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Inhomogeneity of microstructure and mechanical properties in the nugget of friction stir welded thick 7075 aluminum alloy joints

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ABSTRACT

In this study, 20 mm thick AA7075-T6 alloy plates were joined by friction stir welding. The microstructure and mechanical properties of the nugget zone along the thickness direction from the top to the bottom was investigated. The results showed that the microstructure including the grain size, the degree of dynamic recrystallization, the misorientation angle distribution and the precipitation phase containing its size, type and content exhibited a gradient distribution along the thickness direction. The testing results of mechanical properties of the slices showed that the nugget was gradually weakened along the depth from the top to the bottom. The maximum ultimate tensile strength, yield strength and elongation of the slice in the nugget top-middle are obtained, which are 415 MPa, 255 MPa and 8.1%, respectively.

1. Introduction

7075 aluminum alloy (AA7075) is considered as one of the strongest aluminum alloys in industrial use today. With high strength to weight ratio, good fracture toughness and corrosion resistance, it has been used widely in aircraft structural components [1–3]. This alloy is a precipitation strengthened alloy containing Zn, Mg and Cu as the main alloying elements, and its strength is derived from the precipitation of η phase ($MgZn_2$), S phase (Al_2CuMg) and T phase (AlMgZnCu) [4].

However, this alloy is difficult to join by conventional fusion welding since lots of problems such as voids, cracks and large residual stress are found in the weld. AA7075 possessing a high content of copper has a wide melting range with a low solidus temperature, and it is extremely sensitive to welding crack during fusion welding. Moreover, the dendritic structures are easily formed in the fusion zone, which can significantly reduce the mechanical properties of the joints [5,6]. So far, aluminum alloys have been successfully joined by solid-state joining technologies which produce the joints without recasting material, thereby could eliminate issues with solidification cracking and other defects [7].

As a solid-state joining technology, friction stir welding (FSW) is highly suitable for welding aluminum alloys, especially for 2xxx and 7xxx series aluminum alloys which are typically considered to be un-weldable [8]. During the FSW process, a tool with a special shoulder and pin is inserted into the workpieces, and then moved forward along the weld line. The frictional and deformational heat generated by the rotating tool quickly softens the metal. The plasticized metal under the shoulder is extruded by the rotating tool, and transported from the advancing side to the retreating side where it is consolidated into a complete weld [9].

Currently, the majority of investigations about FSW aluminum alloys have been focused on plates below 8 mm thick, including material flow [10,11], microstructure evolution [2,12] and mechanical properties [13]. Far more scarce works consider the case of thicker welds, in spite of their industrial interest. In addition, whatever the thickness, many of the FSW studies have shown the existence of the inhomogeneity in the nugget. This is mainly reason attributed to a difference of thermal history along the thickness direction of the plates during FSW.

For instance, McWilliams et al. [14] investigated the FSW on 25.4 mm thick aluminum alloy AA2139-T8 plates by the numerical simulation and experimental method, and found that the tensile strength of upper weld nugget was higher than that of low weld nugget due to the different in strain hardening between the various nugget positions. Similarly, Srinivasa Rao et al. [15] reported the difference in the microstructure and mechanical properties of the joints of FSW 10 mm and 16 mm thick 7075-T651 aluminum alloy plates owing to different heat inputs. Moreover, Ghetiya et al. [16] thought that the temperature histories at different regions greatly

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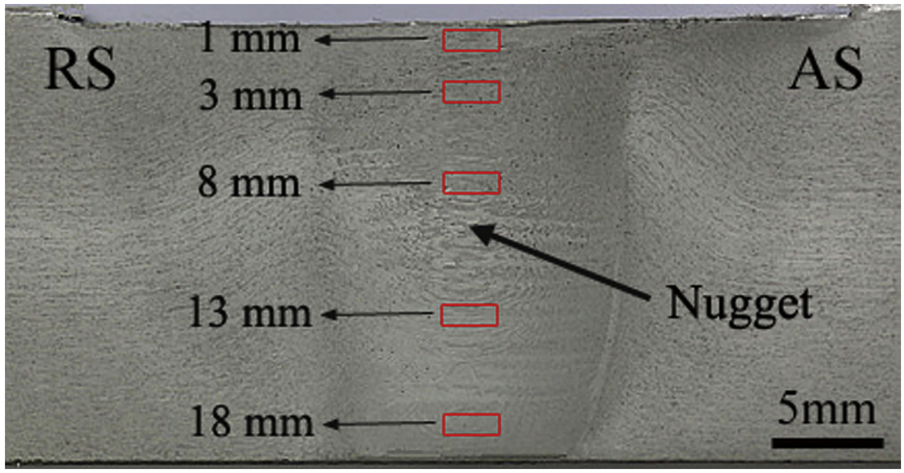

Fig. 1. Optical micrograph of cross section of FSW joint. The red bold boxes indicate the locations of the sampling of both the TEM thin foils and the specimens for EBSD.

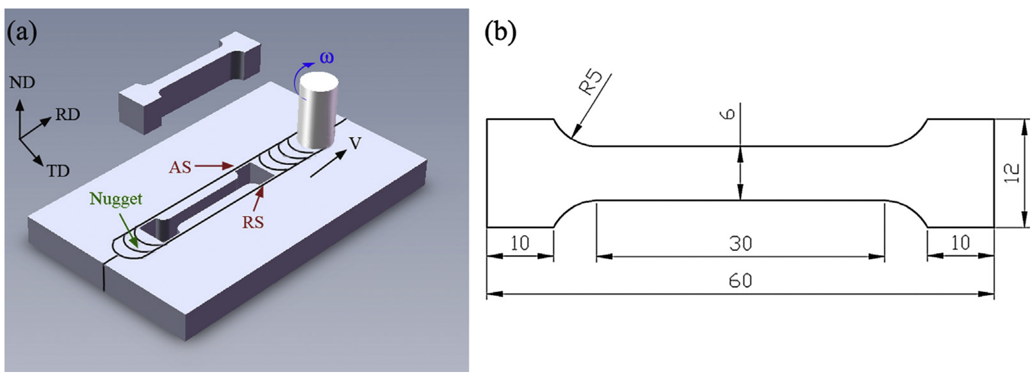

Fig. 2. Schematic diagram of tensile specimens: (a) cut position; (b) detailed size.

varied. Khandkar et al. [17] studied the transient temperature distributions during FSW aluminum alloy by a three-dimensional thermal model and experiment method, and found the temperature gradually decreased along the thickness in the nugget.

In addition, Xu et al. [18] stated that the temperature measured by thermocouples reduced from the top surface to the bottom surface for FSW 14 mm thick AA2219 alloy plates, and the peak temperature difference along the thickness of the plate was more than 20 °C. Canaday et al. [19] concluded that the peak temperature could be higher in mid-thickness in FSW of 32 mm thick AA7050 alloy plates, which obviously affected local microstructure and hardness. Martinez et al. [20,21] proved that a significant heat gradient existed through the thickness of the weld, resulting in microstructure difference in the welded zone for FSW 13 mm and 17.5 mm thick 7449 aluminum alloy plates. Also, Guo et al. [22] investigated the friction stir double-sided butt welding 5A06 aluminum alloys with thickness of 108 mm, and indicated that the grain size of equiaxed grains in weld nugget zone (WNZ) including shoulder affected zone (SAZ) and pin affected zone (PAZ) decreased gradually along the thickness direction, and the PAZ exhibited superior tensile properties compared with SAZ.

Based on the data mentioned above, the microstructure in the WNZ along the thickness direction is varied and heterogeneous due to the existence of temperature and strain differences for thick aluminum alloys. Besides, some detailed studies about the effect of heat gradient along the thickness on the microstructure evolution and metallurgical properties such as grain size, precipitate distribution and tensile properties of the WNZ for FSW thick 7075 aluminum alloys are lacking.

Table 1
Chemical composition and mechanical properties of 7075-T6 aluminum alloy.

Zn	Mg	Cu	Si	Fe	Mn	Cr	Ti	Al
5.7–6.0	2.6–2.85	1.6–2.1	0.35	0.5	0.3	0.25	0.2	Bal.

Therefore, the aim of this study was to further investigate the consequences of the microscopic heterogeneity of microstructure evolution, precipitate distribution and mechanical properties including hardness distribution, tensile property and fracture feature along the thickness direction in the WNZ.

2. Experiments

In the present study, the base material (BM) was 20 mm thick aluminum alloy 7075-T6 plate. Table 1 shows the chemical compositions of the BM. The welding specimens with dimensions of 200 mm (length) × 100 mm (width) × 20 mm (thickness) were prepared for friction stir butt welding on an X53 K type FSW machine. The welding direction was normal to the rolling direction. For the tool, its handle and shoulder were made of H13 die steel, while the pin's material was GH4169 alloy. The diameter of tool shoulder was 38 mm. The diameter of the pin in the root was 14 mm, while it was 8 mm in the head, and its length was 19.5 mm. Moreover, the pin was threaded with three flats on the surface, and the thread pitch was 2 mm. In the experiments, the process parameters were optimized by trial and error. The rotation speed of 235 r/min, welding speed of 37.5 mm/min and spindle's tilt angle of 2° were selected. Also, the plunge depth of the shoulder was 1 mm during FSW.

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