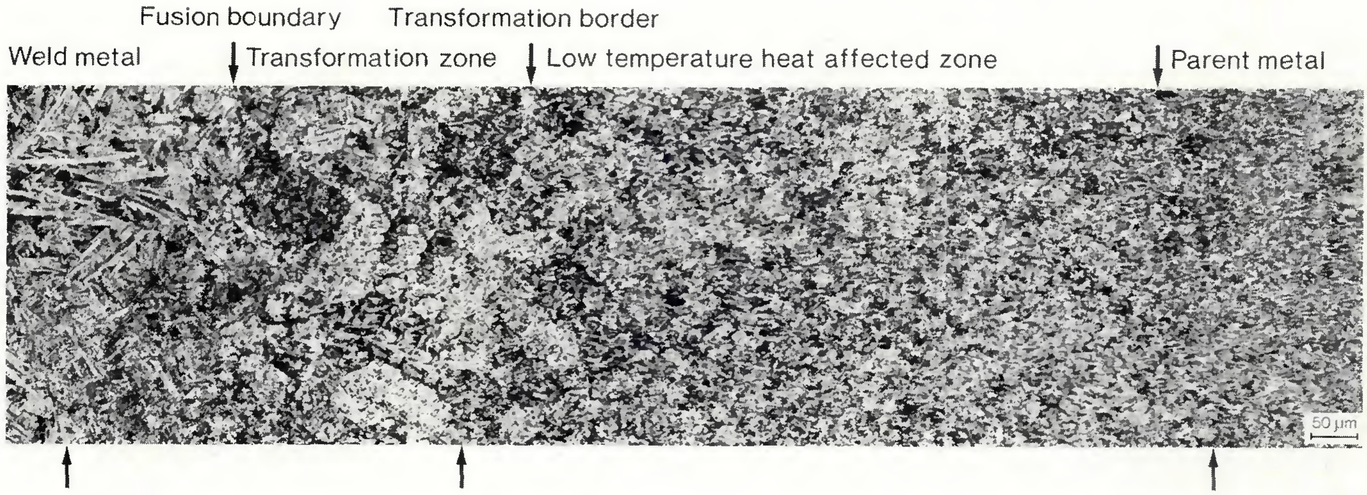

Fig. 13 — Tube B after EB welding. Longitudinal section of welded joint

of the base metal. EB welded joints also have less elongation than the base metal. The decreased elongation is caused by deformation localized in the base metal.

4. The tube base metals are mechanically anisotropic. Upon welding, the Knoop hardness in the different orientations is equalized, so that the weld metal and the transformation zone become mechanically isotropic. Knoop hardness yield loci of base metal and transformation zone can be used to predict where welded Ti-3Al-2.5V tubes will begin to deform plastically under different stress ratios and to estimate where failure will occur. For example, in testing under internal pressure with the stress ratio $\sigma_\theta : \sigma_z = 2:1$ the plastic deformation will begin in the transformation zone for both GTA and EB welded specimens. This will give transformation zone failures.

5. EB welding gives a considerably finer primary grain size than GTA welding. Upon cooling from the welding temperature, the β phase in the weld metal and the transformation zone is transformed into α phase and hexagonal martensite, α''.

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