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Abnormal microstructure in the weld zone of linear friction welded Ti–6.5Al–3.5Mo–1.5Zr–0.3Si titanium alloy joint and its influence on joint properties

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ABSTRACT

A detailed investigation on an unexpected abnormal microstructure formed near the weld line in the linear friction welded Ti–6.5Al–3.5Mo–1.5Zr–0.3Si titanium alloy joint had been performed. Microstructure observations with the help of optical microscope, electron backscatter diffraction and transmission electron microscope with an energy dispersive X-ray spectroscopy were conducted to determine the compositions and phases near the weld line. The results indicate that the abnormal microstructure may be obtained at a low friction pressure and consists of α phase in the form of spherical particles. Tensile strength and fracture characteristics were also examined to clarify the influence of α grains. It is found that the tensile strength is only about 49% of the parent material. The explanation to the formation of spherical α is that lamellar α breaks up, spheroidizes and coalesces to form bigger particles by squeezing out the softer intergranular β phase. The effect of post-weld heat treatment (PWHT) was also investigated to optimize the joint microstructure and mechanical properties. The results suggest that the defects still exist after PWHT, and consequently the appropriate process parameters should be used to achieve a good weld.

1. Introduction

Titanium alloys have been investigated extensively and widely used for aerospace industrial applications for their unique properties such as low density, high specific strength, wide operating temperature range and high corrosion-resistant ability [1]. The poor antioxidation capacity at elevated temperatures [2], however, limits their service temperatures below 600 °C. 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. Solid-state welding techniques can avoid this problem since the material does not reach the melting point. Therefore, linear friction welding (LFW), as a solid-state welding process, which has already been used in manufacturing and repairing blisks, offers great potential for further applications [3].

LFW joins materials together through the relative reciprocating motion of two components under a compressive force [4,5]. A schematic diagram of this process is shown in Fig. 1 [6]. As the components do not reach melting conditions, it can therefore be carried out in air without protective measures [7]. This process has four distinct phases, including the initial phase, the transition phase, the equilibrium phase and the deceleration (or forging) phase [8]. LFW offers many advantages, such as no solidification defects (e.g., hot cracking, porosity, segregation, etc.) [9], and is very suitable for welding titanium alloys without protection. Although LFW has been used to manufacture blisks by Rolls & Royce, MTU, etc. [10], its wider applications have been limited due to the lack of fundamental understandings, such as the evolution of microstructure, the bonding mechanism of the joint, and the effect of post-weld heat treatment.

LFW has been used successfully to join a variety of materials such as steels [9,11,12], dissimilar materials (aluminum to magnesium [13], aluminum to copper [14]), Ni-based superalloys [3,15], and titanium alloys with most of the work done on aircraft engine alloys. The available literature on LFWed titanium alloys has focused on experimental studies and numerical analyses. Vairis and Frost [8] firstly reported the change of impact strength of LFWed Ti-64 joints with process parameters. Wanjara and Jahazi [16] investigated the influence of welding parameters on the microstructure, microhardness, and mechanical properties of LFW Ti-64 joints. Romero et al. [17] studied the effect of forging pressure on the microstructure and microhardness of LFWed Ti-64

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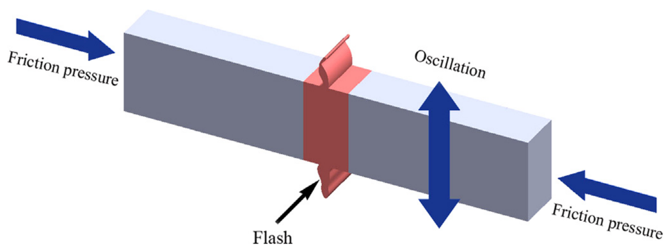

Fig. 1. Schematic diagram of the LFW process [6].

Table 1
Nominal chemical composition of TC11 titanium alloy (wt%).

Ti	Al	Mo	Zr	Si	O	Fe	C	N	H
Bal.	6.51	3.51	1.58	0.27	0.1	0.072	0.012	0.013	0.0007

joints. Dalgaard et al. [18] examined mechanical properties such as microhardness and tensile strength of a near-β Ti alloy by altering the frequency of oscillation and axial pressure. Nevertheless, very few publications have been concerned on the relationship between process parameters and microstructure and mechanical properties of LFWed Ti–6.5Al–3.5Mo–1.5Zr–0.3Si (TC11 according to Chinese classification) alloy joints, except one by Lang et al. [19] showing the microstructure characteristics of the joints. The high strength α+β TC11 alloy, similar to the Russia alloy BT9 [20], has been studied for its high strength to weight ratio, good corrosion resistance while having a high service temperature of 500 °C and widely used in manufacturing blades, disks and other airplane components [21].

More recently, our preliminary work showed that friction pressure and forging pressure have a strong influence on the microstructure and mechanical properties of LFWed Ti–6Al–4V joints [22]. Under low friction pressure and forging pressure, some abnormal structures were observed in the weld zone which were confirmed to be spherical α grains. However, the formation mechanism of these α grains had not been completely identified. In this study, the effect of friction pressure on microstructure and mechanical properties of LFWed TC11 was studied, in which the similar abnormal structures did appear in the weld zone. The formation mechanism of these spherical α grains was discussed in detail. For better understanding of the microstructure evolution and mechanical properties, the effect of post-weld heat treatment (PWHT) was also investigated.

2. Experimental procedures

A titanium alloy (TC11) with the beta-transus temperature of about 1009 °C was used and its nominal chemical composition is given in Table 1. The microstructure revealed by optical microscope (OM) is a typical α+β structure consisting of equiaxed prior-alpha and intergranular transformed beta microstructure (mixture of lamellar alpha and beta phases) as shown in Fig. 2.

The dimensions of the specimens being joined were 10 mm in width (W), 17 mm in length (L), and 45 mm in height (H) with the faying face in the $W \times L$ plane. Prior to welding, the contact surfaces of the samples were cleaned in an acetone bath. The LFW machine (XMH-160 type) used to weld TC11 blocks was developed at Northwestern Polytechnical University (China). The influence of the welding parameters was studied by changing friction pressure. The typical two sets of welding parameters employed are illustrated in Table 2. Note that only the relative

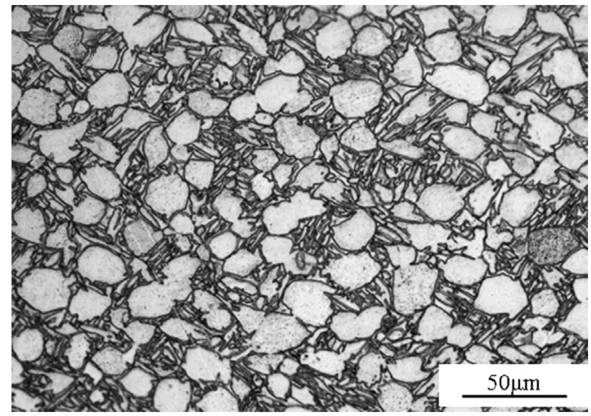

Fig. 2. OM micrograph of the base metal.

Table 2
Welding parameters used in this study.

Specimen no.	Frequency (Hz)	Amplitude (mm)	Friction pressure (MPa)	Friction time (s)
S-1	*F*	*A*	1.5*P*	3
S-2	*F*	*A*	*P*	3

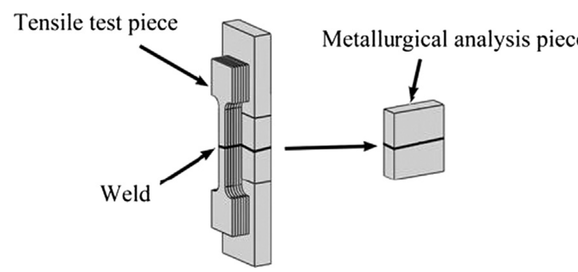

Fig. 3. Schematic drawing of sampling.

values can be disclosed in this study due to the proprietary nature of the process parameters.

The welded samples were sectioned into two parts along the direction of oscillation as illustrated in Fig. 3, one part was for metallurgical examination, and the other part was for tensile strength testing which was carried out at room temperature. Subsequently, the samples were heat treated using a vacuum resistance furnace by duplex annealing (950 °C for 1 h AC+530 °C for 4 h AC, AC stands for air-cooling).

The polished specimens for metallographic analysis were etched with Keller's reagent (1 ml HF+1.5 ml HCl+2.5 ml HNO_3 +95 ml H_2O). The microstructures of these specimens were examined using OM and scanning electron microscope (SEM). Tensile properties of each joint were evaluated from three tensile samples using a universal testing machine (AG-X, Shimadzu, Japan) at a cross-head speed of 1 mm min^{-1}. To analyze the experimental results, the microstructures were observed by a dual beam FIB-SEM (FEI Quanta 3D) equipped with an electron backscatter diffraction (EBSD) system (AZtecHKL software) and an energy dispersive X-ray spectroscopy (EDX) system using Oxford SDD detector. For transmission electron microscopy (TEM), thin lamellae were made by a FIB lift-out technique [23–25] and observed by a high resolution TEM (FEI Tecnai F20) with a scanning mode (STEM) and an EDX system, and a TEM (JEOL JEM-2100) with an EDX.