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Strain hardening behavior of linear friction welded joints between TC11 and TC17 dissimilar titanium alloys

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ABSTRACT

The influence of strain rate on the tensile properties and its distribution of linear friction welded (LFWed) dissimilar joints between Ti–6.5Al–3.5Mo–1.5Zr–0.3Si (TC11) and Ti–4Mo–4Cr–5Al–2Sn–2Zr (TC17) titanium alloys were studied in this paper. Furthermore, strain hardening behavior, strain rate sensitivity and fracture characteristic of the LFWed joints have been evaluated. It was found that a great deal of ultra-fine grains appear on the TC11 side of weld zone (WZ). The microstructure on the TC17 side of WZ is composed of coarsened β phase, a lot of slip lines and dislocation networks within the boundaries of β grains generate under high temperature deformation by transmission electron microscope (TEM). A distinctive asymmetrical hardness profile is observed across the joint, with higher hardness on the TC11 side of WZ and lower hardness on the TC17 side of WZ, respectively. While the yield strength (YS), ultimate tensile strength (UTS) of the joint increase, both hardening capacity and strain hardening exponent n-value decrease with increasing strain rate, meanwhile, the strain-hardening rate θ increases at a given true stress. Strain rate sensitivity of the welding joint decreases with increasing plastic strain. Moreover, the fracture location of the LFWed joints between TC11 and TC17 titanium alloys almost locate at the regions with lower hardness. Additionally, ductile fractures and a mixed cleavage fractures appear respectively at the center and edge area of the LFWed joints.

1. Introduction

Titanium and its alloys have been successfully and increasingly used in the aerospace industrial area for their unique properties, such as low density, high specific strength, wide operating temperature range and superior corrosion-resistant ability [1–4]. At high temperatures, the metal reacts strongly with atmospheric gases such as oxygen and nitrogen, thus the welding in air would make the joint completely brittle. Therefore, only in a vacuum or a protective atmosphere are Ti and its alloys weldable. The traditional fusion welding usually exist poor shielding of the welding zone or impure shielding gas during the welding process, which could lead to serious contamination [5]. Therefore, the solidification problems appear, e.g. porosity, hot cracking, segregation, etc. To overcome these problems, linear friction welding (LFW) is considered to be an ideal process to join titanium and its alloys.

LFW is a solid state process for joining materials together through intimate contact of a plasticized interface, which is generated by frictional heat produced as one component is moved relatively to another under pressure [6–8]. It is a complicated and quick thermo-mechanically coupled physical process, which is suitable for materials with low thermal conductivity and high temperature mechanical properties [9]. Therefore, the process is considered to be particularly appropriate for joining of titanium and nickel alloys [10–12]. The development of LFW has been driven by the aeroengine manufacturing industry to fabricate integrally bladed disks (blisks) giving light weight and improved performance over the existing slotted blade/disk assemblies [8]. There are some research works related with LFW of titanium alloys in recent years. Vairis and Frost [13,14] systematically analyzed the change laws in different phases of the Ti–6Al–4V alloy LFWed joints at variable frequencies and amplitudes of oscillation. The process is divided into four distinct phases: in the first phase, the two materials are brought in contact under pressure and heat is generated from solid friction; in the transition phase, heat affected zone expands and the true contact area is considered to be 100% of the cross-sectional area, and the soft plasticized layer is no longer able to support the axial load; in the equilibrium phase, axial shortening increases sharply and heat is conducted away from the interface and a plastic zone develops; in the deceleration phase, the relative motion is stopped abruptly and forging pressure is applied to consolidate the weld. Karadge et al. [15] examined the microstructure and texture development in as-welded and post weld heat treated Ti–6Al–4V LFWed joints. Frankel et al. [16]

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compared the residual stresses between Ti–6Al–4V and Ti–6Al–2Sn–4Zr–2Mo LFW. Romero et al. [6] examined the effect of the forging pressure on the microstructure and residual stress development in Ti–6Al–4V LFW. Refs. [17–19] investigated the microstructure and mechanical properties of LFWed joints of Ti–6Al–4V alloy, such as impact toughness and fracture characteristics.

The strength, ductility, toughness and deformability of materials are intimately related to strain hardening characteristics [20]. For this reason, many investigations have been carried out on the strain hardening behavior and physical mechanism of conventional metallic materials [21,22]. Hitherto many studies have been reported on the strain hardening behavior of Ti alloys. For example, Bystrzanowski et al. [23] investigated the tensile flow behavior of Ti–46Al–9Nb sheet material and observed only stage III strain hardening at high temperatures. Honarmandi and Aghaie-Khafri [24] studied the strain hardening behavior of Ti–6Al–4V and TiAlx alloys, respectively, by means of compression testing at high temperatures and observed different stages of strain hardening. In spite of many studies focused on the strain hardening behavior of titanium alloys as well as the strain hardening behavior of welded joints, there were few reports about the dynamic mechanical behavior of LFWed dissimilar titanium alloy joints until now. However, for the reliable design of the gas turbine structural components, it was very important to understand the mechanical behavior of LFWed joints as well as the strain rate effect on it. Therefore, this study was aimed at evaluating the strain rate effects on the mechanical properties, deformation and fracture behavior of LFWed joints with TC11 and TC17 dissimilar alloys. Due to the different stress and environmental status of the blade and disk, for example, the disk bears large tensile stress on the low temperature and the blade bears small stress on the high temperature, therefore, dual alloy (TC11 as blade and TC17 as disk) – dual property blisk can play a greater extent their excellent performance, and work in a larger temperature gradient and stress gradient conditions.

2. Materials and methods

The materials used in the present study are forged TC11 and TC17 titanium alloys, and their chemical compositions were listed in Table 1. Both alloys were machined into the plates with a dimension of 130 mm × 75 mm × 20 mm, and then mechanically and chemically cleaned before welding. The LFW machine was developed by Beijing Aeronautical Manufacturing Technology Research Institute (China) and was carried out with oscillation frequency of 40 Hz, amplitude of 3 mm, friction pressure of 50 MPa, and friction time of 3.6 s.

Metallographic samples of the welded joints cut perpendicular to the welding direction were prepared and examined via optical microscopy (OM), scanning electron microscopy (SEM) and transmission electron microscope (TEM). Vickers microhardness was determined using a load of 500 g and a dwell time of 15 s. All the microhardness values presented in this study were an average of three series of values taken on the same specimen. The center point of the WZ was determined carefully after observing the weld geometry under microscope and all the indentations were adequately spaced to avoid any potential effect of strain field caused by adjacent indentations.

Table 1
Chemical composition (wt%) of TC11 and TC17 titanium alloys.

elements	Al	Mo	Cr	Si	Sn	Zr	Ti
TC11	5.8–7.0	2.8–3.8	–	0.2–0.4	–	1.0–2.0	Allowance
TC17	4.5–5.5	3.5–4.5	3.5–4.5	–	1.5–2.5	1.5–2.5	Allowance

Tensile tests were performed using ASTM-E8M subsized samples on a fully computerized tensile testing machine at room temperature and strain rates from 10^{-5} to $10^{-2}\,s^{-1}$. Subsized tensile specimens of 100 mm long with a gauge length of 25 mm (or a parallel length of 32 mm) and gauge width of 6 mm were machined perpendicularly to the welding direction using electro-discharge machining (EDM). The gauge area was ground up to #1000 SiC papers to remove the EDM cutting marks and to achieve a smooth and consistent surface. Three specimens in each case were tested to check the reproducibility of the test data. The 0.2% offset YS, UTS, ductility and the work hardening properties were evaluated. Fracture morphologies after tensile testing were examined using SEM to identify the fracture mechanisms.

3. Results and discussion

3.1. Microstructure

The microstructures of the base metals (BM) are shown in Fig. 1. It is seen that the BM consists of $\alpha+\beta$ phases. The microstructure of TC11 alloy is composed of equiaxed prior-α phase and intergranular transformed β phase (mixture of lamellar α and β phases). The volume fraction of β phase is about 47.4% [25]. TC17 alloy is rich in β phase and is composed of basket-weave microstructure, and α phase precipitates uniformly within grains [26]. After LFW, a remarkable change of microstructure occurs in the WZ and thermo-mechanically affected zone (TMAZ) as shown in Fig. 2(a)-(d). It can be clearly seen that the welding interface between the TC11 and TC17 alloys. The microstructures of WZ between TC11 and TC17 alloys are different each other. The microstructure on the TC11 side of WZ consists of acicular and fine martensites α' and α'' during the thermo–mechanical processing due to high thermal conductivity and fast cooling rate and a relatively short dynamic recrystallization (DRX) period [8,27,28], as shown in Fig. 2(b) and (d). In contrast, the microstructure on the TC17 side of WZ is composed of coarsened β phase (Fig. 2b and c), which is attributed to more β-stabilizing alloying elements existing in Table 1 and long DRX period with low thermal conductivity. The results lead to the presence of a soft zone [29–31]. The percentage of DRX increases with temperature above 1000 °C [32]. For further to investigate the microstructural features in the WZ of LFWed joints, TEM test method was applied on the TC11 and TC17 sides of WZ as shown in Fig. 2(e) and (f). Lots of slip lines and dislocation networks within the boundaries of β grains are generated under high temperature deformation on the TC17 side of WZ during the LFW process. The β grain of the body-centered cubic (BCC) crystal structure is shown by the selected-area diffraction pattern (SADP) with a typical diffraction pattern of zone axis [001]. Due to the high stacking fault energy (SFC) of titanium alloys, dislocations are hard to break down [33]. During the deformation, the dislocations are tangled with the help of crossing and climbing, more dislocations gather and high-angle subgrain boundaries appear. On the TC11 side of WZ, the martensite α' of the hexagonal close packed (HCP) crystal with the SADP forms during the fast cooling and the certain dislocation density occurs due to the thermoplastic deformation [33–35]. The microstructures of TMAZ on both TC11 and TC17 sides become elongated along the flow direction of plasticized materials, which are almost parallel to the weld line and the streamline (Fig. 2c and d). The microstructure of the joint at the edge zone is similar with the center zone. However, the width of the edge zone is wider than the central region due to more energy stored at the edge zone by the heat reflux of the flash after welding. The reason is that the