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Cyclic deformation of dissimilar welded joints between Ti–6Al–4V and Ti17 alloys: Effect of strain ratio

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ABSTRACT

Cyclic deformation characteristics of electron beam welded (EBWed) joints between Ti–6Al–4V and Ti17 (Ti–5Al–4Mo–4Cr–2Sn–2Zr) titanium alloys were evaluated via strain-controlled low-cycle fatigue tests at varying strain ratios at a constant strain amplitude. The welding led to a significant microstructural change across the dissimilar joint, with hexagonal close-packed (HCP) martensite α' and orthorhombic martensite α'' in the fusion zone (FZ), α' in the heat-affected zone (HAZ) of Ti–6Al–4V side, and coarse β in the HAZ of Ti17 side. A distinctive asymmetrical hardness profile across the joint was observed with the highest hardness in the FZ and a lower hardness in the HAZ of Ti17 side than in the Ti17 base metal (BM), indicating the presence of soft zone. The strength and ductility of the dissimilar joint lay in-between those of two base metals (BMs). Unlike wrought magnesium alloys, the Ti–6Al–4V BM, Ti17 BM, and joint basically exhibited symmetrical hysteresis loops in tension and compression in the fully reversed strain-controlled tests at a strain ratio of $R_\varepsilon = -1$. At a strain ratio of $R_\varepsilon = 0$ and 0.5, a large amount of plastic deformation occurred in the ascending phase of the first cycle of hysteresis loops of Ti–6Al–4V BM, Ti17 BM, and joint due to the high positive mean strain values. Fatigue life of the joint was observed to be the longest at $R_\varepsilon = -1$, and it decreased as the strain ratio deviated from $R_\varepsilon = -1$. A certain degree of mean stress relaxation was observed in the non-fully reversed strain controlled tests (i.e., $R_\varepsilon \neq -1$). Fatigue failure of the dissimilar joints occurred in the Ti–6Al–4V BM, with crack initiation from the specimen surface or near-surface defect and crack propagation characterized by fatigue striations.

1. Introduction

Titanium alloys have been increasingly used in key structural applications in aerospace, nuclear engineering, automotive, marine and chemical industries because of their low density, high specific strength, excellent fatigue and superior corrosion resistance [1–3]. Among titanium alloys, Ti–6Al–4V is the most commonly used alloy with a bimodal microstructure (i.e., primary α grains surrounded by $\alpha+\beta$ lamellar structure), which is essentially ductile [4] and has been widely used in low and high-temperature applications [5]. Ti17 alloy (Ti–5Al–2Sn–2Zr–4Mo–4Cr) is a type of alpha–beta titanium alloy which is rich in β-stablizing elements and has been used for the manufacture of aircraft engine components whose service temperature does not exceed 500 °C [6]. Such structural applications of these titanium alloys inevitably involve joining and welding of similar Ti-to-Ti alloys and dissimilar Ti-to-Al, Ti-to-Mg and Ti-to-steel alloys, which can provide more possibilities for the flexible design of the product by using each material efficiently, i.e., benefiting from the individual performance of each material [7]. Similar titanium alloy components can be joined via a variety of welding methods, such as electron beam welding (EBW) [8], laser beam welding (LBW) [9], linear friction welding (LFW) [10], friction stir welding (FSW) [11], gas tungsten arc welding (GTAW) [12] or tungsten inert gas (TIG) welding [13], among which EBW has drawn particular attention due to its high energy density, a deep and narrow joint, a small heat-affected zone (HAZ), low residual stresses and minimal distortion of welded materials [14–16]. On the other hand, structures with welded joints are frequently subjected to cyclic or thermal stresses (such as during takeoff and landing for an aircraft turbine engine) [17] and high strain rate deformation in service such as car crash, and the impact of foreign objects. Such loading may result in the occurrence of worrying fatigue failure, since the welded joints are more susceptible to this type of failure in view of the microstructural change caused by welding. Therefore, it is necessary to evaluate the mechanical properties of these weldments, especially fatigue resistance and cyclic deformation characteristics.

The earlier studies concerning the welded joints of titanium alloys were mainly conducted on microstructure, phase morphology,

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Table 1
Chemical composition of Ti–6Al–4V titanium alloy.

Element	Al	V	Fe	C	N	H	O	Ti
Content (wt%)	6	4	0.3	0.1	0.05	0.015	0.2	Balance

Table 2
Chemical composition of Ti17 titanium alloy.

Element	Al	Mo	Cr	Sn	Zr	Fe	C	N	H	O	Ti
Content (wt%)	5	4	4	2	2	0.3	0.05	0.04	0.012	0.15	Balance

Table 3
Test parameters under different strain ratios at a strain amplitude of 0.8% and a strain rate of $1 \times 10^{-2}\ s^{-1}$.

Strain ratio (R_ε)	Maximum strain (ε_{max}) (%)	Minimum strain (ε_{min}) (%)	Mean strain (ε_{mean}) (%)
0.5	3.2	1.6	2.4
0	1.6	0	0.8
−1	0.8	−0.8	0
−3	0.4	−1.2	−0.4
−∞	0	−1.6	−0.8

hardness, tensile and S–N curve properties [18–23]. For example, Tomashchuk et al. [18] studied the nature of intermetallic phases, the mechanism of weld formation, and the effect of the local accumulation of intermetallic phases on the microhardness in an electron beam welded (EBWed) Ti–6Al–4V/copper/AISI 316L joint. Tuppen et al. [19] performed stress-controlled fatigue tests to determine S–N curves of diffusion-bonded dissimilar Ti–6Al–4V/Ti–4Al–4Mo–2Sn–0.5Si titanium alloy joints. Several studies on the strain-controlled low cycle fatigue behavior of welded joints have also been reported [24–35]. For example, Feng et al. [27] studied cyclic deformation characteristics of friction-stir-welded 7075 Al alloy with triangular waveform, strain ratio of $R_\varepsilon = -1$, at a constant strain rate of $1 \times 10^{-2}\ s^{-1}$ and strain amplitude from 0.2% to 1.0%. Fu et al. [26] reported strain controlled low cycle fatigue tests for EBWed Ti–6Al–4V titanium alloy joints with triangular waveform, strain ratio of $R_\varepsilon = -1$, and strain amplitude from 0.25% to 0.6%. As reported in the earlier publications [24,25], the cyclic deformation behavior of EBWed dissimilar titanium alloy joints with triangular waveform, strain ratio of $R_\varepsilon = -1$, at a constant strain rate of $1 \times 10^{-2}\ s^{-1}$, and strain amplitude from 0.2% to 1.2% was also studied. However, to the authors′ knowledge, no study on the low cyclic fatigue behavior of EBWed dissimilar titanium alloy joints with emphasis on the effect of strain ratio has been reported in the open literature. Only a few studies have been reported on the effect of strain ratio on the low cyclic fatigue behavior of other hexagonal close-packed (HCP) materials, i.e., Mg alloys [36–39]. The questions remain elusive on the nature of the tension–compression symmetry and what would be the cyclic stress response in the dissimilar titanium alloy joints upon changing the strain ratio. The present study was, therefore, aimed at exploring cyclic deformation behavior of EBWed Ti–6Al–4V/Ti17 alloy joints under a constant strain amplitude with different strain ratios.

2. Material and experimental procedure

The materials used in the present study are forged Ti–6Al–4V and Ti17 titanium alloys of 10 mm in thickness, with chemical compositions listed in Tables 1 and 2, respectively. Both alloys were machined into plates with a dimension of 140 mm × 80 mm × 10 mm, and then mechanically and chemically cleaned before welding. EBW was performed using HDZ-15B EBW machine with an accelerating voltage (V) of 60 kV, an electron current (I_b) of 68 mA, a focus current (I_f) of 2230 mA, and a welding speed (v) of 500 mm/min.

Metallographic samples were cut from the EBWed workpieces perpendicular to the welding direction, then ground, polished and etched using Keller′s reagent (12 ml HF, 36 ml HNO_3 and 42 ml H_2O). Microstructures were examined via optical microscope and JSM-6380LV scanning electron microscope (SEM). 0.5 mm thick samples for transmission electron microscopy (TEM) observations were cut from the EBWed workpieces perpendicular to the welding direction, and ground down to a thickness of about 120 μm. Then 3 circular foil samples were made from the fusion zone (FZ), HAZ on both sides and were ground further down to a thickness of about 70 μm. TEM observations were carried out via JEM-3010 microscope with the foil samples prepared using electro-polishing in an electrolyte of 6% $HClO_4$ + 34% C_4H_9OH + 60% CH_3OH (volume fraction) to observe the microstructure in the FZ and HAZ on both sides. Microhardness was determined across the weld at a distance of 5 mm (middle) from the bottom surface, using a computerized Buehler hardness tester with a load of 500 g and a dwell time of 15 s at an interval of 0.1 mm.

Tensile specimens with a gauge length of 25 mm and a thickness of 1 mm and fatigue specimens with a gauge length of 12.5 mm and a width of 3 mm were machined perpendicular to the welding direction with the FZ located in the middle of the gauge length using electro-discharge machining (EDM). The gauge area was ground along the loading direction up to #600 SiC papers to remove the EDM cutting marks and to achieve a smooth surface. The tensile tests were carried out according to ASTM E8 standard using a computerized United tensile testing machine at a strain rate of $1 \times 10^{-2}\ s^{-1}$ with a 25 mm extensometer and at least three specimens were tested. Total strain controlled, pull–push type fatigue tests with a 12.5 mm extensometer in accordance with ASTM-E606 were conducted in air at room temperature using a computerized Instron 8801 fatigue testing system at five different strain ratios R_ε $(=\varepsilon_{min}/\varepsilon_{max})$ of 0.5, 0, −1, −3, and −∞ (Table 3), at a given total strain amplitude of 0.8% and a constant strain rate of $1 \times 10^{-2}\ s^{-1}$. At least two samples were tested at each strain ratio, and triangular loading waveform was applied during the tests. For the sake of comparison, some samples of extruded AM30 magnesium alloy (with a composition of 3.4 wt% Al, 0.33 wt% Mn, 0.16 wt% Zn, 0.0026 wt% Fe, 0.0006 wt% Ni, 0.0008 wt% Cu, and balance Mg) were also tested. Fatigue crack initiation site and crack propagation mechanisms were examined on the fracture surfaces of failed samples via SEM.

3. Results

3.1. Microstructure

Fig. 1 shows the microstructure of the Ti–6Al–4V base metal (BM) and Ti17 BM, respectively. It is seen that Ti–6Al–4V had a characteristic bimodal microstructure, consisting of a mix of equiaxed α grains and inter-granular $\alpha+\beta$ lamellae (Fig. 1(a)), while Ti17 was composed of fine α plates embedded in the β matrix (Fig. 1(b)). A considerable microstructural change occurred across the weld after EBW, as shown in Fig. 2, where more detailed microstructures in the FZ and HAZ (TEM images) are shown in Fig. 2(b)–(d). The FZ was narrow (∼2 mm wide) and consisted mainly of fine martensite α' and α'' phase (Fig. 2(c)) due to the fast cooling during EBW. Edwards et al. [40] and Akhonin et al. [41] also observed the similar fine acicular microstructure in the FZ of EBWed titanium alloy joints. This was, however, in sharp contrast