Journal of Materials Science & Technology 31 (2015) 375–383

Contents lists available at ScienceDirect

Journal of Materials Science & Technology

journal homepage: www.jmst.org

Effects of the Reversely Rotating Assisted Shoulder on Microstructures During the Reverse Dual-rotation Friction Stir Welding

J.Q. Li [1, 2], H.J. Liu [1, *]

[1] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China
[2] Capital Aerospace Machinery Company, Beijing 100076, China

ARTICLE INFO

Article history:
Received 14 April 2014
Received in revised form
9 June 2014
Accepted 24 July 2014
Available online 14 January 2015

Key words:
Friction stir welding
Reverse dual-rotation friction stir welding
High-strength aluminum alloy
Microstructures
Precipitates

The reverse dual-rotation friction stir welding (RDR-FSW) has the capability to adjust the heat generation because of the separately designed tool shoulder and tool pin. The welding torque exerted on the workpiece by the reversely rotating shoulder is opposite to that exerted by the rotating tool pin, so the total welding torque is reduced, which is beneficial to reducing the clamping requirement of workpieces. In the present paper, a RDR-FSW joint was welded in a condition similar to the optimal welding condition of conventional FSW, and microstructures in various zones were investigated by comparison, aiming to highlight effects of the reversely rotating assisted shoulder. Due to the heat conduction of the middle cylinder and the bottom end cover on which the assisted shoulder was machined, the thermal effect of RDR-FSW was smaller than that of the conventional FSW. Moreover, the effect of assisted shoulder on the plastic flow or deformation of material or was constrained in a thin layer near the weld top surface, and thus the flow of material especially along the thickness direction was clearly decreased in the RDR-FSW. In the heat-affected zone (HAZ), the precipitate coarsening was the main evolution and was completed through the dissolution of small precipitates and the continuous growth of large precipitates. By contrast, the dissolution degree of precipitates increased significantly in the thermo-mechanically affected zone (TMAZ), and a small amount of original meta-stable precipitates transformed to block-shaped stable precipitates. Precipitate evolutions in the shoulder affected zone (SAZ) and the weld nugget zone were similar, i.e. the majority of original meta-stable precipitates dissolved into the matrix and the remainder transformed to stable precipitates, though the dissolution degree was greater in the SAZ. Compared with the conventional FSW joint, the coarsening degrees of precipitates in the HAZ and TMAZ of RDR-FSW joint were much smaller, as well as the dissolution degrees of precipitates in all four specified zones.

1. Introduction

High-strength aluminum alloys, such as the 2xxx and 7xxx series, have been widely applied in aircraft and aerospace engineering because of their high strength-to-weight ratio, good fracture toughness and superior cryogenic properties[1,2]. Unfortunately, they are classified into difficult-to-weld materials when conventional fusion welding processes are applied. As a solid-state joining technique, friction stir welding (FSW) has solved the problems associated with the fusion welding of high-strength aluminum alloys, thus producing better joint property[3,4]. Actually, the thermal cycle of FSW is sufficient to change precipitates, which exerts the main strengthening effect, and finally deteriorates the joint property[5,6]. At present, the post-weld heat treatment[7–9] and the in-process forced cooling[10–13] are two main measures to improve the joint property further. The post-weld heat treatment is beneficial to the reprecipitation of precipitates, which dissolve into the matrix during the welding process, while the in-process forced cooling inhibits the transformation and dissolution of strengthening precipitates. As for the larger-scale aluminum components, both the post-weld heat treatment and the forced cooling are constrained. The dual-rotation FSW has the capability to adjust the heat generation and the thermal effect, and thus it can be applied to improve the joint property conveniently[14]. In the dual-rotation FSW, the shoulder and the tool pin are designed separately, and thus the heat generation and the temperature field can be controlled through adjusting their respective rotation speeds. Li

* Corresponding author. Tel.: +86 451 8641 3951; Fax: +86 451 8641 6186.
E-mail address: liuhj@hit.edu.cn (H.J. Liu).

http://dx.doi.org/10.1016/j.jmst.2014.07.020

et al.[15–17] and Widener et al.[18] have researched the non-rotational shoulder assisted FSW (NRSA-FSW), in which the heat generation of shoulder was reduced at the greatest degree. Although the maximum tensile strength was much lower than the optimal tensile strength obtained by conventional FSW when the rotating sub-size concave shoulder plunged deeper than the non-rotational assisted shoulder, the higher tensile strength could be obtained when the assisted shoulder plunged deeper than the rotating sub-size concave shoulder. It needs to be noted that increasing plunge depth of the assisted shoulder would lead to the increase of welding process loads such as the transitional force, which has adverse effects on both the welding process and the tool system. To obtain high joint property and avoid heavy process loads, a set of driving components were added in the NRSA-FSW tool system. Compared with the co-rotating dual-rotation FSW, in which the assisted shoulder and the tool pin have the same rotation direction, the welding torque exerted by the assisted shoulder on the workpiece cancels off a part of the welding torque exerted by the rotating tool pin during the reverse dual-rotation FSW (RDR-FSW), and thus the total welding torque exerted by the RDR-FSW tool system can be reduced greatly and the clamping requirement can also be reduced[19,20]. Due to the reduced process load and clamping requirement, the size and mass of the FSW equipment and the fixture can be reduced, facilitating engineering applications of the RDR-FSW.

As for high-strength aluminum alloys, the microstructural evolution in the welded joint is the decisive factor of joint property. In order to demonstrate microstructural characteristics in the RDR-FSW joint and clarify the essential reason of improving joint properties, the high-strength aluminum alloy 2219-T6 was chosen to be butt-welded by RDR-FSW in the present paper. Microstructures in various zones of the RDR-FSW joint were investigated in detail through comparing with the conventional FSW joint, and effects of the reversely rotating assisted shoulder on microstructures were also analyzed. This will lay a foundation for understanding the advantages of RDR-FSW in reducing the thermal effect of welding cycles and improving the joint property.

2. Experimental

The high-strength aluminum alloy 2219-T6 (6.48Cu, 0.32Mn, 0.23Fe, 0.06Ti, 0.08V, 0.04Zn, 0.49Si, 0.20Zr, Al balance, in wt%) with the thickness of 5.0 mm was chosen as the base material (BM). The tensile strength and elongation of BM were 445 MPa and 11.4%, respectively. Rectangular welding samples with 300 mm in length and 80 mm in width were prepared with the length direction perpendicular to the rolling direction of BM plate. To avoid the pollution caused by the oxide film or other impurities, both the top surface and the abutting surface were processed by the steel wire brush and cleaned by the acetone before welding. Two welding samples were clamped together on the worktable with the abutting line on the backing plate and then butt-welded using an FSW machine (FSW-3LM-003) along the longitudinal direction.

Fig. 1 shows the self-designed RDR-FSW tool system, which is composed of the tool pin and the reversely rotating assisted shoulder. During the RDR-FSW process, the tool pin rotates with the spindle of FSW machine, while the assisted shoulder rotates independently and reversely driven by two servo motors. Therefore, the rotation speed and direction of the tool pin are the same as the spindle, while those of the assisted shoulder can be adjusted through the actuator of driving motors. The sub-size concave shoulder designed on the tool pin is helpful to hinder the ingress of plasticized materials at the interface between the rotating tool pin and the assisted shoulder. Just as the tool shoulder in conventional FSW, the sub-size concave shoulder also generates heat and supplies a forge effect. The assisted shoulder is machined on the bottom end cover, which is fixed on the middle cylinder through four bolts. Through a deep groove ball bearing and a tapered roller bearing, the middle cylinder is assembled with the shaft, at the end of which is the tool pin. During the welding process, the plunge depth of the sub-size concave shoulder is 0.1 mm smaller than that of the assisted shoulder so that the assisted shoulder can play its role on the whole weld width. Geometric dimensions of main components in the RDR-FSW tool system are designed according to the conventional FSW tool. The conical threaded tool pins in both the RDR-FSW and the conventional FSW have a median diameter of 4.52 mm and a length of 4.80 mm. The sub-size concave shoulder has an inner diameter of 5.94 mm and an outer diameter of 9.80 mm, while the re-entrant angle is 10° just as the tool shoulder in conventional FSW. As for the assisted shoulder, the inner diameter of 10.0 mm is designed to ensure a 0.1 mm gap between the sub-size concave shoulder and the assisted shoulder, while the outer diameter of 14.0 mm is designed to be the same as the shoulder diameter of the conventional FSW tool.

In the experiment, the tilted angle of the tool to the *Z*-axis of FSW machine was 2.5° for both the conventional FSW and the RDR-FSW. According to previous researches on conventional FSW of 2219-T6, both the weld formation and the joint property were the optimal at the tool rotation speed of 800 r/min, the welding speed of 200 mm/min and the plunge depth of 0.2 mm[21,22]. Furthermore, the tool rotated counter-clockwise. To ensure a similar welding condition for the RDR-FSW process, the tool pin rotated counter-clockwise and the assisted shoulder rotated clockwise. Meanwhile, plunge depths of the sub-size concave shoulder and the reversely rotating assisted shoulder were 0.1 mm and 0.2 mm, respectively. Correspondingly, rotation speeds of both the tool pin

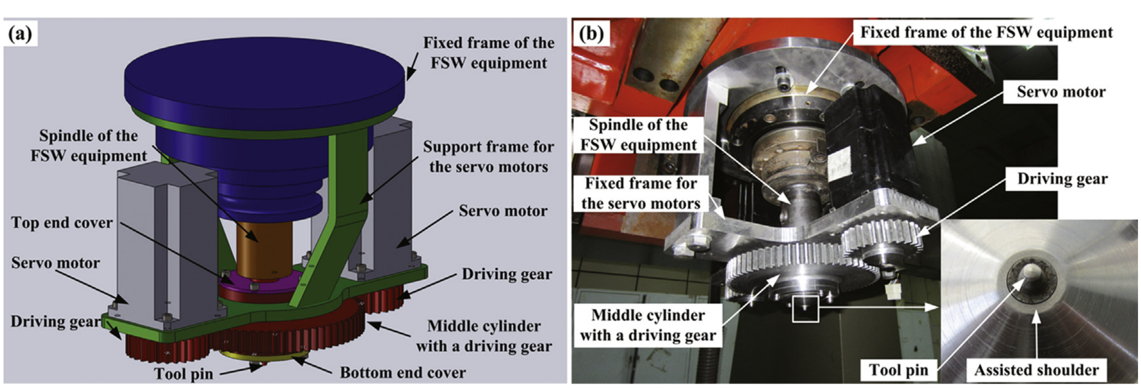

Fig. 1. Tool system for the RDR-FSW: (a) schematic view, (b) tool set-up photo.