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Characteristics of the reverse dual-rotation friction stir welding conducted on 2219-T6 aluminum alloy

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ABSTRACT

Reverse dual-rotation friction stir welding (RDR-FSW) has great potential to obtain appropriate welding conditions through adjusting the independently rotating tool pin and surrounding shoulder. The welding torque exerted on the workpiece by the reversely rotating shoulder also cancels off a part of the welding torque exerted by the rotating tool pin, thus the clamping requirement for the workpiece is also reduced. In the present paper, a tool system for the RDR-FSW was designed and successfully applied to weld high strength aluminum alloy 2219-T6, and then microstructures and mechanical properties of the optimized joint were investigated to demonstrate the RDR-FSW characteristics. The weld nugget zone was characterized by the homogeneity of refined grain structures, but there was a three-phase confluction on the advancing side formed by different grain structures from three different zones. The tensile strength of the optimized joint was 328 MPa (73.7% of the base material), showing an obvious improvement when compared with the optimized joint welded by the FSW without the reversely rotating assisted shoulder. The tensile fracture occurred in the ductile fracture mode and the fracture path propagated in the weakest region where the Vickers hardness is the minimum.

1. Introduction

Because of its advantages in welding aluminum alloys especially the high strength aluminum alloys (e.g. the 2xxx and 7xxx series) which are classified as non-weldable materials by conventional fusion welding processes, the friction stir welding (FSW) has attracted extensive concerns since it was invented by The Welding Institute (TWI) of UK in 1991 [1,2]. As a solid-state joining technique, FSW has been applied to weld almost all series of aluminum alloys in the past two decades [3,4]. With the further development, some variant techniques were developed from the conventional FSW, including preheated FSW [5,6], skew-stir FSW [7,8], twin-stir FSW [8] and dual-rotation FSW [8].

In conventional FSW, the tangential speed on the tool shoulder increases from zero at the tool pin center to the maximum speed at the maximum diameter of the shoulder. Due to the obvious speed gradient, over-heating or even incipient melting along the shoulder edge on the weld surface can occur depending on the materials and the applied process conditions. The over-heating or incipient melting has great deterioration on microstructures and mechanical properties of the FSW joint especially for the high strength aluminum alloys [9,10]. When the conventional FSW is applied to weld thick plates, this phenomenon is particularly serious because the shoulder diameter of the utilized FSW tool is larger [11]. To avoid this problem, the dual-rotation FSW has been proposed as a variant technique [8]. During the dual-rotation FSW process, there is a speed differential between the independently rotating tool pin and surrounding shoulder. Therefore, it allows for a high rotation speed of the tool pin without a corresponding increase of the shoulder peripheral speed, providing an approach to reduce any tendency towards overheating or incipient melting through optimizing rotation speeds of both the tool pin and the surrounding shoulder. A double-side butt weld of 16 mm thick 5083-H111 aluminum alloy using a non-optimized welding condition was made to demonstrate that the dual-rotation FSW is practicable for certain applications [8]. Furthermore, FSW eliminates welding defects associated with conventional fusion welding processes, though the produced thermal cycle is sufficient to modify the original alloy temper in certain high strength aluminum alloys such as 2xxx and 7xxx series and then produce a reduction in the mechanical properties. Therefore, solutions should be found out to reduce the peak temperature and the holding time at the elevated temperature in the thermal cycle. The dual-rotation FSW is a potential method and the preliminary experiment conducted on AA7050-T7451 showed that both the peak temperature and the holding time at the elevated temperature are reduced when compared with the conventional FSW [8]. Since the dual-rotation FSW was proposed, no detailed research on microstructures, mechanical properties and process optimization has been carried out up to the present. As for the conventional FSW, the large process load

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(including the axial plunge force, transitional force and welding torque) also constrains its applications in many industries where aluminum alloy structures are applied widely, such as the on-site manufacturing and the in-orbit repair of space stations whose construction has become an important step to exploit the outer space. Crawford et al. [12] and Widener et al. [13] carried out researches on the high-rotation speed FSW to reduce the process load. Meanwhile, a non-rotational shoulder was directly added to surround the rotating tool to eliminate the appeared flash defects and cavity defects. Li et al. [14] also researched on the non-rotational shoulder assisted FSW (NRSA-FSW), in which the diameter of the rotating sub-size concave shoulder was decreased to twice the plate thickness to reduce the process load further and the outer diameter of the assisted non-rotational shoulder is the same as the shoulder diameter in conventional FSW tool (about three times the plate thickness). The NRSA-FSW can produce defect-free joints in a wide range of welding parameters and reduce the welding torque and axial plunge force greatly, but the transitional force is still large because the non-rotational shoulder plunges into the specimens and slides on the specimen along the joint line. Utilizing the tool system designed based on the NRSA-FSW tool system, the dual-rotation FSW will reserve advantages of the NRSA-FSW and the transitional force can be reduced significantly because the assisted shoulder rotates when it slides on the specimen along the joint line.

In the present paper, the reverse dual-rotation FSW (RDR-FSW) was proposed based on the dual-rotation FSW. All advantages can be realized in the RDR-FSW. Furthermore, the RDR-FSW is beneficial to reduce the clamping requirement of welding samples. The welding torque exerted on the workpiece by the reversely rotating shoulder also cancels off a part of the welding torque exerted by the rotating tool pin, thus the total welding torque exerted on the workpiece by the RDR-FSW tool system is reduced further. Due to the reduced process load and clamping requirement, the size and mass of the FSW equipment and the fixture can be decreased, laying a foundation for applications of the FSW technique in the on-site manufacturing and the in-orbit repair of space stations. In order to demonstrate characteristics of the RDR-FSW, a tool system was designed and utilized to weld high strength aluminum alloy 2219-T6, which is widely applied in the aerospace industry. When the experiment was conducted, the assisted shoulder and the tool pin rotated independently in different rotation directions and at different rotation speeds. The focus was placed on the weld formation, characteristics of microstructures in various zones and mechanical properties of the welded joints.

2. Experimental procedure

The base material (BM) utilized in the experiment was 5 mm thick 2219-T6 aluminum alloy plate (6.48Cu, 0.32Mn, 0.23Fe, 0.06Ti, 0.08 V, 0.04Zn, 0.49Si, 0.20Zr, Al bal., in wt.%). The tensile strength and the elongation of this BM were 445 MPa and 11.4%, respectively. The Vickers hardness is in the range from 125 to 135 Hv. Rectangular welding samples with a dimension of 300 mm long by 80 mm wide were prepared. When the top surface and abutting surface were cleared by acetone, two welding samples were clamped together on the worktable with the abutting line on the backing plate. The butt-welded joints were obtained using an FSW machine (FSW-3LM-003) along the longitudinal direction, perpendicular to the rolling direction of the plate.

Fig. 1 shows the self-designed tool system for the RDR-FSW, including the schematic view and the set-up photo. The RDR-FSW tool system is composed of the tool pin rotating with the spindle of the FSW machine during the welding process and the surrounding assisted shoulder rotating independently and reversely driven by two servo motors. The tool pin is mounted on a sub-size concave shoulder which is extended from the shaft, and the shaft is fixed on the spindle of the FSW machine. Therefore, the tool pin rotates at the same rotation speed and in the same rotation direction as the spindle during the welding process. Except for generating heat and supplying a forge effect just as the shoulder in the conventional FSW tool, the sub-size concave shoulder is also helpful to hinder the ingress of plasticized materials at the interface between the rotating tool pin and the assisted shoulder. The assisted shoulder is machined on the bottom end cover, which is fixed on the middle cylinder through four bolts. The middle cylinder is assembled with the shaft through a deep groove ball bearing and a tapered roller bearing. With the help of these two bearings, the step on the shaft and the top end cover, the sub-size concave shoulder retracts into the assisted shoulder about 0.1 mm. In another word, the plunge depth of the sub-size concave shoulder is 0.1 mm smaller than that of the assisted shoulder during the welding process. On the middle cylinder, there is also a driving gear which engages with two driving gears mounted on the output shaft of the servo motor. Two servo motors are installed on the fixed frame symmetrically. When the enable signal is simultaneously supplied to actuators of these two servo motors, the twin-motor synchronous driving of the assisted shoulder can be realized. Through adjusting the rotation direction and the rotation speed of the servo motor, the assisted shoulder will rotate in the expected direction at the set speed. Geometric dimensions of main components in the RDR-FSW tool system are listed in Table 1, including the conical threaded tool pin, sub-size concave shoulder and assisted shoulder.

In the experiment, the tool pin rotated counter-clockwise, while the assisted shoulder rotated clockwise. The tilted angle of the tool with respect to the *Z*-axis of FSW machine was 2.5° for all joints. Meanwhile, plunge depths of the sub-size concave shoulder and the surrounding reversely rotating assisted shoulder were 0.1 mm and 0.2 mm, respectively. Adjusting the rotation speed of the assisted shoulder (400–1200 rpm), the tool pin rotation speed (600–1000 rpm) and the welding speed (50–300 mm/min), the optimized welding parameters were obtained according to the weld formation and tensile properties. The optimized rotation speed of the assisted shoulder, tool pin rotation speed and welding speed were 800 rpm, 800 rpm and 150 mm/min, respectively. Therefore, the optimized joint welded at this optimized welding condition was chosen to demonstrate the characteristics of the RDR-FSW, focusing on microstructures in various zones and mechanical properties. After welding, specimens for metallographic analyses, tensile tests and Vickers hardness tests were cross-sectioned from the welded joint perpendicular to the welding direction. When the metallographic samples were polished using a diamond paste and etched with the Keller's reagent, a stereomicroscopy (Olympus-SZX12) and an optical microscopy (OM, Olympus-MPG3) were applied to characterize the weld formation and microstructures, respectively. The tensile test was performed at room temperature using a computer-controlled universal testing machine (Instron-5569) at a constant crosshead speed of 1.0 mm/min. Tensile specimens are machined perpendicular to the welding direction with a gauge length of 50 mm and a width of 15 mm, referring to China National Standard GB/T 2651-2008 (equivalent to American Standard ASTM B557-2) [15]. Three tensile specimens were prepared and tested for each joint, and the average is used to estimate the tensile property. Finally, the fracture location was characterized by the above-mentioned stereomicroscopy, while characteristics of the fracture surface were analyzed by a scanning electron microscopy (SEM, Hitachi-S4700). Using a Vickers indenter, the Vickers hardness was measured on the polished cross-section with a spacing of 0.5 mm between two adjacent indentations. The scanning line for the