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Impact toughness and fracture analysis of linear friction welded Ti–6Al–4V alloy joints

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ABSTRACT

Linear friction welding (LFW), as a relatively new solid-state joining technique, has great potentials in welding of non-axisymmetric components, especially for cost-effectively machining blade/disc (blisks) assemblies. In this study, Ti–6Al–4V alloy was jointed by the LFW process under the appropriate processing parameters developed before. The microstructure, impact toughness and fracture characteristics of LFW Ti–6Al–4V joint were investigated. The results showed that a sound weld was obtained consisting of a superfine $\alpha + \beta$ microstructure in the weld center (about 70 μm thickness). The weld presents a higher impact toughness (61.3 ± 5.8 J/cm^2) than the parent Ti–6Al–4V because of the superfine microstructure formed in the weld. The fracture surface exhibits three typical regions: the thin fibrous zone close to the notch, the radiation zone in the middle and the shear lip zone at the other three sides, corresponding to the crack initiation, propagation and shear failure zones, respectively. The crack develops a short distance along the weld center and thermomechanically affected zone after its initiation, and then extends into the parent metal due to the lowest impact toughness of the parent.

1. Introduction

Linear friction welding (LFW) is a relatively new solid-state bonding process aiming at extending the current applications of rotary friction welding (RFW) to non-axisymmetric components. LFW involves joining of materials through the relative reciprocating motion of two components under an axial force as schematically shown in Fig. 1. LFW is observed to have four distinct phases, including the initial phase, the transition phase, the equilibrium phase, and the deceleration (or forging) phase [1,2]. During LFW, the frictional heat is generated and results in a continued plasticization of the interfacial region between the components. A flash is formed through the displacement of plastically deformed materials toward the weld edges. Once a sufficient plasticization has occurred, a forging force is applied, to produce a consolidated joint seam with the limited thermomechanically affected zone (TMAZ) and heat affected zone (HAZ). Although available for more than 15 years, LFW has only found the industrial application in aircraft engine manufacture, in part due to the high cost of the welding machines. LFW has proved to be an ideal process for joining turbine blades to discs where the high value-added cost of the components justifies the cost of a LFW machine. This approach is more cost-effective than machining blade/disc (blisks) assemblies from solid billets. LFW has been used successfully to join a range of materials including titanium alloys [1–6], steels [7,8], intermetallic materials, aluminium, nickel, copper, and even dissimilar material combinations with the emphasis on aircraft engine alloys [9]. Although LFW has great application potentials in industries, there are few research reports available on LFW except some pioneer works [1–8]. Therefore, a large amount of research work is required to develop both scientific and practical knowledge of LFW.

The previous studies showed that a sound weld of titanium alloys with the refinement of microstructure could be obtained by LFW [1–6]. The weld presented a much higher hardness [3–5], and slightly better tensile properties [4,5] than the parent titanium alloys owing to the refined structure. In addition, the impact toughness of joints will be more important in applications for aerospace engines. However, few reports focused on this topic. Hence, the objective of the present work was to investigate the impact toughness of LFW Ti–6Al–4 V alloy joints and their fracture characteristics.

2. Experimental procedures

Ti–6Al–4V blocks with a configuration of 10 mm width (W), 17 mm length (L) and 45 mm height (H) were welded in the plane $W \times L$. The typical microstructure of parent Ti–6Al–4V consists of a bimodal $\alpha + \beta$ structure in the form of elongated α grains (dark gray) and intergranular mixture of lamellar α and β grains (Fig. 2). A LFW machine (XMH-160) developed in Northwestern Polytechnical University (China) was employed to weld Ti–6Al–4V blocks. According to many preliminary experiments during

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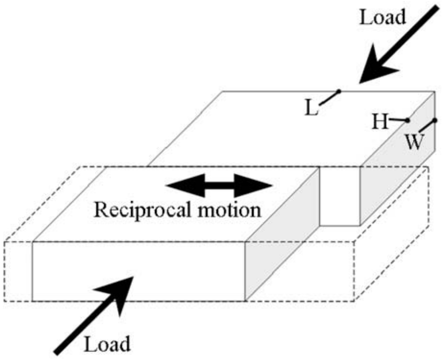

Fig. 1. Schematic of the LFW process.

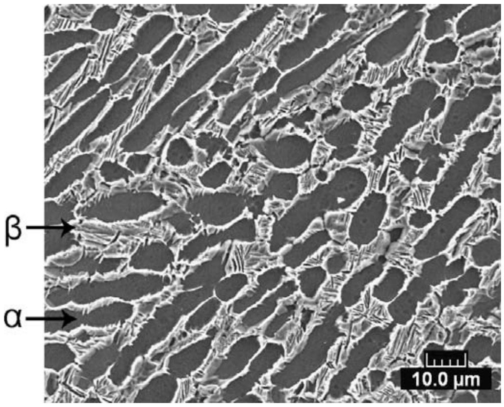

Fig. 2. SEM micrograph of parent Ti–6Al–4V alloy.

the development of the used welding machine, it was found that the friction time was the important factor as the appropriate force, frequency and amplitude were applied [7]. Through an observation of flashes of the joints obtained at different friction times, a good formability of flash and appropriate axial shortening were obtained for LFW Ti–6Al–4V at around 8 s. Therefore, the appropriate welding parameters were fixed as shown in Table 1. Five samples were made for the impact test and one for the metallographic analysis.

Table 1
LFW parameters used in this study

Frequency (Hz)	33
Amplitude (mm)	4
Friction force (kN)	17.9
Friction time (s)	8
Forging force (kN)	36.8
Forging time (s)	4

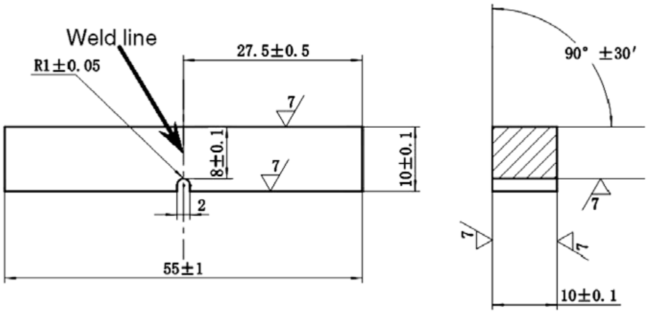

Fig. 3. Configuration and size of impact test specimen according to standard Mesnager U-notch Impact (GB/T229-1994).

The configuration and size of impact test specimens are shown in Fig. 3. The Mesnager U-notch specimens were machined from the welded blocks. A drop-hammer impact testing machine (JD-300B, Wuzhong Materials Testing Machine Co. Ltd., Ningxia, China) was used to measure the impact toughness of joints at room temperature. The specimens were polished on one lateral side and etched by a solution of 100 ml H_2O + 3 ml HF + 6 ml HNO_3 before machining the U-notch for the precise alignment of the weld line in the center of U-notch.

The joint macrostructure was observed by a digital camera. The microstructure of the joint cross-section (etched) was examined by scanning electron microscope (SEM), as well as the fractography.

3. Results and discussion

3.1. General features of LFW Ti–6Al–4V joint

Fig. 4 shows the typical macro photo and microstructure of LFW Ti–6Al–4V joint under the present welding conditions. From a visual inspection of the weld interface, an obvious flash from all sides of the joint was observed as illustrated in Fig. 4a. The flash is comprised of many ridges, which are generated as a result of the oscillating extrusion process during welding. This is the typical phenomenon in LFW and sometimes reflects the quality of weld. The axial shortening of five samples was estimated to be about 5 mm, which is enough to form a sound weld according to the results by Vairis and Frost [1]. It is clearly seen from Fig. 4b that a good weld was formed including the weld center of about 70 µm thickness and the thin TMAZ close to that. The superfine $\alpha + \beta$ microstructure was presented in the weld center, which contributes to the higher microhardness and tensile strength of joint compared to the parent metal [5]. In addition, the highly deformed α and β-phases oriented along the deformation direction were ob-

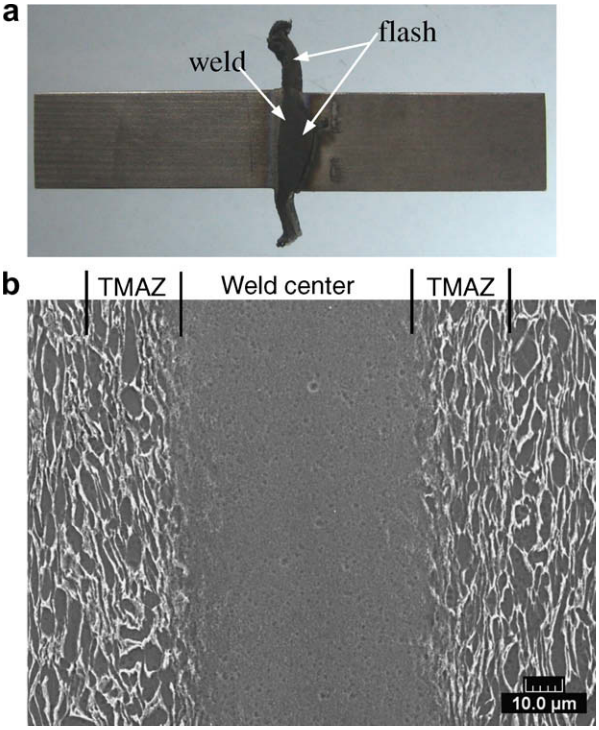

Fig. 4. (a) Macro photo, and (b) Microstructure of LFW Ti–6Al–4V joint under the present welding conditions.