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Effect of tool pin eccentricity on microstructure and mechanical properties in friction stir welded 7075 aluminum alloy thick plate

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ABSTRACT

Four different tools with the pin eccentricity of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm were designed to friction stir weld 10 mm thick AA7075-O plate. The effect of pin eccentricity on microstructure, secondary phase particles transformation and mechanical properties of the joints was investigated. The results show that the nugget area (A_{NZ}) increases firstly and then decreases with increasing the pin eccentricity. When the pin with 0.2 mm eccentricity is applied, the A_{NZ} is the largest; meanwhile the grains size is the smallest which is about 3 μm and secondary phase particles are the most dispersive in nugget zone compared with other tools. While the grains are coarsened to 7–11 μm as the eccentricity is more than 0.4 mm, some coarse hardening particles get to cluster in the thermo-mechanically affected zone. The joints produced by the pin with 0.2 mm eccentricity perform the highest tensile strength and elongation, which is attributed to better interfaces, finer grains and more dispersive secondary phase particles.

1. Introduction

7075 aluminum alloy is a precipitation hardened wrought material based on Al–Zn system, which is one of the strongest aluminum alloy used in many aircraft structural components due to its high strength to weight ratio and its natural aging characteristics [1,2]. However, this alloy is relatively difficult to weld using conventional fusion welding techniques because of its copper content, which leads to an extremely sensitive to weld crack and liquation crack in the heat affected zone and severely degrades mechanical properties within the joint [3,4]. It is possible to overcome the problem of solidification crack by using a suitable heat-treatable aluminum alloy filler, but the resulting joint efficiencies are unacceptably low [5]. Further, there are also several porosities and lack-of-fusion problems during fusion welding [6]. Therefore, the usage of conventional fusion welding in this AA7075 is limited.

Compared with conventional fusion welding, friction stir welding (FSW), invented in 1991 by The Welding Institute (TWI) of UK, is a new environmentally friendly, energy-effective and versatile solid-state joining technology [7], in which the material that is being welded does not melt and recast [8]. The FSW technique has great advantages to weld some materials which are impossible almost to be welded, such as aluminum and its alloy of 7XXX series, and it can avoid the generation of cracks and porosities to significantly improve mechanical properties of the weld [9–11]. The principle of FSW procedure is easily understood, a non-consumable rotating tool with the shoulder and pin plunges into slowly the workpiece, and then moves forward along the weld line to be joined. Heat is generated by the tool friction between the tool and the workpiece, which makes materials deform to result in a circulatory flow of plasticized materials around the pin surface. Plasticized materials underneath the shoulder are subjected to extruding by the rotation and traverse movement of the pin, and then are transported from the advancing side to the retreating side where it is joined into a weld [12,13].

Tool pin profile can observably influence material flow which was relative to microstructure evolution and mechanical properties of the weld [14]. Many investigators carried out studies on the effects of pin or shoulder geometry on material flow [15], microstructure and performances of friction stir welded aluminum alloys [16–18]. However, current papers about pin eccentricity are extremely reported, especially for aluminum alloy thick plates. The pin eccentricity is defined as the distance from the centre of shoulder diameter to the centre of pin diameter at the trailing edge of the shoulder, and diagrammatic drawing of tool pin eccentricity is shown in Fig. 1. Furthermore, the tools about pin eccentricity are designed in previous experiments by trial and error, and there

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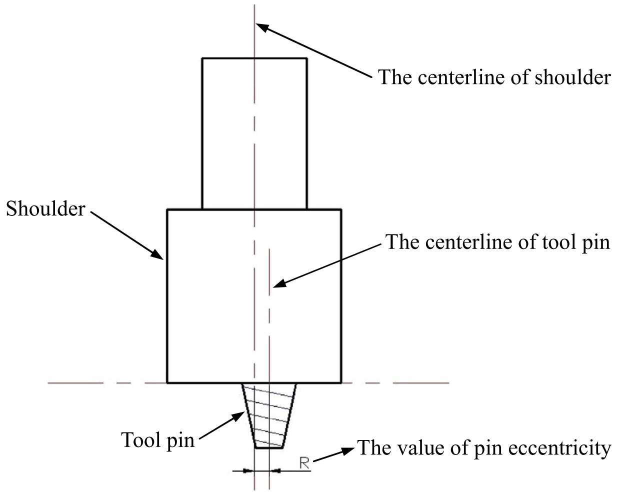

Fig. 1. Diagrammatic drawing of tool pin eccentricity.

is no agreement with the value of that. Thomas and Nicholas [19] demonstrated that the eccentricity allowed incompressible material to pass around the pin profile due to dynamic orbit with relative eccentricity. Khodaverdizadeh et al. [20] reported that pin profiles with flat faces had higher eccentricity to produce more pulsating stirring action in the flowing material. Xu et al. [21] investigated different pin profiles and concluded that the tool with three spiral flutes had better stirring action due to its eccentricity and enabled easier flow of plasticized material to increase the interface between the pin and plasticized materials. But, a detailed study about the influence of pin eccentricity in material flow and its flow path is not clear during FSW, and its effect on microstructure and mechanical properties of the joints for friction stir welded aluminum alloy thick plate is lacking. Therefore, the aim of this study is to investigate the effect of pin eccentricity on microstructure, secondary phase transformation and mechanical performances in friction stir welded 7075 aluminum alloy thick plate. For this purpose, four different tools with a pin eccentricity of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm are designed to weld the plates, respectively, and the microstructure and mechanical properties of the welds are analyzed and compared.

2. Experimental procedures

Some rolled plates of 7075 aluminum alloy with a thickness of 10 mm in annealed condition were used as the base material in this study, and the nominal chemical compositions and mechanical properties of this alloy are listed in Table 1. The Al alloy plates with a size of 200 mm × 100 mm were prepared for longitudinally friction stir butt welding on a modified horizontal-type milling machine, and the welding direction was parallel to the rolling direction. Each tool made of GH4169 steel was applied during FSW process, the shoulder diameter was 28 mm, the tapered threaded pin diameter at the root was 10 mm, instead it was 5 mm at the head, and the length of pin was 9.7 mm. Four different tools with a pin eccentricity of 0.1 mm, 0.2 mm, 0.3 mm and 0.4 mm were used in these experiments, which were labeled for No. 1, No. 2, No. 3 and No. 4 tool, respectively. A constant title angle of the rotating tool of 2° from the vertical axis of FSW machine was used. The plunge depth of shoulder or pin was kept an invariable 0.5 mm. And the same welding parameters including rotation speed of 375 rpm and welding speed of 30 mm/min were used during FSW.

The samples for metallographic observation were removed from the welded plates transverse to the welding direction, then which were ground and polished using standard metallographic technique, and etched with Keller's reagent (2 ml hydrofluoric acid, 3 ml hydrochloric acid, 5 ml nitric acid and 190 ml water) for 20 s to observe the microstructures of the weld in different regions.

Vickers hardness was measured using a HX-1000 model microhardness tester along the center lines of the cross-section with a loading of 100 g and a dwell time of 10 s, and an interval between two points was 0.5 mm. As per the ASTM: B557M-10, tensile test samples were cut vertically to the welding directions by the wire-electrode cutting, and machined to prepare tensile specimens. The dimensions of the tensile specimens are shown in Fig. 2. Tensile properties were evaluated using three tensile specimens cut from the same weld, and the surface and edges of specimens were rounded and polished to avoid the surface stress concentration. Tensile tests were carried out using a WDS-100 universal testing machine with an initial strain rate of 1 mm/min at room temperature. The fracture surfaces of tensile samples were examined using a TESCAN VEGA II-LMH scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectroscopy (EDX) system. Secondary phase particles were analyzed using a JEOL 2010 transmission electron microscope (TEM) operating at 200 keV. TEM samples were prepared by twin-jet electro-polish in a solution of 25 vol.% of HNO_3 and 75 vol.% of methanol at a temperature of −30 °C. The voltage was set as 12 V.

3. Results and discussion

3.1. Macrostructure observations

The macrostructures of the joints in friction stir welded 7075-O aluminum alloy by different tools at constant rotation speed of 375 rpm and welding speed of 30 mm/s are illustrated in Table 2 at low magnification. The advancing side and the retreating side of the joint are denoted by AS and RS, respectively. It is found that the surface appearances using the No. 1 and No. 2 tools are characterized by smooth surfaces and little flashes after FSW. Even if a little of flash is produced, it is very easy to remove as a continuous chip. However, a large number of flashes are produced and the crowns are rougher when the plates are welded by the No. 3 and No. 4 tools. To exhibit the weld further, the macrostructures of the joints are cross-sectioned vertically to the welding direction. The observations including nugget zone shape, nugget zone height (H), nugget zone width (W_{NZ}), nugget zone area (A_{NZ}) and the quality of the joints from the macrostructures are presented singly in Table 2. It is clear that the joints fabricated by four tools are defect-free and some complete onion rings are observed in the W_{NZ}. Meanwhile, the nugget zones of the welds are surrounded by the curves in the macrographs, and a great difference in the size of the W_{NZ} and A_{NZ} exists in four samples made by different tools. By measuring the sizes accurately, the A_{NZ} is 122.5 mm^2, 133.7 mm^2, 111.3 mm^2 and 107.6 mm^2; the W_{NZ} is 12.9 mm, 13.7 mm, 11.6 mm and 11.2 mm, respectively, which are

Table 1
Chemical composition (in wt.%) and mechanical properties of 7075-O aluminum alloy.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
0.4	0.5	1.85	0.3	2.86	0.25	6.0	0.2	Balance	235	103	17.9