Optimization of welding parameters for the reverse dual-rotation friction stir welding of a high-strength aluminum alloy 2219-T6

J. Q. Li · H. J. Liu

Abstract As for high-strength aluminum alloys such as 2219-T6, the friction stir welding (FSW) has the capability to reduce the thermal effect and obtain better joint property when compared with conventional welding processes, but its welding thermal cycle is sufficient to change the original strengthening precipitates and deteriorate the joint property. The reverse dual-rotation friction stir welding (RDR-FSW) has been demonstrated to be available for improving the joint property further due to its capability to adjust the heat generation through the separately designed tool shoulder and tool pin. Moreover, the welding torque exerted on the workpiece by the reversely rotating shoulder is opposite to that exerted by the rotating tool pin, thus the total welding torque is reduced, and this is beneficial to reduce the clamping requirement and broaden its application. In the present paper, the optimization experiment of RDR-FSW was conducted on the high-strength aluminum alloy 2219-T6 according to the Box-Behnken design method, aiming to obtain the optimum welding condition and the corresponding optimum tensile strength. A mathematical response model was developed based on the optimization experiment. Applying the RDR-FSW, the optimum tensile strength of 357 MPa was obtained, and this is obviously higher than the optimum tensile strength obtained by the conventional FSW and approaches the optimum tensile strength obtained by the underwater FSW which is also proposed to improve the joint property further.

Keywords Friction stir welding · Reverse dual-rotation friction stir welding (RDR-FSW) · High-strength aluminum alloy · Optimization · Welding parameters

1 Introduction

Due to their high strength-to-weight ratio, good fracture toughness, and superior cryogenic properties, high-strength aluminum alloys such as the 2xxx and 7xxx series have been widely applied in the aircraft and aerospace industry [1, 2]. However, they are difficult to be welded by conventional welding processes. Friction stir welding (FSW) is a solid-state joining technique and has solved the problems associated with the fusion welding of high-strength aluminum alloys, thus producing better joint property than those fusion-welded joints [3, 4]. Actually, the thermal cycle of FSW is sufficient to cause the coarsening or dissolution of strengthening precipitates, leading to the deterioration of local mechanical properties of welded joints [5, 6]. To improve the joint property further, the post-weld heat treatment [7–9] and the in-process forced cooling [10–13] were proposed in recent years. 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 will inhibit the transformation or dissolution of strengthening precipitates, thus achieving the purpose to improve the joint property. Unfortunately, both the post-weld heat treatment and the in-process forced cooling are constrained when they are applied in larger-scale aluminum components. The in-process forced cooling is also not convenient to be conducted in some situation. Therefore, it is essential to propose a method from the heat generation of FSW to reduce the thermal effect and improve the joint property further [14].

J. Q. Li · H. J. Liu
State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, People’s Republic of China
e-mail: liuhj@hit.edu.cn

J. Q. Li
Capital Aerospace Machinery Company, Beijing 100076, People's Republic of China
During the FSW process, the tool shoulder generates the majority of heat, up to 80% or more \cite{15, 16}. Therefore, it is feasible to control the heat generation and the temperature field if the tool shoulder and the tool pin are adjusted separately. The dual-rotation FSW, in which the tool shoulder and the tool pin are designed separately, has the capability. It is called non-rotational shoulder-assisted FSW (NRSA-FSW) when the rotation speed of assisted shoulder is zero, while it can be divided into the co-rotating dual-rotation FSW (CDR-FSW) and the reverse dual-rotation friction stir welding (RDR-FSW) when the rotation speed of assisted shoulder is not zero. Li et al. \cite{17–20} have researched on microstructures and mechanical properties of NRSA-FSW joints. It was found that the maximum tensile strength was obviously lower than the optimum tensile strength obtained by the conventional FSW if the rotating sub-size concave shoulder plunged deeper than the non-rotational assisted shoulder but the much higher tensile strength could be obtained if the assisted shoulder plunged deeper than the rotating sub-size concave shoulder. Although the NRSA-FSW with a relatively deeper plunge depth of the assisted shoulder has the capability to obtain much higher tensile strength than the conventional FSW, welding process loads such as the transitional force would increase obviously, producing adverse effects on both the welding process and the tool system. As for the CDR-FSW and the RDR-FSW which are realized through adding a set of driving components in the NRSA-FSW tool system, it is also beneficial to reduce the thermal effect at a high rotation speed of tool pin combined with a low rotation speed of assisted shoulder, and the rotating assisted shoulder also heats and plasticizes surrounding materials. Therefore, welding process loads are reduced, and high tensile strength can also be obtained at the same time. Compared with the CDR-FSW, the RDR-FSW is able to reduce the total welding torque exerted on the workpiece greatly for the reason that the welding torque exerted by the assisted shoulder is opposite to the welding torque exerted by the rotating tool pin, and this is beneficial to reduce the clamping requirement of workpieces \cite{21, 22}. Due to the reduced process load and clamping requirement, the size and mass of the FSW equipment and fixture can be decreased, laying a foundation for applications of the FSW technique in larger-scale aluminum components.

Previous researches have demonstrated characteristics of the RDR-FSW and effects of welding parameters on microstructures and mechanical properties \cite{21, 22}. To widen its application, it is of significance to optimize welding parameters, aiming to obtain the optimum tensile strength and the corresponding optimum combination of welding parameters. Up till now, this work has not been conducted. Hence, the optimization experiments were conducted on the high-strength aluminum alloy 2219-T6 according to the Box-Behnken design method in the present paper, and a mathematical model was developed to predict the tensile strength of welded joints. Utilizing the developed mathematical model, both the optimum tensile strength and the optimum combination of welding parameters were obtained.

### 2 Experimental procedure

The base material (BM) utilized in the optimization experiment was a 5.0-mm-thick plate of high-strength aluminum alloy 2219-T6, whose chemical compositions and mechanical properties are listed in Table 1. Rectangular welding samples of 300 mm long by 80 mm wide were processed by the steel wire brush on both the top surface and the abutting surface, aiming to avoid the pollution caused by the oxide film. After cleaning by the acetone, two welding samples were clamped together on the worktable with the abutting line on the backing plate. Butt-welded joints were welded by an FSW machine (FSW-3LM-003) along the longitudinal direction, which was also perpendicular to the rolling direction of the BM plate.

Figure 1 shows the self-designed RDR-FSW tool system, including the schematic view and the setup photo. In the RDR-FSW tool system, the tool pin and the tool shoulder are designed separately. During the RDR-FSW process, the tool pin rotates with the spindle of the FSW machine, while the assisted shoulder rotates at the reverse direction driven by two servo motors. Therefore, the rotation speed and direction of the tool pin are the same as the spindle of the FSW machine, while those of the assisted shoulder can be adjusted through the actuator of driving motors. To avoid the friction between the tool pin and the assisted shoulder, a gap about 0.1 mm is designed. Furthermore, a sub-size concave shoulder is designed on the tool pin, which is helpful to hinder the ingress of plasticized materials into the gap between the rotating tool pin and the reversely rotating assisted shoulder. Just as the tool shoulder in the conventional FSW tool, this sub-size concave shoulder also generates heat and supplies a forge effect. The bottom end cover, on which the assisted shoulder is machined,

<table>
<thead>
<tr>
<th>Chemical compositions (wt.%)</th>
<th>Mechanical properties</th>
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<tbody>
<tr>
<td>Cu</td>
<td>Mn</td>
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<td>6.48</td>
<td>0.32</td>
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