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Microstructural characteristics and mechanical properties of Ti–6Al–4V friction stir welds

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Abstract

Friction stir welding (FSW) was applied to 3 mm-thick Ti–6Al–4V plates under different rotational speeds. Defect-free welds were successfully produced at rotational speeds of 400 and 500 rpm. The base material (BM) had a deformed α/β lamellar microstructure. FSW produced a full lamellar structure with refined prior β grains in the SZ, while the HAZ contained a bimodal microstructure consisting of the equiaxed primary α and α/β lamellar structure within the prior β structure. An increase in rotational speed increased the sizes of α colonies and prior β grains. The SZ exhibited higher hardness than the BM, with the lowest hardness found in the HAZ. Results of the transverse tensile test showed that all welds fractured in the HAZ and that they exhibited lower strength and elongation than the BM. The tensile test for only the SZ showed it to be characterized by higher strength and elongation than the BM.

Keywords: Friction stir welding; α globularization; Ti–6Al–4V; Lamellar microstructure; Mechanical property

1. Introduction

Titanium (Ti) and Ti alloys have high specific strengths and good erosion resistance, and thus have been applied widely in the aerospace, chemical and nuclear industries [1]. Ti and Ti alloys are currently welded by various welding processes including gas tungsten arc welding (GTAW) [2], gas metal arc welding (GMAW) [3], electron beam welding (EBW) [4], plasma arc welding (PAW) and laser beam welding (LW) [5]. However, all of the fusion welding methods used for titanium alloys still show problems, including the formation of a brittle cast structure, large distortion and residual stress. To avoid problems associated with the melting and solidification of the welded materials, solid-state joining technologies would appear to be more suitable for joining Ti alloys. Friction welding [6] and linear friction welding [7] are used to achieve high integrity joints of Ti alloys with α + β or β processed microstructures, but these processes are limited because they require special geometric specifications of welded materials and removal of the weld flash.

Friction stir welding (FSW), which was developed in the early 1990s at The Weld Institute (TWI) [8], is a solid-state welding process in which a cylindrical-shouldered tool with an extended pin is rotated and gradually plunged into the joint between the workpieces to be welded. FSW has attracted considerable attention in the industrial world due to its many advantages and has been successfully applied to the joining of various types of Al [9–14], Mg [15,16] and Cu [17] alloys. However, FSW of higher temperature materials, such as steels, nickel and Ti alloys, poses difficulties due to wear and deformation of the tool. Thus the challenge has been to devise a tool of harder materials for such applications [18–21].

Some previous reports of the FSW of Ti and Ti alloys appear in the literatures [22–27]. Lee et al. [22] produced a friction stir weld in commercial-purity (CP) Ti using a sintered TiC tool, and reported the microstructure and mechanical properties of the weld. Fonda et al. [23] conducted FSW of a Ti-5-1-1-1 alloy and examined the microstructural changes during such welding. Reynolds et al. [24] examined the feasibility of FSW for β Ti alloy over a wide range of welding speeds and examined the texture evolution during FSW. Juhas and coworkers [25] reported the microstructural features of the SZ and thermo-mechanically affected zone (TMAZ) in FS welds of Ti–6Al–4V. John et al.

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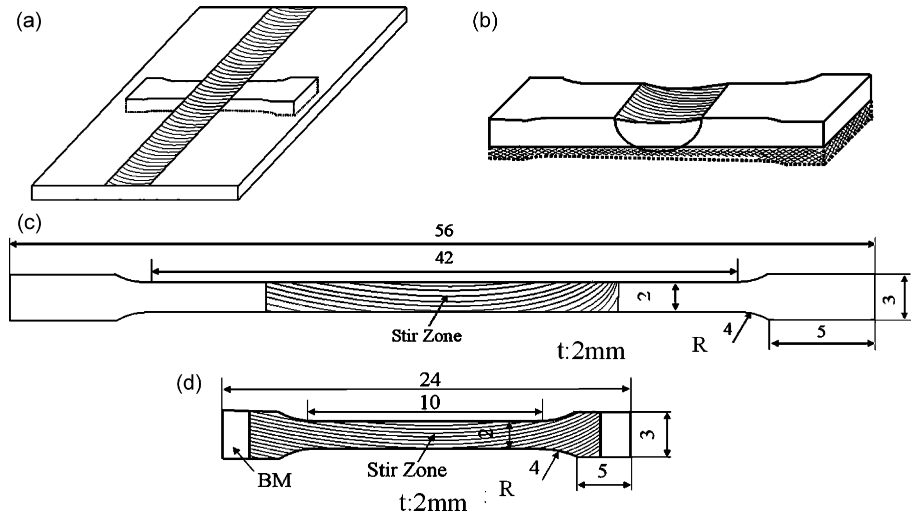

Fig. 1. (a) and (b) are schematic illustrations of the procedure for cutting tensile specimens. (c) Shows configuration of the transverse tensile specimen and (d) show the smaller tensile test specimen.

[26] examined near-threshold fatigue crack growth properties in Ti–6Al–4V FS welds and demonstrated that the fatigue crack growth rate was significantly affected by residual stress in the welds. Pilchak et al. [27] examined the effect of friction stir processing (FSP) parameters on microstructure in investment cast Ti–6Al–4V. They showed that the SZ microstructure depends on the heat-input during FSP, i.e., the low heat-input FSP produces equiaxed α and β grains, while lamellar α/β plates are formed during high heat-input FSP. These cited studies have yielded some important knowledge on the microstructure and properties in FS welded Ti–6Al–4V, but the relationship between microstructure, mechanical properties and welding parameters has not been yet examined in the Ti–6Al–4V FS weld.

In the present study, FS welds in Ti–6Al–4V plates were produced at different rotational speeds and the microstructure, hardness profile and tensile properties of the welds were examined. The objective of the present study was to clarify how the microstructure, mechanical properties and welding parameters are related in Ti–6Al–4V FS welds.

2. Experimental procedures

The material used in this study was commercially available Ti–6Al–4V plates with the following nominal chemical composition: Al 6.09, V 4.02, C 0.011, Fe 0.14, N 0.008, O 0.14, H 0.0023 and balanced Ti (all in mass%). The thickness of the plate was 3 mm. The welding was performed on a machine using a stainless steel backing plate and a Mo-based alloy tool. The tool had a convex shoulder having a diameter of 15 mm and a tapered pin, tapering from 5.1 mm at the shoulder to 3 mm at the pin tip. The shoulder surface had step-spiral patterns to enhance the stirring effect.

The plunged depth and travel speed of the welding tool were constant at 2 mm and 1 mm/s, respectively. The rotational speed was varied between 300 and 600 rpm. Argon gas shielding was employed to prevent the oxidation of the plate surface. The weld produced at a rotational speed of *N* rpm is expressed as the *N* rpm weld throughout this paper.

The microstructure of the stir zone and fracture location was characterized by optical microscopy (OM) under polarized light and by Hitachi S-4300SE scanning electron microscopy (SEM). Specimens for OM and SEM were cut perpendicular to the welding direction and mechanically polished with 6, 3 and 1 μm diamond paste. The final polishing was accomplished using colloidal silica of about 40 nm in diameter, followed by etching in Kroll's reagent (2 vol% HF and 4 vol% HNO_3 in water).

The mean values of prior β grain size and α colony size were calculated for more than 500 grains, respectively.

Transverse tensile test samples were cut perpendicular to the welding direction as shown in Fig. 1a. Partially penetrated welds were produced, some of which contained defects at the bottom of the SZ. In order to examine only the effect of the microstructure on tensile properties, the bottom part of the samples including the defects was removed, as shown in Fig. 1b. The final size of the transverse tensile test samples is shown in Fig. 1c. The mechanical properties of only the SZ were evaluated using a smaller tensile specimen. It should be pointed out that the gauge part of this test sample contained only the SZ, as shown in Fig. 1d. To confirm the fracture location in the transverse tensile specimen, small Vickers indents with a spacing of 1 mm were placed on the initial specimen surface. Tensile tests were carried out at room temperature at a crosshead speed of 1 mm/min using a screw-driven test machine. A Vickers hardness measurement extending across the entire region with a spacing of 1 mm was conducted using a Vickers indenter with a load of 9.8 N and a dwell time of 15 s.

3. Results and discussion

3.1. Microstructural features of welds

The microstructure of the base material (BM) was typical of the deformed α/β lamellar microstructure [28], as shown in Fig. 2. The dark and white regions represent α and β phases in the SEM image, respectively, while the relationship between contrast and phase is opposite in the OM image. For the BM, the