FRACTURE TOUGHNESS OF THICK PLATES OF Ti-6Al-4V WELDMENTS

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The fracture behaviour of thick plates of Ti-6Al-4V alloy joined by means of plasma arc welding (PAW) and two different electron beam welding (EBW) procedures. In the whole temperature range PAW weld metal specimens exhibited higher toughness than base material. This behaviour has been attributed to the acicular microstructure of the weld metal compared to the equiaxic of parent alloy. EBW welded metals also showed higher toughness than base material although no so high as PAW ones. These results could be associated with the presence of a small volume fraction of brittle alpha prime martensite due to the higher cooling rate.

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. At one time or another practically all aerospace structures (airframes, skin and engine components) have benefited from the introduction of these materials. Although the aeronautics sector is still the main consumer of titanium and its alloys, other new areas of industry are becoming interested in their use including steam turbine blades, hydrogen-storage media, high current/high field superconductors, condenser tubing for nuclear and fossil-fuel power generation and other corrosion resistant applications such as components for ocean thermal energy conversion, offshore oil drilling, marine-submersible vessels, desalination and waste treatment plants, pulp and paper, chemical and petrochemical industries (1). The consumption of titanium in these other branches of industry is approximately 20 to 25% of total and is growing 9% per year compared with the 6% growth in the aeronautics sector (2).

Beside the quick pace of titanium metallurgy advance, this was also achieved due to the successful solution of problems associated with the development of methods of titanium alloys welding. Ti-6Al-4V alloy may be welded by a wide variety of conventional fusion and solid state processes although its high chemical reactivity requires special procedures and precautions to avoid contamination of the fusion and heat affected zones both on the arc and root sides (3). Titanium at high temperatures, and particularly in the molten state, is very reactive towards most of the air elements like hydrogen, oxygen and nitrogen which when introduced even in trace amounts embrittle the metal and cause pore formation (4). The reliability of the welding technique in case

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of titanium alloys would thus proceed from its efficiency to ensure the protection of the liquid metal and the surrounding 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 (5).

Electron beam welding involves melting of the base alloy to be joined by the impingement of a focused beam of high energy electrons. This process is very well suited for joining titanium alloys as the high vacuum inside the chamber where the process is carried out shields hot metal from contamination. Moreover, deep joint penetration can be achieved with high power density and a keyhole in the weld metal increasing productivity (6).

Plasma arc welding constitutes an extension of the 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 (7).

The aim of this paper is to study the fracture behaviour of a 17 mm thick Ti-6Al-4V plate welded by plasma arc welding and electrom beam welding.

EXPERIMENTAL PROCEDURE

The base material chosen for the present study was a 17 mm thick of a Ti-6Al-4V alloy, conforming to ASTM B265 Grade 5 (8). Its chemical composition and mechanical properties in the as-received, mill annealed, condition are given in Tables 1 and 2, respectively.

TABLE 1.- Chemical composition of the plate.

Alloy	C	O	N	H	Fe	Al	V	Ti
Ti-6Al-4V	0.01	0.19	0.005	0.0016	0.16	6.51	4.08	Bal

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

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

Coupons from this plate were plasma arc welded in their transverse direction. Square butt welding in an only pass, using direct current and straight polarity, was selected for these joints. High purity argon was used for both producing the plasma column and shielding the melt and hot metal from the atmosphere. This welding procedure was designed as PAW. A second group of coupons was electrom beam welded, also in the transverse direction of the plate using two different beam intensities in order to optimize the welding parameters, as it was found that the use of a low beam energy can induce a lack of penetration but if the beam energy is increased the penetration can be excessive and drop of metals are formed in the root of the joints. Lower beam energy procedure is referred as EBW6A and EBW6B represents the higher energy one.

Fracture toughness characterisation consisted of CTOD tests on preferred three point single edge notch bending specimens according to BS 7448 Part 1 (9). Most of the specimens were notched in the weld metal although an additional number of tests were performed on PAW specimens notched in the heat affected zone. Due to the very thin heat affected zones of the electrom beam welded joints it was not possible to obtain a reliable evaluation of their fracture toughness. Tests were performed in the temperature range between - 60 and + 20° C. After failure a fractographic examination of the fracture surfaces by scanning electron microscopy was carried out.

RESULTS AND DISCUSSION

Figures 1 and 2 exhibit the results obtained in the fracture toughness tests of electron beam and plasma arc welding specimens, respectively. In the last one has also been included the values recorded in the base material in the L-T orientation.

In the whole temperature range PAW weld metal specimens exhibited significantly higher toughness than base material. Moreover no significant decrease in toughness with the testing temperature was observed. Metallographic examination of these weldments revealed an acicular basket-weave microstructure of alpha phase needles, as it is seen in the micrograph of figure 3. However, the parent alloy in the mill annealed condition possesses a more equiaxic microstructure with grains slightly elongated in the rolling direction. Previous studies that were carried out on the same plate demonstrated that the acicular microstructure produced by beta field annealing and air cooling was more than twice tougher than the mill annealed one (10) and this has been associated with the more tortuous crack path as fracture propagates along the boundaries of individual needles linked by ductile dimples. This fracture topography has been also observed in these PAW specimens. Consequently, the higher fracture toughness values have been attributed to the acicular microstructure of weld metal.

Heat affected zone notched specimens showed toughness values intermediate between those of the weld metal and the base plate. These results can be explained considering the presence of a small volume fraction of alpha prime martensite in the heat affected zone due to the higher cooling rate. This phase is hard but very brittle and can reduce the toughness of the material. Fortunately, only a low content of this phase in the microstructure was observed.

Electron beam weldments also showed higher toughness than base material although the recorded differences are not so pronounced as those found in PAW ones. Once again metallographic examination helped to find an explanation to this behaviour.

As it is shown in figure 4 weld metal possesses an acicular microstructure, mainly formed by fine alpha needles but a certain presence of very fine alpha prime martensite needles, that was detected by the use of higher magnification and scanning electron microscopy. The increase in toughness is associated to this acicular alpha microstructure and the crack path deviation. On the other hand the reason for lower values than those obtained in PAW weldments attributed to these small areas of brittle alpha prime martensite. Fractographic analysis of the broken specimens is consistent with this hypothesis.

Comparison between the values recorded in the electron beam weldments corresponding to the two different welding procedures points towards a benefit of the use of lower beam intensity. A lower scattering in toughness values and higher average values was found in the EBW6B specimens welded using a lower beam. This is in good agreement with the above formulated hypothesis as the use of higher heat inputs would increase the cooling rate and facilitate the presence of alpha prime martensite. In a previous paper the benefit of low heat inputs that produces smaller grain in the fusion zone of gas tungsten arc weldments, leading to a higher fracture toughness, has been claimed (11).

However, to obtain the total depth of penetration in a single pass can oblige to use higher beam intensity. An alternative consists in the use of a commercially pure metal as filler metal which reduces the risk of alpha prime martensite formation. This possibility and the use of lower welding speed or beam oscillation to reduce the porosity of the weld deserve to be studied.

CONCLUSIONS

a.- A thick plate of a Ti-6Al-4V alloy has been welded in a single pass using plasma arc welding and electron beam welding processes. Fracture toughness characterisation in the temperature range between - 60 and + 20° C.

b.- PAW weld metal exhibits higher fracture toughness than base material in the whole temperature range. This behaviour has been associated with the acicular microstructure of alpha phase needles of the weld metal compared with the more equiaxic one of the base alloy.

c.- Heat affected zone notched specimens are between those of weld metal and the base plate. This result has been attributed to the presence of a small volume fraction of brittle alpha prime martensite formed due to the higher cooling rate.

d.- Electron beam weldments also showed higher toughness than base material although differences are not so marked as those found with PAW ones. The increase in toughness is considered to be due to the acicular alpha microstructure but the presence of reduced areas of alpha prime hindered that so high values as PAW weld metal ones could be recorded.

e.- A benefit of the use of lower beam intensity was observed and was associated with the lower cooling rate which decreases the amount of alpha prime martensite formed but the necessity to obtain a total depth penetration in a single pass in thick plates can oblige to use higher beam intensity. In this case, the use of a commercial purity titanium filler metal, the use of lower speed or beam oscillation are prone to be considered.

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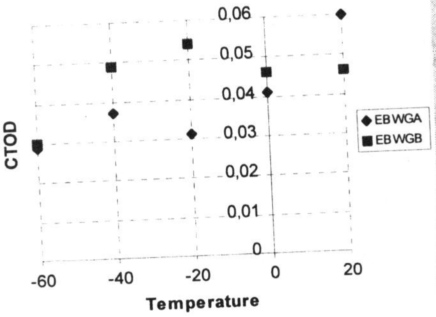

Figure 1. Fracture toughness versus testing temperature graph Electron Beam weldments

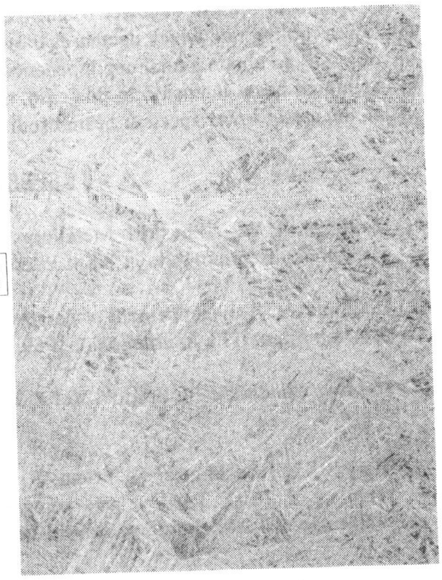

Figure 3. Weld metal microstructure PAW

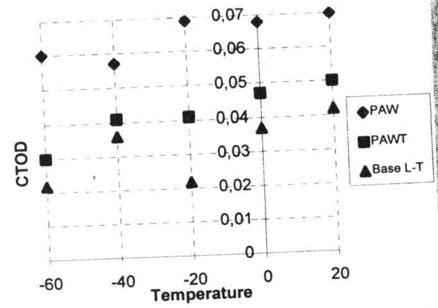

Figure 2. Fracture toughness versus testing temperature graph Plasma Arc weldments

Figure 4. Weld metal microstructure EBW6B