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Eliminating the tearing defect in Ti-6Al-4V alloy joint by back heating assisted friction stir welding

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ABSTRACT

To eliminate the tearing defect in friction stir welding (FSW) Ti-6Al-4V alloy joint, back heating assisted FSW (BHAFSW) method was put forward in this study. Using different back heating temperatures, joint formation and microstructure were mainly discussed. Results show that the temperature gradient along thickness plays a more important part than the welding peak temperature affecting the tearing defect. With increasing the back heating temperature, size of the tearing defect gradually decreases due to reduced temperature gradient. When using 480 °C, defect-free BHAFSW joint with fully lamellar structure along thickness and higher hardness can be obtained. Moreover, the BHAFSW can effectively reduce tool wear during welding.

1. Introduction

Friction stir welding (FSW) is a new solid-state joining technology during which peak temperature does not exceed melting point of the base material (BM). Hence many fusion defects, such as pores and hot cracks can be avoided. FSW was originally used to weld aluminum alloys [1,2] and now has been used to weld some high-melting-point materials such as steel and titanium alloys [3–5].

It is well known that large amount of the heat input during FSW comes from the frictional heat between rotating tool and material being welded [6]. During FSW of high-melting-point alloys, very big forging force and torque are needed to guarantee sufficient heat input, which inevitably results in tool wear and restricts welding efficiency. To overcome this, some researchers proposed external energy assisted FSW [7–11]. Song et al. [7] found out that laser-assisted hybrid FSW not only owned 1.5 times higher efficiency but also fabricated joint with finer microstructure, higher hardness and tensile strength. Similar results were also attained by Sun et al. [8]. Luo et al. [9] used electrical current assisted FSW to weld high-strength alloys such as 2Cr13Mn9Ni4 and Q235B and attained joints with higher hardness and less defects [10]. Moreover, gas tungsten arc welding assisted hybrid FSW was used by Bang et al. [11,12] to fabricate Al/Ti and Al/steel joints. For FSW of Ti-6Al-4V alloy, big temperature gradient along thickness easily leads to tearing defect at joint bottom [13]. But few papers focused on this. The above-mentioned energy assisted methods could even amplify the temperature gradient. Stationary shoulder FSW produced uniform heat distribution [14]. However, less heat input resulted in more serious tool wear owing to bad material thermo-plasticity [5]. Hence, in this study, to reduce temperature gradient along thickness and prolong tool life, a new method, namely back heating assisted FSW (BHAFSW) was proposed. Joint formation, defect and microstructure along thickness were mainly studied.

2. Experiment process

2 mm thick Ti-6Al-4V alloy plate was used as BM. Dimensions of the plates were 200 mm×100 mm. The experiment was conducted on a FSW-3LM-4012 machine using rotating speed of 350 rpm and welding speed of 50 mm/min. The welding process was performed using displacement-controlled mode. Due to good high temperature and wear resistances [15,16], a W-Re alloy tool with a concave shoulder and a threaded pin was used. The shoulder diameter was 12 mm. The pin bottom and tip diameters were 7 mm and 4 mm. The pin length was 1.8 mm. Tilting angle of the tool was 2.5°. The back heating system is shown in Fig. 1a. The resistance heating method was used, in which the Cr20Ni80 resistance wire was used as the heating source (Fig. 1b). The heating bands were powered using common alternating current (320 V). Two heating bands directly contacting the Ti-6Al-4V plates were symmetrically placed in the 2520 steel backing plate grooves. Thermocouple was fixed on the heating band to measure the heating temperatures before welding. Moreover, thermocouples were spot-welded on the joint surface and bottom to measure the temperatures. Three heating temperatures of 300 °C, 370 °C and 480 °C were used. Argon gas shielding was continuously supplied to prevent Ti-6Al-4V

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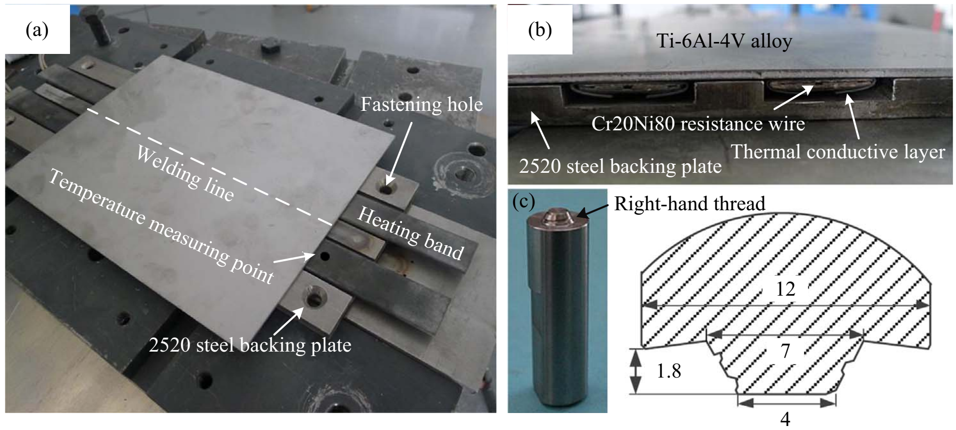

Fig. 1. BHAFSW system and the tool used in experiment: (a) general view, (b) side view and (c) the rotating tool.

alloy from oxidation. Metallographic samples were cut perpendicular to the welding line and then were burnished, polished and etched using Kroll reagent. Microstructure analysis was conducted on optical microscope (OM, Olympus-GX71) and scanning electron microscope (SEM, SU3500 manufactured by Hitachi Company) equipped with an energy-dispersive X-ray spectroscopy (EDS) analysis system. Vickers hardness was measured using a HVS-1000 Vickers hardness tester manufactured by Laizhou Huayin testing Company. The testing force of 300*g* and the dwell time of 10 s were used.

3. Results and discussion

Cross sections of the FSW joints are shown in Fig. 2. The stir zones (SZ) present typical basin-like morphologies. A tearing defect, which spreads along the joint traverse direction, can be observed at the SZ bottom. The tearing defect is big on the conventional joint (Fig. 2a). With increasing the heating temperature, the defect gradually becomes smaller. Defect-free joint can be obtained using the heating temperature of 480 °C (Fig. 2d). Our previous study [17] showed the tearing defect mainly resulted from the high peak temperature and big temperature gradient along thickness. FSW can be divided into heating and cooling stages. The SZ material expands and shrinks during the two stages, leading to welding tensile stress [18]. Owning low thermal-conductivity, very big temperature gradient (162 °C for conventional joint) can be formed along thickness, resulting into different deformation behaviors and big welding tensile stress. Once the welding tensile stress exceeds the material tensile strength, the material will be torn, forming the tearing defect. Moreover, it is seen in Fig. 2e-g that the different microstructures are formed above (lamellar) and below (equaixed) the tearing, showing that phase evolution also leads to residual stress. During BHAFSW, temperature gradient is reduced (125 °C for back heating 300 °C) and is further reduced with increasing the heating temperature (from 97 °C to 71 °C). Hence gradually reducing tearing defect can be obtained (Fig. 2b and c). When using 480 °C, welding tensile stress is smaller than material tensile strength. Hence defect-free joint is obtained (Fig. 2d). However, welding tensile stress is proportional to peak temperature. Higher back heating temperature no doubt leads to higher peak temperature (1048 °C for conventional joint and 1134 °C when using 480 °C). Hence, it is concluded that for the tearing defect, temperature gradient along thickness plays a more important role than peak temperature.

Joint cross section can be divided into SZ, heat affected zone (HAZ) and BM, as marked in Fig. 2a. No obvious thermal-mechanically affected zone (TMAZ) can be observed. Fig. 2h shows the hardness along the SZ bottom lines. BM is characterized by near-equiaxed primary α and transformed β (Fig. 3a). The α and β phases own average grain sizes about 5 µm and 3 µm. Average hardness of the BM is 325HV-330HV. HAZ (Fig. 3b) shows a bimodal structure, consisting

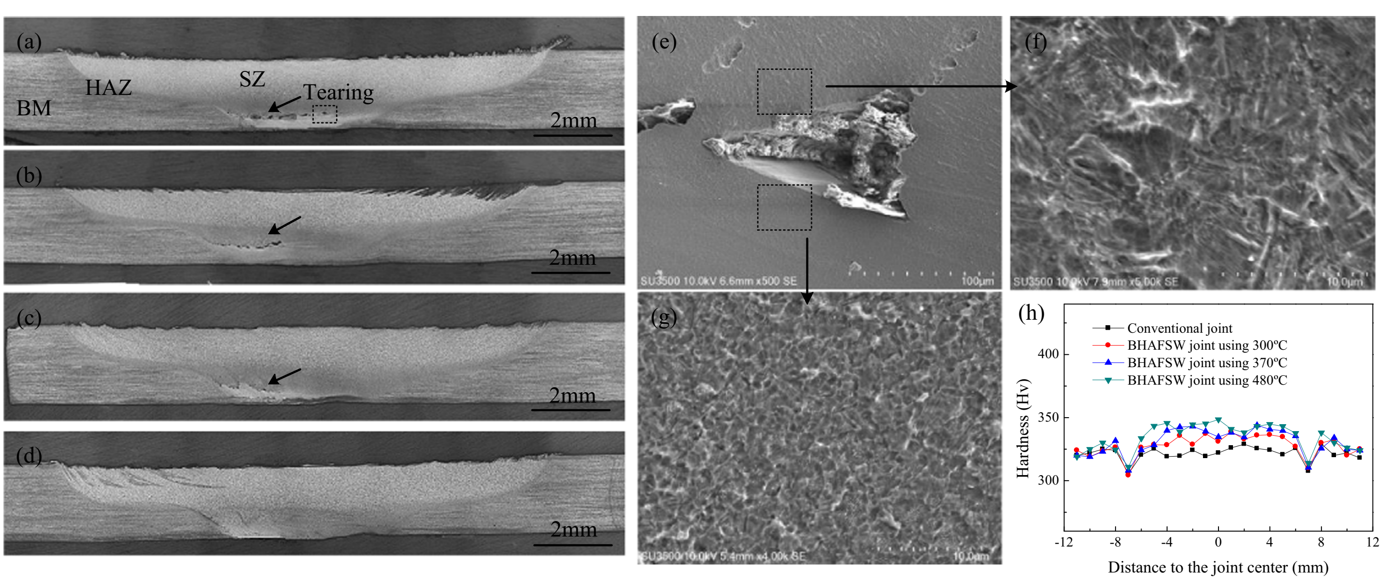

Fig. 2. Cross sections of the (a) conventional joint, (b) BHAFSW joint using 300 °C, (c) 370 °C and (d) 480 °C, (e) the tearing defect, microstructure above (f) and below (g) the tearing defect, (h) hardness of the joints.