Fracture Toughness of Electron Beam Welded Ti – 6Al – 4V Plates

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Abstract: *The influence of the different process variables on the fracture toughness of electron beam weldments carried out on a 17 mm thick plate of a Ti – 6 Al – 4V has been analyzed. The use of filler metal of similar and dissimilar chemical composition or unalloyed sheets of different thickness (0.25, 0.50 and 1 mm) prefixed in the joint have been investigated. When the wire used possessed a composition similar to the base material a significant content of brittle alpha prime martensite was observed. The presence of this phase induced a decrease in the fracture toughness of the joint. However, when unalloyed filler metal was used a predominant acicular alpha phase microstructure was observed and higher toughness achieved. The use of sheet filler metal leads to acicular alpha microstructures very similar to those found in commercially purity titanium weldments and a marked improvement in fracture toughness obtained. Even when tests were carried out on specimens machined from clearly defective zones toughness values were similar to those measured in the sound weld metal zones produced without filler metal*

INTRODUCTION

Designed, primarily for high strength at low to moderate temperatures, Ti - 6Al - 4V is presently 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. This alpha – beta alloy offers the possibility of modifying its mechanical properties by the control of the thermomechanical processing. The aerospace industry represents for more than 80% of this usage but it has found also use in other fields such as medical prostheses, which accounts for 3% of the market, automotive, marine and chemical industries, although cost continues to be an inhibitive factor for its use in those applications where weight and corrosion resistance are not critical considerations (1).

Beside the rapid advance achieved in titanium metallurgy the observed increase in the use of these materials is due to the successful solution of problems associated with their welding process. This alloy can be easily joined by a wide variety of conventional and solid state processes. However, because of its high chemical reactivity above 350º C special precautions to avoid contamination of the fusion and heat affected zones, on both the face and root sides, are required (2). Consequently, fusion welding is commonly performed under a high purity inert gas cover or an adequate vacuum level.

Further, the in-service performances of the welded joints markedly depend on weld metal and heat affected zone microstructures. Previous work showed that electron beam weld metal possessed higher toughness than base plate, although lower than that achieved in the plasma weld metal. The increase in toughness was associated with the acicular microstructure of fine alpha needles but the presence of a certain volume fraction of brittle alpha prime martensite, formed by rapid cooling from temperatures above the beta transus, precluded to reach the optimum level of toughness (3). Moreover, when low beam energy was used (reference EBW6A) a higher average value of weld metal toughness, but with a significant scatter in the results was obtained This was attributed to some problems of lack of penetration, observed in these joints. On the other hand higher beam energy (EBW6B) weld metal exhibited lower, but more homogeneous, toughness values.

To sum up it was concluded that despite a remarkable improvement in the electro beam welding technology over the last years there are still some drawbacks to be overcome before the best performance of this process could be obtained. Previous works performed on electron beam and laser welded joints clearly demonstrated that the quenching process after welding was responsible for the presence of the alpha prime martensite phase in both the weld metal and the heat affected zone (4).

It was suggested that a further improvement in toughness could be achieved by a reduction of the presence of this brittle phase. One way to reach this result is decreasing the cooling rate but this affects negatively the efficiency of the process. The other alternative, and the most logical one, is based on the use of unalloyed or lower alloy filler metals, which decrease the weld metal hardenability and reduces the volume fraction of this brittle phase in the microstructure without altering the parameters and efficiency of the process (4). Moreover, addition of a filler metal allows to weld thick plates using low power electron beam machines (5) and improves the quality of the joints, by minimizing their porosity and cracking susceptibility (6).

The objective of this paper is to analyze the influence of the use of different filler metals on the fracture toughness of the electron beam weldments of a 17 mm thick plate of a Ti – 6 Al – 4 V alloy.

EXPERIMENTAL PROCEDURE

Material chosen for this study consisted in a 17 mm thick plate of a Ti – 6 Al – 4 V alloy, whose chemical composition and mechanical properties are given in tables 1 and 2, respectively. This plate, as received, was in the mill annealed condition, consisting in a short maintenance at 720º C, followed by air cooling as the final step of its thermomechanical process. Metallographic analysis of this plate revealed a microstructure formed by slightly elongated alpha grains, delineated by beta phase sited along these grain boundaries.

TABLE 1. Chemical composition of the plate

C	O	N	H	Fe	Al	V	Ti
0.01	0.19	0.05	0.0016	0.16	6.51	4.08	Balance

TABLE 2. Mechanical properties of the plate in the longitudinal and transverse orientations

Orientation	Y.S. (MPa)	U.T.S. (MPa)	Elongation (%)
Longitudinal	967	1043	17.0
Long Transverse	1010	1085	16.0

Coupons machined from this plate were electron beam welded in their long transverse orientation. Two different methods for modifying the weld metal composition were considered in this study. First, 1.2 mm diameter wire of Ti – 6Al – 4V, which has a similar composition to the base plate or 1 mm diameter wire of commercially pure titanium were added to the joint. The second alternative consisted in the placement of a prefixed thin sheet in the root of the joint, which is melted with the base plate during the welded process. 0.25, 0.50 and 1 mm thick sheets of commercially pure titanium were considered to accomplish this task. A change in microstructure was obtained by both methods.

Tensile tests specimens were machined in the transverse orientation to the joints, that is in the longitudinal direction of the plate, including weld metal, heat affected zones and base material. These specimens were tested at room temperature recording the values of ultimate tensile strength and reporting the zone where failure was produced Fracture toughness of the various joints was evaluated by means of room temperature CTOD tests, performed on preferred single edge notched three point bending specimens according to British Standard 7448 Part 1. Most of the specimens were notched in the weld metal although a reduced number of tests was performed on heat affected zone notched specimens. However, it must be pointed out that it was not possible to obtain a reliable evaluation of the heat affected zone toughness due to their very small thickness. After failure a fractographic examination of the fracture surfaces by scanning electron microscopy was carried out. Moreover, a metallographic study of transverse sections to each welded joint was performed.

RESULTS AND DISCUSSION

A significant number of weld defects were detected in the weld metal that was produced using a wire of similar composition to the base plate. The presence of these defects was attributed to difficulties found in the control of the filler parameters. The set up of the procedure needs to adjust a great number of variables and cannot be considered an easy task. Nevertheless, an improved control of these process variables was achieved and a marked reduction in the number of defects obtained, but a relatively large amount of martensite is still present in these new joints. Consequently, no noticeable advantage from autogenous weldments performed without filler metal can be claimed and the study of this alternative was abandoned.

The analysis carried out on welded joints produced using an intermediate 1 mm thick sheet of commercially pure titanium showed a abrupt variation of hardness (more than 100 HV10), related with the different microstructures of weld metal, heat affected zone and base plates. Alpha prime martensite was observed in the heat affected zones and the weld metal close to the base material. However, in the rest of the weld metal microstructure consisted in acicular alpha very similar to that found in commercially pure titanium weldments (3). This strong variation in hardness (and very probably also in strength even if this property was not evaluated in this joint) is considered to be excessive and no further work in this line was performed.

Having eliminated these two possibilities the other three ways (addition of unalloyed wire and the use of 0.25 or 0.50 mm intermediate sheets) received a preferential attention. Table 3 summarizes the results that were obtained in the tensile and fracture toughness tests performed on these joint, together with those recorded in the base material and the autogenous electron beam weldments studied in a previous paper (3) that were produced without the use of filler metal.

TABLE 3. Tensile and fracture toughness tests results of the various joints.

FILLER	REFERENCE	U.T.S. (MPa)	Zone of failure	CTOD (mm)
Base material	Ti – 6Al – 4V	1043	-	0.032
No filler	EBW6A (3)	1040	Weld metal	0.060
No filler	EBW6B (3)	1034	Weld metal	0.046
Wire	Commercially Pure Titanium	1003	Weld metal	0.085
Sheet	0.25 mm	1045	Weld metal	0.080
Sheet	0.50 mm	878	Weld metal	0.095

It can be seen in this table that all the electron beam weld metal toughness results are markedly higher than the value recorded in the base plate in the same orientation. Moreover, the use of unalloyed filler metal allowed to obtain a level of toughness which is not only higher than those achieved in autogenous electron beam weldments but also than that obtained in the plasma arc weld metal (0.068 mm).

Weldments produced with an intermediate 0.50 mm thick sheet exhibited the highest toughness value but with the counterpart of having the lowest strength. Metallographic examination of transverse sections to these joints helps to find an explanation to these improvement in toughness and decrease in strength. Even if a certain dilution of alloy elements from the base plates to the intermediate sheet this is not probably complete enough to obtain a homogeneous distribution. Moreover, differences in the thermal cycles of the various zones of the joint during the welding process must be kept in mind. Although no so marked as in the weldments performed with the 1 mm thick intermediate sheet a transition in microstructure from the base material to the weld metal was observed. This last zone exhibited a microstructure constituted by acicular and serrated alpha phase, that reminds that found in commercially pure titanium. Consequently a high level of toughness but a low strength would be expected in good agreement with the experimental results. This sacrifice in strength compared with the base material (around a 16% lower in the weld metal) could be excessive for some applications and an alternative way to improve the fracture toughness must be found.

The use of a thinner intermediate sheet (0.25 mm thick) allows to obtain a more complete dilution and smaller variations in the thermal cycles of the various zones. This would lead to a more homogenous microstructure (and mechanical properties) among the different zones of the joint. Once again the experimental results agree with these expectations. Practically the same strength level than in the base material was obtained although a less marked improvement in toughness is observed. This alternative must be considered for those applications where a high fracture toughness is needed but such a strong loss in resistance cannot be admitted.

The third possibility is based on the use of a wire of commercially pure titanium. Strength and toughness values recorded in the tests performed on specimens machined from this joint are intermediate between those obtained in the joints produced with a 0.25 and a 0.50 mm thick sheets. These joints also exhibited a transition in the microstructure from alpha prime martensite present in the weld metal close to the base material to an acicular or serrated one in the rest of the weld metal, similar to that observed in the weldments carried out using an intermediate unalloyed sheet. This alternative could be used when these intermediate properties of strength and fracture toughness are aimed.

A reduced number of fracture toughness tests was performed on specimens that were machined from defective zones of these joints. Toughness values recorded in these tests were very similar to those measured in the sound weld metal produced by electron beam welding without filler metal (7) and confirm their excellent fracture behaviour. Even if further research is needed to obtain the best properties of these joints a significant step forward has been given.

Metallographic analysis of transverse section to these weldments revealed the existence of a certain amount of alpha prime martensite in their heat affected zones. The presence of this phase was confirmed by the higher hardness values measured in these zones. Unfortunately, the reduced width of these heat affected zones precluded to confine the fatigue crack into this zone and it was not possible to obtain a reliable evaluation of their fracture toughness. Nevertheless, due to the relatively low amount of this phase and the narrowness of these heat affected zones a good fracture behaviour of the whole joint is expected.

CONCLUSIONS

a. Electron beam weldments produced on a 17 mm thick Ti – 6Al – 4V plate using unalloyed filler metal exhibited significantly higher toughness values than those that were autogenously welded. The maximum value is recorded in the joints welded using a 0.50 mm thick intermediate sheet although a noticeable decrease of strength is also observed. The use of a thinner intermediate sheet (0.25 mm) leaded to no so high fracture toughness values but the loss in strength was less marked. On the other hand, even if no tensile tests were performed in these joints, the hardness values of weld metal measured in the joints that were produced using a 1 mm thick sheet is considered excessive and this alternative abandoned.

b. Welded joints produced with unalloyed wire showed toughness and strength values which were intermediate between those obtained in the joints welded with 0.25 and 0.50 mm thick sheets. However, the use of Ti – 6Al –4V wire represented no noticeable improvement in the weld metal microstructure as a significant amount of brittle alpha prime martensite is present in the weld metal and heat affected zones of these joints.

c. Fracture toughness tests performed on specimens that were machined from defective zones of these joints leaded to very similar results than those recorded in the sound weld metal produced without filler metal.

d. Due to the narrowness of the heat affected zones of the electron beam weldements it was not possible to confine the crack within their limits and to obtain reliable toughness values of this zone where a certain amount of alpha prime martensite was observed. Nevertheless, due to the relatively low content of this phase and the very small width of these heat affected zones a good fracture behaviour of the whole joint is expected.

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