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Effects of post-weld heat treatment on fracture toughness of linear friction welded joint for dissimilar titanium alloys

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ABSTRACT

The effect of post-weld heat treatment processing parameters on the microstructure, fracture morphology, fracture toughness and crack propagation direction of the linear friction welded joint for dissimilar titanium alloys was investigated. Results show that weld zone and one side of thermo-mechanically affected zone are weak zones for fracture toughness of linear friction welded joint for dissimilar titanium alloys after welding; post-weld heat treatment can effectively improve the fracture toughness of the weak zones, but has less effect on that of the other side. During the heat treatment process, the fine acicular and equiaxed microstructures in the weak weld zones grow and partly transform into lamellar microstructure which can increase the total length of the crack along with energy consumption and relieve the residual stress, resulting in enhancing the fracture toughness of the joint. Meanwhile, the fracture morphology gradually transforms from intergranular fracture to ductile–brittle mixed fracture and dimple fracture.

1. Introduction

In recent years, aeroengine components are developing in the direction of lightweight and integration. By integrally welding engine rotor blade and disk, BLISK has replaced tenon, mortise, locking device, etc. existing in conventional engine structures with a simple structure, that is light weight and has a high intensity and has been used as a key component of new-type aeroengines [1]. The precision and quality of the weld account for the performance and functional reliability of a BLISK during the manufacturing and repair process. Therefore, linear friction welding, a valid, efficient and environmentally friendly solid-state joining technology, is usually applied to ensure high quality of welding and repairing BLISK [2–5].

In engineering application, blade, mainly taking on aerodynamic loads and high-frequency vibration stress, generally uses equiaxed titanium alloys with high temperature and high-cycle fatigue properties, whereas disk, mainly taking on centrifugal loads, generally uses basket-weave titanium alloys with high creep resistance, low cycle fatigue properties and low fracture toughness [6,7]. Therefore, linear friction welded BLISK, prepared by welding dissimilar titanium blade and disk, gives full play to advantages of two titanium alloys and further improves the integral performance of aeroengines [8].

During the linear friction welding process, heat and stress always act on the friction interface and metal around, leading to a variety of thermal coupling phenomena existing in welded joints including mutual diffusion, dynamic recrystallization, plastic deformation and flow. Defects appeared on friction interface easily causing stress concentration and residual stress. The materials on or around the friction interface with high stress level become the weak zone of the welded joint [9]. After post-weld heat treatment, the joint microstructure becomes homogeneous; the mechanical properties improve with stress relief.

Preliminary results show that the linear friction welded joint for dissimilar titanium alloys could be divided into weld zone (WZ) and thermo-mechanically affected zone (TMAZ), but there was a big difference between microstructures on both sides of the weld interface [10–12]. The fine acicular and equiaxed microstructures were formed under plastic deformation and dynamic recrystallization on the center and edges of the weld interface. The banded microstructures were generated under plastic deformation on the microstructures, which rearranges by the friction direction on both sides of the TMAZ. After post-weld heat treatment, the microstructure in each zone of the welded joint gradually grew up stably.

At present, research on linear friction welding of titanium alloys mainly focuses on welding process, joint microstructure and conventional mechanical properties [13–16]. There are few studies and reports about the effect of joint microstructure on fracture toughness considered as a crucial factor indicating the integrity of a BLISK.

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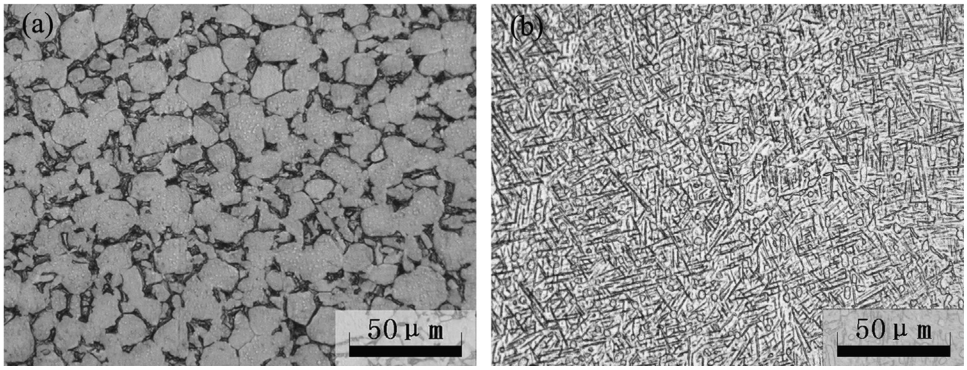

Fig. 1. Base metals: (a) TC4 alloy and (b) TC17 alloy.

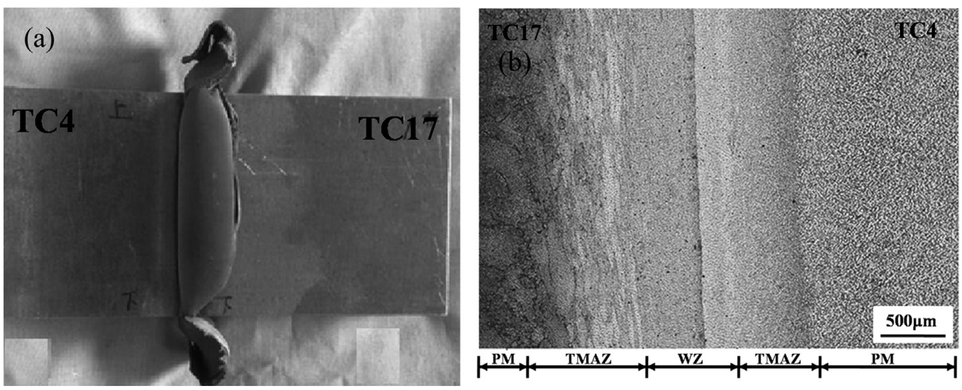

Fig. 2. Linear friction welded joint: (a) linear friction welded joint and (b) microstructure (585 °C, 3 h).

In this paper, focusing on the linear friction welded TC4 (Ti–6Al–4V) and TC17 (Ti–5Al–2Sn–2Zr–4Mo–4Cr) dissimilar titanium alloys, the microstructures of the two base metals are as shown in Fig. 1. The effect of post-weld heat treatment on fracture toughness, microstructure, fracture morphology and crack propagation direction was investigated, which provided a basis for manufacturing and life estimation of BLISK.

2. Materials and experimental methods

Linear friction welded TC4+TC17 dissimilar titanium alloys were prepared based on optimized parameters. The heat mainly generated on TC4. TC17 got to thermoplasticity through thermal conduction and reciprocating friction, forming the joint as shown in Fig. 2a. Under high-temperature condition, TC4 alloy presented lower yield strength but higher strain than TC17 alloy. Therefore, the flash mainly extruded from TC4 to TC17, leading to big differences in width between the welded joint zones, as seen in Fig. 2b. The flash on the welded joint was cut off. The welded joint was processed in a vacuum furnace for 3 h with annealing treatment under the temperatures of 585 °C, 630 °C, 655 °C, 685 °C and 700 °C and removed from the vacuum furnace after cooling. The heating rate was set as 10 °C/min and the vacuum degree was greater than 0.02 Pa.

The CTOD test for welded joint specimens was based on ASTM E1290-08 Standard "Test Method for Crack Tip Opening Displacement (CTOD) Fracture Toughness Measurement". In accordance with the standard, standard three-point bending test specimens for fracture toughness were prepared as shown in Fig. 3a and b. The precrack direction of the specimens was the thickness direction. CTOD was prefabricated on the WZ and both sides of the TMAZ, three specimens for each group. Specimens were tested by MTS-880 servo-hydraulic testing machine at room temperature. The load sensors and the extensometer were set as 100 kN and 0.5%, respectively. After testing, the CS3400 scanning electron microscopy (SEM) and OLYMPUS-BX51M microscope were used for observing the fracture morphology and crack propagation direction of the chosen specimens.

3. Experimental results

3.1. Force-clip gage displacement curve of welded joint zone

It can be seen from Fig. 4a that the maximum absorbed in fracture energy and test load appear at TC4-side TMAZ after welding (AW) due to good plasticity, elongation and thermal stability of the equiaxed microstructure. Although basket-weave microstructure has an advantage in heat resistance, TC17-side TMAZ has lower absorbed in fracture energy and test load with poor plasticity and thermal stability. Meanwhile, complex thermo-mechanically coupled effect in the friction welding interface easily causes stress concentration and residual stress, which leads to lower absorbed in fracture energy and test load. In addition, the WZ and the TC17-side TMAZ where the crack initiation point is close to the unstable propagation point present poor fracture toughness with sudden fracture and decreased load after crack propagation compared with the TC4-side TMAZ.

When heat treatment temperature is low (585 °C, as shown in Fig. 4b), the curve follows the same variation trend as that of the welded joint under AW. With increasing temperature (700 °C), the elements of welded joint get fully diffused. It is observed from Fig. 4c that the energies absorbed in fracture and test load in the WZ and TC17-side TMAZ are significantly improved to or near the level of the fracture toughness of TC4-side TMAZ. It is concluded that the energy