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The effect of the welding parameters and tool size on the thermal process and tool torque in reverse dual-rotation friction stir welding

L. Shi [a], C.S. Wu [a,b,*], H.J. Liu [b]

[a] MOE Key Lab for Liquid-Solid Structure Evolution and Materials Processing, and Institute of Materials Joining, Shandong University, Jinan 250061, China
[b] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

Reverse dual-rotation friction stir welding (RDR-FSW) is a novel variant of conventional friction stir welding (FSW) process. The key feature is that the tool pin and the assisted shoulder are separated and rotate reversely and independently during welding process, thus it has great potential to improve the weld quality and lower the welding loads through adjusting the rotation speeds of the tool pin and the assisted shoulder independently. A 3D model of RDR-FSW process is developed to analyze the effect of welding parameters and tool size on the thermal process and the tool torque quantitatively. The model considers the effect of the welding parameters on the dimensionless slip rate and the friction coefficient between the tool-workpiece contact interfaces. It is found that with an increase of the radial distance, the locations of peak and valley values of heat generation rate at the shoulder-workpiece contact interfaces vary from the retreating side (RS) to the advancing side (AS) and from the AS to the RS, respectively. Although the reverse rotation of the tool pin and the assisted shoulder has little effect on the total heat generation, the corresponding material flow pattern and the distribution of heat generation rate lead to a more homogeneous temperature distribution and a much lower torque exerted on the workpiece in RDR-FSW process. The model is experimentally validated by comparing the measured thermal cycles with the calculated data.

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1. Introduction

Friction stir welding (FSW) process has been proved to be a successful solid-state joining process for aluminum alloys [1,2]. During the process, a specially designed rotating tool is inserted into the adjoining edges of the workpieces and then moved all along the line of joint [3]. The heat generated by both friction and plastic deformation softens the material near the tool, and severe plastic deformation and flow of this plasticized metal occurs as the tool moves. Material is transported from the front of the tool to the trailing edge where it is forged into a joint [4,5]. The simultaneous rotation and transverse motion of the tool create asymmetrical temperature distribution and material flow between the two sides of the weld, which leads to different microstructures and mechanical properties between the advancing side (AS) and the retreating side (RS) of the weld [6]. The asymmetry of the welded joint is a unique characteristic of the FSW method, which leads to the deterioration of microstructures and mechanical properties of the weld [6]. During the conventional FSW, relatively high rotation torque and plunge force are needed for the purpose of adequately softening the material to form a good weld [7–9]. The relatively high stress subjected by the tool causes severe tool wear and premature tool failure [9]. In addition, the relatively high tangential speed at the periphery of the shoulder may cause overheating or even incipient melting along the shoulder edge when thick plates are joined [10–12], which leads to the mechanical property degradation of the joint, especially for welding precipitation-hardened aluminum alloys [3,13,14].

To overcome the above shortcomings of the conventional FSW, the reverse dual-rotation friction stir welding (RDR-FSW) process has been proposed as a variant technique [10–12]. In RDR-FSW, the tool pin and assisted shoulder are separated and rotate with opposite direction independently, as shown in Fig. 1. Thus, the tool pin can rotate in a relatively high speed while the assisted shoulder can rotate in an appropriate matching speed. In this way, the tendency towards overheating or incipient melting can be avoided through optimizing rotation speeds of both the tool pin and the assisted shoulder [11,12]. In RDR-FSW, the welding torque exerted on the workpiece by the tool pin is partly offset by the reversely rotating assisted shoulder. As a result, the total torque exerted on the workpiece by the tool is reduced. Thus, the

* Corresponding author. Fax: +86 531 8839 2711.
E-mail address: wucs@sdu.edu.cn (C.S. Wu).

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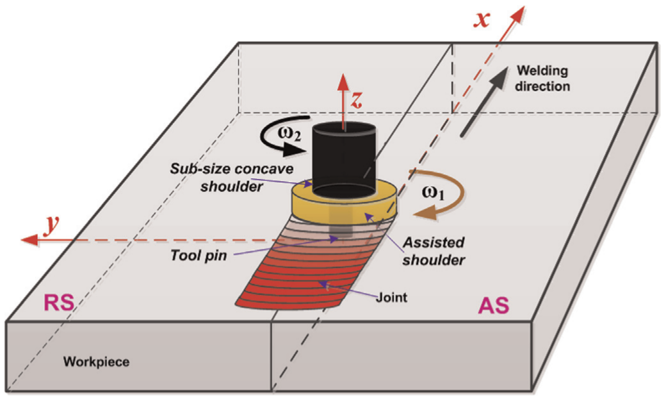

Fig. 1. Schematic drawing of reverse dual-rotation friction stir welding (RDR-FSW).

clamping equipment can be simplified, and the size and mass of the welding equipments can be lowered [10–12]. In addition, the differences of the temperature distribution and material flow between the AS and the RS can be reduced by the reverse rotation of the tool pin and the assisted shoulder. Thus, the homogeneity of temperature fields and microstructures can be improved [12,15,16]. In a word, the RDR-FSW process has great potential to reduce the tool torque and improve the properties of the joints through adjusting the rotating speed of the tool pin and the assisted shoulder independently [10–12,15,16]. However, the reverse and independent rotating of the tool pin and the assisted shoulder increases the complexity of the process and the number of the process parameters. The complicated interactions among the welding parameters and physical variables simultaneously affect the thermal process and the final properties of the joints [17–19]. In order to optimize the process and the relevant properties of the joints, a fundamental knowledge of the complex thermal process should be required, and a rigorous numerical model coupled with experimental validation is suitable.

In the past decades, numerous thermal models [20–23], thermo-mechanical or thermo-flow coupled models [24–30] have been developed to analyze the thermal process in conventional FSW. Furthermore, a model to evaluate the tool torque in conventional FSW has been established, and the effect of welding parameters on tool torque has been analyzed [31]. All those provide significant progress in quantitative understanding of the conventional FSW process. Recently, Shi et al. [15,16] developed a model to analyze the heat transfer and material flow in RDR-FSW. However, the effect of the welding parameters on the dimensionless slip rate and friction coefficient between the tool-workpiece contact interfaces has not been considered in the model, which leads to an over predicted value of the temperature near the tool. In addition, there is no quantitative analysis of the tool torque during RDR-FSW.

In this study, a numerical model is developed to analyze the heat generation, temperature distribution, material flow and tool torque for different welding parameters and tool size in RDR-FSW process. The dimensionless slip rate and friction coefficient at the tool-workpiece contact interfaces are determined under different welding conditions. The effect of the welding parameters and tool size on the thermal process and tool torque during RDR-FSW process are quantitative analysis. To validate the model, the calculated thermal cycles are compared with the corresponding measured data.

2. Numerical modeling

2.1. Geometric model description

A schematic drawing of RDR-FSW is shown in Fig. 1. In RDR-FSW, the tool pin with the sub-size concave shoulder is mounted on the spindle of a conventional FSW machine, while the assisted shoulder is mounted on the fixed frame of the conventional FSW machine through a self-designed support frame [11,12]. In this way, the tool pin with sub-size concave shoulder rotates with the same rotation speed and direction of the spindle. However, the assisted shoulder is driven by two servo motors mounted on the self-designed support frame so that it rotates independently and reversely. During the RDR-FSW process, the side of the weld where the pin rotation and welding direction are the same is defined as advancing side (AS), and the opposite side of the weld is defined as retreating side (RS). Detailed description of the RDR-FSW process can be found in literatures [11,12].

2024 Aluminum alloy plates (500 mm in length, 300 mm in width, and 5 mm in thickness) are welded by RDR-FSW. The dimensions of the tool is given in Table 1. Table 2 lists the nominal chemical composition of the 2024 aluminum alloy. The yield strength of 2024 aluminum alloy is obtained from literature [32]. The specific heat capacity and the thermal conductivity are obtained from literature [33], which is given in Table 3.

The geometric model is shown in Fig. 2a. A 3D Cartesian coordinate system is established on the plate. The origin of coordinate system is located at the intersection between the bottom surface of the workpiece and the tool axis. The welding direction is identical to the positive *x*-axis, and the *z*-axis is along the thickness of the plate (towards to the top surface of the workpiece). The commercial CFD code FLUENT was used to conduct the numerical simulation [4]. The sensitivity analyses of the size of the Eulerian calculation domain were conducted. In order to compare the calculated results with the experimentally measured data, the calculation domain equal to the real workpiece dimension was used to conduct the numerical simulation. Non-uniform grid system was used to discretize the calculation domain. Finer grids were used near the tool to resolve the severe plasticized material flow and heat convection. The design and number of mesh elements were determined by considering both the efficiency and accuracy of the computation. The grid dependence study was conducted, and the calculation accuracy was found independent on the grid system. Top views of mesh system for finite volume calculation was shown in Fig. 2b.

2.2. Governing equations

RDR-FSW process involves fully-coupled heat generation, heat transfer, material flow and microstructure evolution. Only the quasi-steady state (the welding period) is dealt with in this study. In the quasi-steady state, the material near the tool is heated to a relatively high temperature, and only the plastic deformation is considered. The plasticized material during the RDR-FSW process is assumed to behave as an in-compressible and single-phase

Table 1
Tool dimensions for RDR-FSW (Unit: mm).

Assisted shoulder		Sub-size concave shoulder		Tool pin		
Outer diameter	Inner diameter	Outer diameter	Inner diameter	Diameter at the root	Diameter at the tip	Pin length
14.0	10.0	10.0	6.0	6.0	4.0	4.8

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