Fracture toughness of the weldments of thick plates of two titanium alloys

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ANNOTATION

Thick plates of commercially pure titanium and Ti-6Al-4V alloy have been joined in a single pass using plasma arc and electron beam welding. Maximum fracture toughness was achieved in commercially pure titanium plate joined by electron beam welding. This high fracture toughness has been associated with the acicular microstructure of the weld metal. In the welding of Ti-6Al-4V plate maximum toughness was obtained in plasma arc weldments due, once again, to the presence of an acicular microstructure. Electron beam weldments also showed higher toughness than base material but the presence of small amounts of alpha prime martensite in the microstructure hindered to obtain values so high as plasma arc weld metal ones. Comparison between the values recorded in the tests carried out on electron beam weld metal points towards a benefit of the use of lower beam intensity.

Key words: Titanium alloys, fracture toughness, microstructure, arc welding, electron beam welding.

1. INTRODUCTION

Titanium and its alloys began to be used in the early 50s due to their excellent properties of strength to weight ratio, higher than other candidate materials of suitable toughness, excellent resistance to corrosion and good fatigue properties which made them attractive for aeronautical applications. Commercially pure titanium was developed due to aerospace demands for a material lighter than steel and more heat resistant than aluminium alloys but nowadays it is also widely used in chemical, marine and similar applications, heat exchangers, cryogenic vessels, components for chemical processing and desalination equipment, condenser tubing, pickling baskets, anodes, pumps, vessels and piping systems. Commercially pure titanium contains from 99 to 99.5% titanium plus small amounts of iron, carbon, hydrogen, nitrogen and oxygen. Higher contents of these elements increase the strength at room and elevated temperatures but ductility, fracture toughness and corrosion resistance decrease. Titanium denominated grade 2 according to ASTM B265 standard offers a good combination of medium tensile properties with cold formability being the most widely used of all commercially pure titanium grades.

Ti-6Al-4V presently is the most widely used titanium alloy, accounting for more than 50% of all titanium tonnage in the world and to date no other titanium alloy threatens its dominant position. The aerospace industry represents for more than 80% of its usage but it is also used in medical prostheses, chemical, marine and automotive applications. Depending on the application the oxygen content may vary from 0.08 to more than 0.2% by weight, the nitrogen adjusted up to 0.05% and the two main alloy elements, aluminium and vanadium may reach 6.75% and 4.5%, respectively. The higher the contents of these elements, particularly oxygen and nitrogen, the higher the strength but lower presence of oxygen, nitrogen and aluminium will improve ductility, fracture toughness, stress corrosion resistance and resistance against crack growth of the material.

Beside the quick pace of titanium metallurgy advance, this expansion was also achieved due to the successful solution of problems associated with the development of methods of welding. These alloys may be joined by a wide variety of conventional and solid state processes although its chemical reactivity requires special precautions to avoid contamination of the fusion and heat affected zones both on the face and root sides (1). Fusion welding of titanium is performed principally in inert gas-shielded arc and high-energy beam welding processes.
Titanium at temperatures above 450° C, and particularly in the molten state is known to be very reactive towards most of the atmosphere elements like oxygen, nitrogen and hydrogen which when introduced, even in trace amounts, embrittles the metal causing pore formation (2). Insufficient protection of the hot titanium from the surrounding atmosphere usually leads to pick up of nitrogen and, mainly, due to the preferential affinity of the metal for this element. Moreover, if moisture is present in the atmosphere or in the materials to be welded, hydrogen and oxygen can be picked up.

The reliability of the welding technique in case of titanium alloys thus proceed from its efficiency to ensure the protection of the liquid metal and the hot areas against contamination from the atmosphere. That is why, protection or shielding is commonly provided by a high purity inert gas cover in the open or in a vacuum chamber. When welding in the open adequate protection to the joint can be provided by an auxiliary inert gas shielding. Plasma arc welding constitutes an extension of the traditional gas tungsten arc welding process in which the arc plasma is constricted by a nozzle, thereby increasing its temperature and energy density as compared with the more diffuse GTAW arc. This higher energy density provides greater penetration capabilities, allowing the production of full penetration, keyhole square-butt welds in thick plates (3).

Electron beam welding is very well suited for joining titanium as the high vacuum inside the chamber where the process is carried out shields hot metal from contamination. This process involves melting of the base alloy to be joining by the impingement of a focused beam of high-energy electrons. Moreover, deep joint penetration can be achieved with the high beam power density and a keyhole in the weld metal increasing productivity and the lower heat input, when compared to gas tungsten arc welding, allows to obtain a better weld metal microstructure (4).

Further, the in-service performances of the welded structures significantly depend on solidification structures. While low heat inputs are expected to produce smaller grain size in the fusion zone, these heat inputs have to be adjusted to produce fully penetrated plasma arc or electron beam weld beads in order to keep high the productivity. This is specially difficult when welding of thick plates is performed.

The aim of this paper is to investigate the influence of the welding procedure on the fracture behaviour at various temperatures of thick plates of commercially purity titanium, that were welded using gas tungsten arc, plasma arc and electron beam, and Ti-6Al-4V alloy joined by plasma arc and electron beam welding.

2. EXPERIMENTAL PROCEDURE

Materials chosen for the present study consisted in a 12 mm thick plate of commercially pure titanium conforming to ASTM B265 Grade 2 and a 17 mm thick mill annealed plate of Ti-6Al-4V conforming to ASTM B265 Grade 5. Their chemical compositions and tensile properties in the as-received condition in the longitudinal and transverse directions are given in Tables 1 and 2, respectively.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>O</th>
<th>N</th>
<th>H</th>
<th>Fe</th>
<th>Al</th>
<th>V</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPT</td>
<td>0.02</td>
<td>0.14</td>
<td>0.014</td>
<td>0.0020</td>
<td>0.12</td>
<td>-</td>
<td>-</td>
<td>Balance</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>0.01</td>
<td>0.19</td>
<td>0.05</td>
<td>0.0016</td>
<td>0.16</td>
<td>6.51</td>
<td>4.08</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Table 1. Chemical composition of the commercially pure titanium and Ti-6Al-4V alloy thick plates used for this study.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Orientation</th>
<th>Y.S. (MPa)</th>
<th>U.T.S. (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPT</td>
<td>Longitudinal</td>
<td>383</td>
<td>480</td>
<td>26.6</td>
</tr>
<tr>
<td>CPT</td>
<td>Transverse</td>
<td>480</td>
<td>529</td>
<td>26.9</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>Longitudinal</td>
<td>967</td>
<td>1043</td>
<td>17.0</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>Transverse</td>
<td>1010</td>
<td>1085</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Table 2. Mechanical properties of the plates in the longitudinal and transverse orientations.

Ti-6Al-4V alloy in the as received condition exhibited a slightly elongated alpha grains delineated by beta phase along these grain boundaries. This microstructure is the result of the mill annealing treatment that was given consisting in a short maintenance at 720° C, followed by air cooling as the final step of its thermomechanical process. Commercially pure titanium plate also showed slightly elongated alpha grains as result of its rolling process.
Coupons from these plates were welded in their transverse direction. Gas tungsten arc welding (GTAW), plasma arc welding (PAW) and electron beam welding (EBW) were used for the 12 mm thick plate of commercially pure titanium while both plasma arc welding (PAW) and electron beam welding were selected for the joining 17 mm thick plate of Ti-6Al-4V.

GTAW was performed in the open using direct current and straight polarity. Primary gas shielding was provided by the 19 mm diameter torch nozzle using high purity (99.999%) argon with a flow rate between 6 and 10 l/min. The solidified weld metal was protected from the atmosphere until it cooled to 450°C where oxidation is not a problem by means of a trailing shield. The shielding of the root of the weld and the adjacent parent metal was achieved by feeding a separated supply of high purity argon with a flow rate of 22 l/min. Filler metal used in these weldments consisted of 2.4 mm diameter wire of titanium grade 2. Two different welding procedures were considered. In that designed as S.F a double V joint profile with an insert backing of filler metal in the root was used. However, a 90-degree double V groove butt-welding was selected for the H.I. procedure.

Square butt welding in an only pass, using direct current and straight polarity, was selected for the plasma arc welding joints of both alloys. High purity argon was used for both producing the plasma column and shielding the melt and hot metal from the atmosphere. Only one welding procedure for each alloy was considered in this study. Both plates were welded in a single pass, obtaining total penetration and a good weld root, without significant defects.

A second group of coupons were electron beam welded. A search of the optimum welding parameters was carried out and the difficulty to obtain a good weld metal root was realised. With a set of parameters it is observed a lack of penetration but if the beam energy is slightly increased the penetration becomes excessive and the characteristics drops of metal are found in the root due to the low surface tension of the titanium melt. Lower beam energy welding procedure of Ti-6Al-4V is referred as EBW6A while coupons welded with higher energy were marked as EBW6B. Commercially pure titanium was also electron beam welded using two different procedures. The reason was the significant scatter of toughness values in the welded coupons joined with the focal position on the surface, designated Ti-1. Focus position was moved in the second welding procedure to 2 mm below this surface and these specimens referred as Ti-2.

Fracture toughness characterisation consisted of CTOD tests on preferred three point single edge notch-bending specimens according to British Standard 7448 Part 1. Most of the specimens were notched in the weld metal although an additional number of tests were performed on GTAW and PAW specimens notched in the heat affected zones. Due to the very thin heat affected zones of the electron beam joints it was not possible to obtain a reliable evaluation of their fracture toughness. After failure a fractographic examination of the fracture surfaces by scanning electron microscopy was carried out. Moreover, a metallographic study of each welded joint was performed on transverse sections to the welded joint.

3. RESULTS AND DISCUSSION

Figures 1, 2 and 3 exhibit the results obtained in the fracture toughness tests of gas tungsten arc, plasma arc and electron beam welded joints of the commercially pure titanium coupons, respectively.

![Figure 1: CTOD vs temperature in titanium grade 2 GTAW weldments](image-url)
Figures 2 and 3 show the influence of the testing temperature on the fracture toughness of plasma arc and electron beam welding of the Ti-6Al-4V alloy.

Figure 4 and 5 show the influence of the testing temperature on the fracture toughness of plasma arc and electron beam welding of the Ti-6Al-4V alloy.
Base materials fracture toughness values in both longitudinal and transverse orientation are included in figures 6 and 7 for commercially pure titanium and Ti-6Al-4V respectively for comparison with these welding joints results.

![Figure 6: CTOD vs temperature in titanium grade 2 base plate in longitudinal and transverse orientations](image)

![Figure 7: CTOD vs temperature in Ti-6Al-4V base plate in longitudinal and transverse orientations](image)

It can be easily checked that in the commercially pure titanium maximum toughness was achieved in the joints carried out by electron beam welding with values that are even significantly higher than those measured in base material. This improvement has been associated with the acicular microstructure of the weld metal compared with the more equiaxial one in the plate. In a previous work carried out on the same plate it was demonstrated that acicular microstructure produced by beta field annealing and air-cooling was more than twice tougher than the mill annealed one (5). Although the material that was analysed in this study (a Ti-6Al-4V alloy) is different than the commercially pure titanium of these welded joints, the positive influence of the acicular microstructure can be extrapolated. Fractographic examination of the fracture surfaces of these specimens revealed the more tortuous crack path in beta annealed specimens as fracture propagates along the boundaries of individual needles linked by ductile dimples. A very similar crack deviation was observed in the electron weld metal specimens of commercially pure titanium.

Comparison between the values of fracture toughness recorded in electron beam welded coupons revealed that toughness is specially high in Ti-1 weldments, where some values are as high as three times those recorded in base material. However, a larger scatter in values is evident in these toughness results. In order to reduce this scatter focus position was moved to 2 mm below the plate surface (Ti-2). Results obtained in the fracture toughness tests of specimens welded using this procedure are much more homogeneous than the previous ones and although are lower than the maximum values recorded in Ti-1 coupons, are still better than base material ones and did not seem to be affected by the testing temperature.

Plasma arc weld metal also exhibited toughness values higher than those of the base material but lower than electron beam weld metal ones. Moreover, a very low value was obtained in the specimen that was tested at -20°C. Scanning electron microscope analysis of the fracture surface of this specimen revealed the presence of a weld metal defect, very near of the fatigue crack front, promoting a quick failure. This must be considered a very
localised defect and no affect to the global welding procedure qualification that is considered satisfactory. Once again, metallographic examination of the transverse sections of these welded coupons revealed a basket-weave microstructure of alpha needles that according previously performed study is clearly tougher than the nearly equiaxic mill annealed base material. It is more difficult to find a reason for the higher toughness of electron beam weld metal compared to plasma arc welded one, as both possess an acicular microstructure. One plausible explanation would be based in the different morphology and, possibly, nature of the needles formed in one or another welded joints. Vickers hardness measurements carried out on transverse sections to the welded joints lead to values slightly higher in electron beam weld metal than in the plasma arc ones (210 versus 190 HV10) supporting the above formulated hypothesis in the sense that there is a certain microstructural difference between both welding joints.

Gas tungsten arc weld metal also exhibited an acicular microstructure and values higher than those of the base material. However, weld metal specimens showed lower toughness values than base plate ones, having been associated to the presence of some weld defects (lack of fusion) in the weld root of these joints. The presence of these weld defects is more frequent in S.F. specimens. In a previous paper on the fatigue behaviour of these welded joints it was found that Paris exponent recorded in tests carried out on specimens where these kind of defects was present was as high as twice the values measured in sound specimens (6). This observation points toward a marked influence of their presence that even overcomes the benefit of the acicular microstructure.

H.I. weld metal fracture toughness average value is lower than that of S.F procedure but individual values are much more homogeneous. This result that is in good agreement with that obtained in another previous work (7) seems to indicate that the use of lower heat input must be recommended to obtain higher fracture toughness but the risk of the presence of weld defects is more marked. Heat input must be the lower one but assuring that a sound joint is achieved.

A failure in the argon shielding during the welding of two coupons using the H.I. procedure induced an oxidation of the weld metal. Three specimens machined from these welded coupons were tested at 20, -20 and -60° C. Values recorded in these tests did not seem to be affected by the testing temperature but were significantly lower (about 40%) than those obtained in the shielded joints supporting the necessity to prevent contamination of the hot metal.

Plasma arc welding specimens notched in the heat affected zone exhibit fracture toughness values that are higher than those in the weld metal. Once again, the acicular microstructure of this zone is considered responsible of this high fracture toughness.

Specimens notched in the heat-affected zone of the gas tungsten arc weldments possessed very similar fracture toughness. Nevertheless, it must be pointed out that due to the double V groove of these joints notch is partially out of the heat-affected zone. Consequently, recorded values cannot be considered as fully representative of the actual fracture toughness of these heat-affected zones.

In the Ti-6Al-4V welded coupons maximum toughness was achieved in the weld metal that was produced by plasma arc welding being significantly higher than values measured in the base material. These high values have been attributed, once more, to the acicular microstructure of this weld metal. As it has been indicated above the study carried out about the influence of the microstructure of this alloy on its fracture toughness revealed that maximum toughness was achieved when microstructure consisted in needles of alpha phase (5).

Heat affected zone notched specimens showed toughness values that were intermediate between those of the weld metal and the base material. These results can be explained considering the presence of a small amount of alpha prime martensite associated with the higher cooling rate. As it is discussed below, this phase is hard but very brittle and can reduce significantly the toughness of the material.

Electron beam weldments also showed higher toughness than base plate although the differences are not so pronounced as those found in plasma arc welded ones. Metallographic examination of these samples helped to explain this behaviour. Electron beam weld metal possesses an acicular microstructure, mainly formed by fine alpha needles but a certain volume fraction of very fine alpha prime martensite needles was detected by the use of higher magnification and scanning electron microscopy. The increase in toughness is associated to the acicular microstructure and the crack path deviation. On the other hand the reason for lower values than those obtained in plasma arc weldments attributed to these small areas of brittle alpha prime martensite. Previous studies have shown that this phase is hard but very brittle and its presence decreases the material toughness.
Fractographic analysis of the broken specimens is consistent with this hypothesis. Fortunately, only a small amount of this phase was found in these weldments.

Comparison between the values recorded in the tests carried out on specimens notched in the electron beam weld metal corresponding to the two different welding procedures points towards a benefit of the use of lower beam intensity. Lower scattering in toughness values and higher average values were found in the EBW6B specimens, produced using lower input. This result is in good agreement with the above-formulated hypothesis as the use of higher inputs would increase the cooling rate and facilitate the formation of alpha prime martensite. However, to obtain the total depth of penetration in a single pass can oblige to use higher beam intensity. An alternative that deserves to be explored consists in the use of commercially pure titanium as filler metal, which reduces the risk of alpha prime martensite formation. The use of this filler metal, together with lower welding speed or beam oscillation to reduce the porosity of the weld are also considered for in-depth research.

4. CONCLUSIONS

a.- Thick plates of commercially pure titanium and Ti-6Al-4V alloy have been joined in a single pass using plasma arc and electron beam welding obtaining sound joints without the presence of significant defects. However, gas tungsten arc weldments of commercially pure titanium carried out in several passes exhibits some defects (lack of fusion) that decrease their fracture toughness and fatigue performance.

b.- Maximum fracture toughness was achieved in commercially pure titanium plate joined by electron beam welding. This high fracture toughness has been associated with the acicular microstructure of the weld metal compared with the more equiaxic one of the base material. Focusing 2 mm below the surface leaded to lower values but much more homogeneous than those recorded in specimens joined with the focal position on the plate surface.

c.- Plasma arc weldments also showed higher fracture toughness values than base plate but lower than those obtained in electron beam weld metal. This difference in toughness has been attributed to some differences in the morphology and nature of the needles present in electron beam or plasma weld metal.

d.- Gas tungsten arc weld metal also exhibited an acicular microstructure that it was expected to lead to an improvement in toughness in comparison with the base material. However, due to the presence of welding defects, such as the lack of fusion observed in the root, no increase in toughness is achieved.

e. In the welding of Ti-6Al-4V plate maximum toughness was obtained in plasma arc weldments due, once again, to the presence of an acicular microstructure formed by alpha needles.

f.- Heat affected zone notched specimens possesses a toughness that laid between those of weld metal and the base material. This result is attributed to the presence of a small volume fraction of brittle alpha prime martensite formed due to the higher cooling rate.

g.- Electron beam weldments also showed higher toughness than base material but the presence of small amounts of alpha prime martensite in the microstructure hindered to obtain values so high as plasma arc weld metal ones.

h.- Comparison between the values recorded in the tests carried out on specimens notched in the electron beam weld metal corresponding to the two different welding procedures points towards a benefit of the use of lower beam intensity. However, the necessity to obtain full depth penetration in a single pass could oblige to use higher input.

i.- The possibility to use commercially pure titanium as filler metal which reduces the risk of alpha prime martensite formation in the electron beam weldments deserves to be investigated.

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6. REFERENCES


