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Strain-controlled fatigue properties of linear friction welded dissimilar joints between Ti–6Al–4V and Ti–6.5Al–3.5Mo–1.5Zr–0.3Si alloys

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ABSTRACT

The purpose of this study is to evaluate the microstructure, microhardness and fatigue properties of linear friction welded (LFWed) dissimilar joints between Ti–6Al–4V (TC4 according to Chinese classification) and Ti–6.5Al–3.5Mo–1.5Zr–0.3Si (TC11) titanium alloys. A significant microstructure change across the dissimilar joint occurs after linear friction welding (LFW), with martensite in the weld zone (WZ) and small recrystallized grains in the thermo-mechanically affected zone (TMAZ) on the TC4 side. A characteristic asymmetrical hardness profile across the dissimilar joint is observed with significantly higher hardness values in the WZ, and no soft zone is present in the dissimilar joint. The LFWed dissimilar joint exhibits essentially symmetrical hysteresis loops and an equivalent fatigue life to the base metals, which increases with decreasing strain amplitude. While cyclic stabilization appears at lower strain amplitudes up to 0.6% for the joint, cyclic softening basically occurs at higher strain amplitudes. In the joint fatigued at a high strain amplitude of 1.2%, a short initial cyclic hardening occurs, corresponding to the presence of twinning and the resistance to the dislocation movement. Fatigue failure of the dissimilar joint occurs on the TC4 side and is far from the weld line, suggesting that a highly durable and sound dissimilar joint is achieved via the present solid-state LFW. Fatigue crack initiation occurs from the specimen surface or near-surface defect, and crack propagation is mainly characterized by fatigue striations which are perpendicular to the crack propagation direction, in conjunction with some secondary cracks.

1. Introduction

Due to low density, high strength, and excellent fatigue and superior corrosion resistance, titanium alloys have been increasingly used in many critical structural applications in aerospace [1–3]. These materials are particularly suitable for service temperature below 600 °C and high dynamic load applied to the components, such as disks, vans and blades of compressor [4]. Usually, blade and disks (blisks) which are subjected to different operating temperatures and stresses require dual properties. For the blades high creep resistance and fracture toughness are necessary due to the relatively high operating temperature and low working stress, while for the disks high strength, good ductility and superior low-cycle fatigue properties are necessary due to relatively low service temperature and high stress. There are currently a number of titanium alloys which can meet these requirements; however, how to join dissimilar titanium alloys to achieve high structural integrity is an important topic.

There are several welding methods to join titanium alloys, such as linear friction welding (LFW) [5–8], electron beam welding (EBW) [9], laser beam welding (LBW) [10], friction stir welding (FSW) [11], tungsten inert gas (TIG) welding [12]. Among these, LFW is an advanced solid-state process, which is especially suitable for welding titanium alloys. LFW involves a reciprocating movement of one component relative to the other with the aid of axial force to generate frictional heat. This technique is promising in the global manufacturing industry due to its advantages of high quality, high efficiency, energy conservation, and the absence of liquid or fusion zone [5]. In addition, LFW usually uses non-symmetric components with respect to rotary friction welding (RFW). Therefore, LFW has been considered as an innovative technique in the manufacturing and maintenance of aero-engine blisks. The blisks are often unavoidably involved in fatigue resistance under dynamic/alternating loading, which would result in the occurrence of worrisome fatigue failure. Therefore, it is necessary to evaluate the fatigue resistance and cyclic deformation characteristics of the linear friction welded (LFWed) joints.

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Previous studies on the LFWed titanium alloys mainly focused on the microstructure, phase morphology, hardness, tensile and finite element simulations [13–19]. Vairis et al. [13,14] revealed the nature of LFW using Ti–6Al–4V (TC4 according to Chinese classification) and showed that the process has four distinct phases. Li et al. [5] and Wanjara et al. [6] studied the microstructure and hardness in LFWed TC4 joints. Ma et al. [15] examined the tensile properties and microstructure of the dissimilar LFWed TC4/Ti–6.5Al–3.5Mo–1.5Zr–0.3Si (TC11 according to Chinese classification) joint. Frankel et al. and Preuss et al. [8,16] studied the effect of heat treatment on the residual stresses of the LFWed joint. Turner et al. [17] and Sorina-Müller et al. [18] reported the temperature change and material flow in the LFW process. Studies on the strain-controlled or stress-controlled fatigue behavior of titanium joints remain quite limited to date [19–24]. For example, Wang et al. [19,20] reported the cyclic deformation 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%. Fu et al. [21] reported strain controlled low cycle fatigue (LCF) 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%. Mohandas et al. [22] studied the stress-controlled LCF behavior of friction welds and electron beam welds of the α–β titanium alloy (Ti–6.5Al–3.3Mo–1.6Zr–0.3Si) at ambient temperature, and reported that the friction welds exhibit considerably superior LCF behavior compared with EBWed joints. To the authors' knowledge, no information on the strain-controlled fatigue behavior of LFWed dissimilar joints between TC4 and TC11 alloys is available in the literature. It is unknown what the effect of the welding on the strain-controlled fatigue properties would be in the LFWed dissimilar joints between TC4 and TC11. Therefore, the objective of the present study was to evaluate cyclic deformation behavior of LFWed dissimilar joints between TC4 and TC11 under a constant strain ratio with different strain amplitudes.

2. Materials and experimental procedure

The materials used in the present study are forged TC4 and TC11 titanium alloys with the compositions listed in Tables 1 and 2, respectively. Both alloys were machined by electro-discharge machining (EDM) into blocks with dimensions 70 mm × 18 mm × 11 mm (the weld interface had dimensions of 18 mm × 11 mm, where the thickness is 11 mm and the length along oscillation is 18 mm). LFW was performed using the lab-made machine (type XMH-160, Northwestern Polytechnical University, Xi'an, China). Based on the previous research, a combination of optimized welding parameters was selected in the present study.

Metallographic samples for microstructure observations were cut from the linear friction welded (LFWed) joints perpendicular to the oscillation direction, then ground using emery papers up to a grit number of 1200 and then polished. The polished samples were

Table 1
Chemical compositions of TC4 titanium alloy.

Element	Al	V	Fe	C	N	H	O	Ti
wt%	6	4	0.3	0.1	0.05	0.015	0.2	Bal.

Table 2
Chemical compositions of TC11 titanium alloy.

Element	Al	Mo	Zr	Si	Fe	C	N	H	O	Ti
wt%	6.5	3.5	1.5	0.3	0.25	0.1	0.05	0.012	0.15	Bal.

etched using Keller's reagent (12 ml HF, 36 ml HNO_3 and 42 ml H_2O). Microstructures were examined via optical microscopy (OM) and scanning electron microscopy (SEM) using a JSM-6380LV microscope and 3D fractographic analysis capacity. Microhardness was determined across the weld using a computerized Buehler Vickers microhardness tester with a load of 500 g and a dwell time of 15 s at an interval of 0.025 mm across the WZ.

Fatigue specimens with a gauge length of 12.5 mm (or a parallel length of 16 mm) and a width of 3 mm were machined perpendicularly to the oscillation direction using EDM. The gauge section of fatigue samples was ground progressively along the loading direction with emery papers up to grit #600 to remove the EDM cutting marks and to achieve a smooth surface. Total strain controlled, pull–push type fatigue tests were conducted using a computerized Instron 8801 fatigue testing system at different strain amplitudes from 0.2% up to 1.2% with an interval of 0.2% at room temperature. A triangular waveform with a strain ratio of $R = -1$ was applied at a constant strain rate of $1 \times 10^{-2}\ s^{-1}$ during the tests, where R is the minimum peak strain divided by the maximum peak strain in the strain-controlled fatigue tests. The strain-controlled testing at low strain amplitudes was carried on until 10,000 cycles, and then tests were changed to load control at 50 Hz. At least two specimens were tested at each strain amplitude. Fatigue crack initiation site and crack propagation mechanisms were examined on the fracture surfaces of failed samples via SEM.

3. Results and discussion

3.1. Microstructure

The microstructure of the base materials (BMs) of TC4 and TC11 is shown in Fig. 1. It is seen that both TC4 and TC11 alloys have a typical bimodal microstructure consisting of a combination of equiaxed α grains and inter-granular α+β lamellae. More lamellae are observed in the TC11 alloy. According to the previous studies [5–8], the microstructure of the LFWed joint is normally classified as weld zone (WZ) and thermo-mechanically affected zone (TMAZ) since the grains in the TMAZ are elongated, as seen in Fig. 2(a). It is clear that a huge microstructural change occurs in the WZ and TMAZ after LFW. The weld line can be obviously seen from Fig. 2(a). It is of special interest to see that TC4 and TC11 alloys have a varying WZ, that is, the thickness of the TC11 WZ (~1100 μm) is larger than that of the TC4 WZ (~700 μm). This would be associated with the difference in the thermal conductivity on both sides of the dissimilar joint during LFW. TC11 titanium alloy has a higher thermal conductivity at high temperatures than TC4, which is confirmed in the literature [25], leading to a wider WZ and coarse microstructure on the TC11 side than on the TC4 side. The WZ on both sides of the weld line is mainly composed of martensitic α′ phase (Fig. 2(b)), which is attributed to the fast cooling during LFW. Li et al. [5], Turner et al. [17] and Sorina-Müller et al. [18] reported that the interface temperature of LFWed TC4 joints could arrive at about 1200 °C which is higher than the beta transus temperature of TC4 (995 °C) [26] and TC11 (1020 °C) [27]. The subsequent cooling rate could reach about 410 °C/s and the martensitic phase α′ with a hcp crystal structure will be formed [28,29]. Thus the original α and β phases at the location of WZ quickly transformed to high-temperature β phase, which is in turn transformed to α′ phase (Fig. 2(b)) due to the very fast cooling rate. It is also observed that martensite on the TC4 side is finer than that on the TC11 side as shown in Fig. 2(a), which is due to the higher thermal conductivity on the TC11 side as mentioned above, leading to the coarser martensite on the TC11 side.