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Characterisation studies of linear friction welded titanium joints

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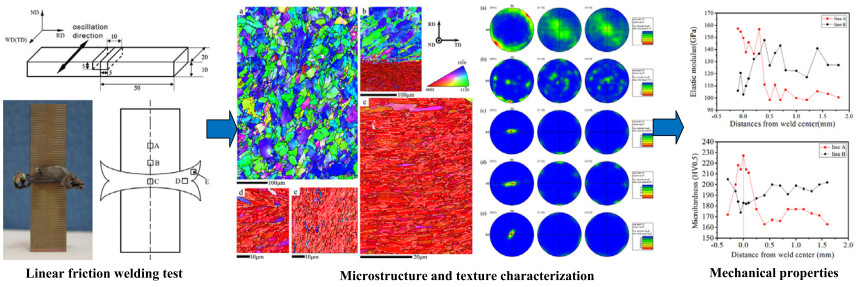
HIGHLIGHTS

- Limited continuous dynamic recrystallization occurred in the weld zone in linear friction welding of pure titanium.
- The texture evolution mechanism in linear friction welded Ti joints was clarified.
- The formation mechanism of mixed microstructure in the welds was proposed.
- The anisotropic mechanical properties in linear friction welded Ti joints were observed and explained.

GRAPHICAL ABSTRACT



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ABSTRACT

The microstructure and texture evolution during linear friction welding (LFW) of pure titanium joints were investigated with scanning electron microscope, transmission electron microscope and electron back-scattering diffraction. The unique combination of high temperatures and strain rates during LFW causes limited continuous dynamic recrystallization in the weld center zone (WCZ), leading to a mixed microstructure of refined grains with severe elongated grains. Under the combined effect of axial pressure and shear stress, the texture across the weld line changes significantly. In parent metal, the c-axis of grains is parallel to the RD-TD plane and has an angle of 45° to TD, then in the thermomechanically affected zone the c-axis turns parallel to the welding interface and along the TD, finally in WCZ the c-axis turns to the ND and the P_1 $(\{10\bar{1}0\}\langle 11\bar{2}0\rangle)$ texture forms. Compared with the ideal hcp shear textures, the present results show that material flow during LFW of titanium indeed arises from the simple-shear deformation and is governed by prismatic slip rather than twinning. The strong texture in LFWed joints is the cause of the anisotropic mechanical properties.

1. Introduction

Linear friction welding (LFW) is a solid-state oscillatory joining process [1,2], in which significant amounts of frictional heat are generated at the interface of two components under certain combination of pressure, amplitude and frequency of oscillation. This process effectively extends the current applications of rotary friction welding (RFW) to non-axisymmetric components such as aircraft engine blades to discs (blisks). According to Vairis and Frost [3–5], LFW is observed to have four distinct phases, which are the initial phase, the transition phase, the equilibrium phase, and the deceleration (or forging) phase, as shown in Fig. 1. During this process, frictional heat is generated which produces continuous yielding of the interfacial region between the components. Furthermore, the plastically deformed material is displaced out of the interface to the weld edges to form a flash (upset metal). Once

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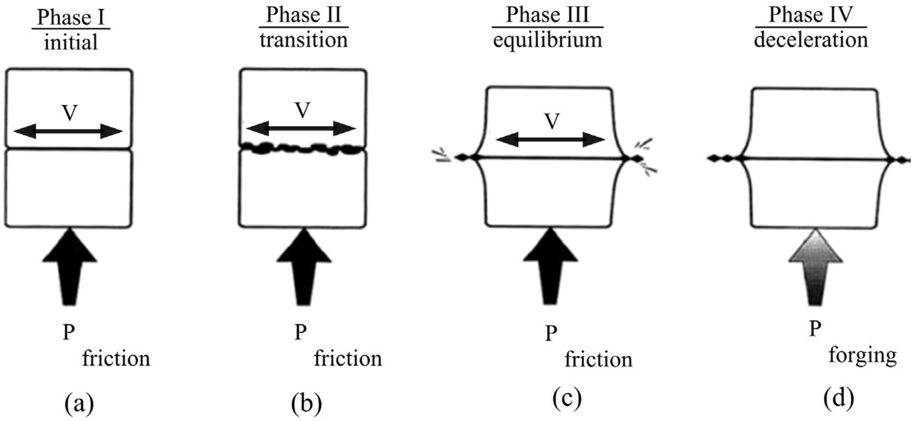

Fig. 1. The linear friction welding process: (a) initial phase, (b) transition phase, (c) equilibrium phase and (d) deceleration phase [4].

sufficient plastic deformation has been produced, a forging force is applied for a consolidated joint with limited thermomechanically affected zone (TMAZ) and heat affected zone (HAZ).

Although some work has been carried out on LFWed superalloy joints [6–8] and aluminium alloys joints [9–11], the majority of published papers have been on the welding parameters, microstructure and mechanical properties of LFWed titanium alloys joints [12–14]. Vairis and Frost [3] found that there is a minimum power input required to achieve welding conditions for Ti-6Al-4V (Ti64), which depends on both frequency and amplitude of oscillation. Wanjara et al. [15] analyzed the effect of processing parameters on the weld line characteristics to identify that frequency and amplitude have the most pronounced impact on weld quality, with friction pressure and axial shortening a secondary effect on it. They observed a Widmanstätten α-β transformation microstructure in the weld center zone (WCZ) as local temperature reached is higher than the β-transus (995 °C) and as it is combined with deformation and rapid cooling after joining lead to recrystallization of the beta grain structure. Karadge et al. [16] found the formation of α' martensite in the weld line region of LFWed Ti64 joint. Li et al. [17,18] studied the microstructure of LFWed Ti64 joints to identify that dynamic recovery and recrystallization are a result of intensive plastic deformation and the fast heating and cooling processes during welding, and concluded that dynamic recovery is the main mechanism in thermal deformation of Ti64. In addition, dynamic recrystallization is partial in LFWed Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti17) joints [19]. For Ti-6.5Al-1.5Zr-3.5Mo-0.3Si (TC11), dynamic recrystallization has occurred in the WCZ and the flash, whereas the phase transformation occurs simultaneously with material deformation during welding without dynamic recrystallization in the TMAZ [20].

Karadge et al. [16] first studied the microstructure and microtexture development in the as-welded and post weld heat treated (PWHT) lab-scale (LS) and full-scale (FS) Ti64 linear friction welds. They found that at the weld line a strong $\{10\bar{1}0\}\langle 11\bar{2}0\rangle$ transverse texture presented in both welds for the as-welded and PWHT conditions. Romero et al. [21] from the same group focused on the effect of forging pressure on the microstructure and texture of LFWed Ti64 joint. A strong α-Ti texture was generated in the weld line, which could be reduced with weld pressure. The LFW of near-β titanium alloy Ti-5Al-5V-5Mo-3Cr (Ti-5553) was investigated by Dalgaard et al. [22]. They found that in the as-welded condition, this alloy undergoes complete dynamic recrystallization in the WCZ where the grains are predominantly oriented with their $\langle 111\rangle$ directions parallel to the weld oscillation direction. These strong textures produced in LFWed joints are quite different from isothermal compression [23] and hot rolling [24,25] where texture weakens with deformation. Further to these, the effect of texture on the mechanical properties has not been investigated in these works.

In this work, commercially pure titanium (CP-Ti) instead of $\alpha + \beta$ titanium alloy was chosen to examine the recovery and recrystallization behaviors, together with the texture development, in view of the complex effect of prior β on the final texture distribution in $\alpha + \beta$ titanium alloys [26,27]. It is accepted that dynamic recrystallization is hard to occur for pure titanium due to its greater stacking fault energy (0.31 J/m^2 [28]). However, studies suggested that dynamic recrystallization for pure titanium can be present under severe deformation. Chen et al. [29,31] studied the grain refinement mechanism of CP-Ti during equal channel angular pressing (ECAP) and pointed out that grain refinement during ECAP is dominated by continuous dynamic recrystallization (CDRX), contrary to Suwas et al. [32] who reported that CP-Ti underwent extensive dynamic recovery (DRV) rather than discontinuous dynamic recrystallization (DDRX) during ECAP. In addition, Liu et al. [33] found that the microstructure evolution during solid-state friction stir welding (FSW) of CP-Ti is governed by full dynamic recrystallization.

The above-mentioned publications have provided important insights into the grain refinement mechanism and microstructure development of CP-Ti. However, due to the very complicated and quick thermomechanical coupling in linear friction welding compared to other severe plastic deformation processes like ECAP and FSW, the grain refinement mechanism of CP-Ti is still not clear. In order to improve our understanding of the bonding nature of LFW joints, the microstructure and texture evolution of CP-Ti during LFW was systematically examined. Also, microhardness and micro-indentation tests were carried out to investigate the effect of texture on joint mechanical properties.

2. Experimental procedure

The welding equipment used was the LFW machine developed in house by Northwestern Polytechnical University. To investigate the microstructure changes during LFW, the LFW machine was stopped during the process cycle at specified times (0.5, 1, 2, 3 and 4 s), and the samples were quenched into liquid nitrogen to suppress further changes in microstructure. The process welding parameters were set to appropriate values (Table 1) based on our previous studies on Ti64 joints [17,18].

Table 1
Linear friction welding parameters used for pure titanium.

Sample no.	Friction time (s)	Frequency (Hz)	Amplitude (mm)	Pressure (MPa)
1#	4	35	2.5	50
2#	3			
3#	2			
4#	1			
5#	0.5			