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 \( \beta \) grain size than GTA welding. Upon cooling the \( \beta \) phase is transformed into \( \alpha \) 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.
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. In the as-welded condition, cut from the tube ends, the tube specimens were set up horizontally in a chuck, centered against the root side. The welds were inspected by x-ray radiography. All specimens were examined by means of dye penetrant tests and x-ray radiography. The samples were manipulated in a closed welding chamber made 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. The 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 % HNO₃ + 5 % HF + 60 % H₂O. 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 diam 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 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](image1.png)  
*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](image2.png)  
*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.

**Mechanical Anisotropy**

In Ti-3Al-2.5V tubes undergoing plastic deformation the basal poles of the hexagonal a 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
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 anisotropy 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, α + β → β upon heating and β → α + β 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, 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 $\sigma_x / \sigma_z = 2:1$ is of great importance. The inter-

![Fig. 6 — Parent tube B after GTA and EB welding. Knoop hardness in the f direction](image)

![Fig. 7 — Yield loci of base metal and transformation zone after GTA and EB welding of tube B](image)
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.

**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 needle shaped 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 decrease 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
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 \( \sigma_1: \sigma_2 = 2:1 \) 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 \( \beta \) phase in the weld metal and the transformation zone is transformed into \( \alpha' \) phase and hexagonal martensite, \( \alpha'' \).

References
1. Andersson, T., and Lundqvist, B., Brazing of the Titanium Alloy Ti-3Al-2.5V, Internal report, Sandvik AB

WRC Bulletin 193
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