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Numerical modeling for the effect of pin profiles on thermal and material flow characteristics in friction stir welding

Hao Su [a], Chuan Song Wu [a,*], Marcel Bachmann [b], Michael Rethmeier [b]

[a] MOE Key Lab for Liquid-Solid Structure Evolution and Materials Processing, Institute of Materials Joining, Shandong University, Jinan 250061, China
[b] Federal Institute for Materials Research and Testing, Berlin 12205, Germany

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ABSTRACT

Understanding the influence of tool/pin shapes on the thermal and material flow behaviors in friction stir welding is of great significance for the optimal design of tool/pin based on a scientific principle. In this study, a numerical method based on computational fluid dynamics is employed to quantitatively analyze the thermo-physical phenomena in friction stir welding with two tools of different pin shapes (axisymmetrical conical tool and asymmetrical triflat tool). Through combining a steady state model with a transient state model, both the computation efficiency and accuracy are ensured. The boundary conditions of heat transfer and material flow are determined with considering a partial sticking/sliding contact condition at the tool–workpiece interface. The total heat generation, heat density and temperature distribution during the welding process with triflat tool are elucidated and compared with that of conical tool, and the material flow patterns and deformation regions of various pin orientations are illustrated in detail. It is found that the deformation zone caused by triflat tool is larger than that by conical tool, which is validated by the weld macrographs. The computed thermal cycles and peak temperature values at some locations are in good agreement with the experimentally measured ones.

1. Introduction

A friction stir welding (FSW) tool, as a critical component of the process, is a major factor affecting the weld quality [1,2]. The tool generally includes a shoulder and a special designed pin, and serves two primary functions [1–3]: (a) generating heat by friction at the tool–workpiece interface and plastic deformation, and (b) transporting the material from the front of the tool to the trailing edge to produce a joint. Most of the tools in practical applications consist of a flat shoulder and a cylindrical/conical pin with or without thread. Recently, experimental investigations have shown that tool shape, including tool size and profile, has a significant influence on the macrostructure [4,5], microstructure [6–8], welding force [9,10], and mechanical properties [5,6,8] of the joint, and a complex-shaped pin is found to be capable of improving the joint property compared with the traditional cylindrical/conical pin. However, the underlying mechanism, such as the variation of the thermal/flow behaviors with different tool/pin profiles, has not been fully understood.

The tool/pin shape and size are important variables in FSW. Mehta et al. [11] and Arora et al. [12] optimized the shoulder diameter based on the principle of maximum utilization of supplied torque by establishing a computational fluid dynamics (CFD) model. Buffa et al. [13] investigated the influence of pin angle on the material flow and grain size by using a 3D FEM model. However, these studies generally focused on an axisymmetrical pin and its horizontal profile was circular. Since the variety of pin profiles plays important role in determining the microstructures and properties of friction stir welds, understanding of their correlations is crucial for the optimal design of the tool/pin shape and size.

Both experimental and numerical methods have been employed to investigate on the complex heat generation, temperature distribution, material flow and metallurgical characteristics during the FSW with various pin profiles. Lorrain et al. [14] analyzed the material flow of two unthreaded pins: straight cylindrical pin (SC) and tapered cylindrical pin with three flats (TC3F), and found that TC3F pin changes the material flow and creates the variation of the material flow velocity than SC pin. Zhao et al. [15] studied the material flow of three different pins: column pin, taper pin and taper screw thread pin using a marker insert technique (MIT), and a 3D flow visualization showed that the vertical material flow is more obvious when taper thread pin is used.

Numerical simulation methods provide a quantitative understanding of the heat generation and material flow, but the work for various tool/pin profiles is just started. Colegrove and

* Corresponding author.
E-mail address: wucs@sdu.edu.cn (C.S. Wu).

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Shercliff [16] investigated the temperature, force, and material flow with Triflute tool and Trivex tool by using a 3D CFD model based on a single rotating reference frame. In the model, slip boundary condition was adopted by applying a limiting shear stress at the tool–workpiece interface. Moreover, they analyzed the force and pressure condition with Triflat tool, Triflute tool, Trivex tool and Cylindrical tool by developing a 3D steady state thermal model and a 2D moving mesh flow model [17]. In their study, the temperature field from the 3D thermal model was imposed on the 2D flow model. Colegrove and Shercliff [16,17] observed that the traverse force was lower when the Trivex tool was used, and found that no obvious change in heat input by different tool shapes. Feulvarch et al. [18] proposed a 3D moving mesh technique for the Trivex tool, and the mesh is composed of 2 parts: a first one which is fixed around the stirring zone and a second one which includes the base material near the tool and moves with a rotational solid motion corresponding to the tool's velocity. The simulation results were found to be independent of the radius of the moving mesh zone. Besides, the material flow produced by a tool with threaded pin was studied by Colegrove and Shercliff [19] and Ji et al. [20], and both models were 3D steady-state and a sticking boundary condition was imposed at the tool–workpiece interface. Hirasawa et al. [21] investigated the plastic flow of various tool shapes during friction stir spot welding (FSSW) using a particle method. They suggested that a tool with triangular pin enhanced the material flow and resulted in high strength spot welds.

Although lots of efforts have been made to investigate the thermal and material flow behaviors in FSW with various tool/pin shapes, some intractable problems remain unsolved. Firstly, the contact condition at the tool–workpiece interface was generally considered as full sticking or a hypothetical limiting shear stress, which was discrepant with the real FSW process. Secondly, the thermal model was generally simplified and not precisely expressed for the asymmetrical tool/pin, while it was adequately developed for the axisymmetrical tool/pin [22–24]. Moreover, most of the models were steady state, which can only capture a "snap-shot" of the flow at a particular instant in time [19]. As for an asymmetrical tool/pin, the tool–workpiece interface is constantly changing, so that a transient model is more appropriate to demonstrate the flow characteristics during the rotating of the tool.

The emphases of this study are on the numerical analysis and comparison of heat generation, temperature distribution and material flow under various tool/pin shapes during FSW process. A steady state moving reference model is developed firstly, followed by a transient moving mesh model. Both models are 3D full coupled CFD model. The method is capable of economizing the computational time, and visualizing the instantaneous plastic flow during FSW of a complex tool/pin shapes. Two tools with representative pin shapes have been selected: the traditional conical tool (CT, symmetrical about the axis) and the triflat tool (TT, asymmetrical about the axis). The thermal model and velocity boundary conditions are analyzed in detail by considering the contact condition at the tool–workpiece as partial sliding/sticking, especially for TT. The friction coefficient and slip rate between the tool and workpiece for two tools are calculated by using the measured tool torque and axial force. The heat generation, temperature distribution and material flow of TT is quantitatively compared with that of CT, and the periodic characteristic of the plastic material flow on different pin orientations during the rotation of TT is demonstrated. The computed values of strain rate and non-Newtonian viscosity for various pin orientations are elucidated. The feasibility of the method is validated by comparing the predicted thermal cycles and peak temperature values at some points with the experimentally measured ones.

2. Experimentation

AA2024-T4 aluminum alloy plates were friction stir welded. The chemical composition of this alloy is listed in Table 1. The plates were with dimensions of 6 mm in thickness, 200 mm in length and 105 mm in width). The schematic sketches of conical tool (CT) and triflat tool (TT) are shown in Fig. 1. Note that the screw thread with pitch of 1 mm on the pin side of CT and the pin side arc area of TT is not represented in Fig. 1. Other features of the two tools were consistent: the diameter of tool shoulder was 15.00 mm, the top and bottom diameter of pin was 6.00 mm and 4.00 mm respectively, and the length of the pin was 5.75 mm. The experiments were conducted by using FSW-3LM-3012 machine. The tilt angle of tool toward the trailing direction was kept constant at 2.5°, and the plunge depth of the shoulder into the workpiece was set to 0.15 mm during the welding process. Four different parameters (tool rotation speed in rpm/welding speed in mm/min) were

Table 1
Chemical composition of the workpiece (AA2024).

Element	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Al
wt%	0.15	0.25	4.58	0.63	1.59	<0.10	0.20	<0.10	Balance

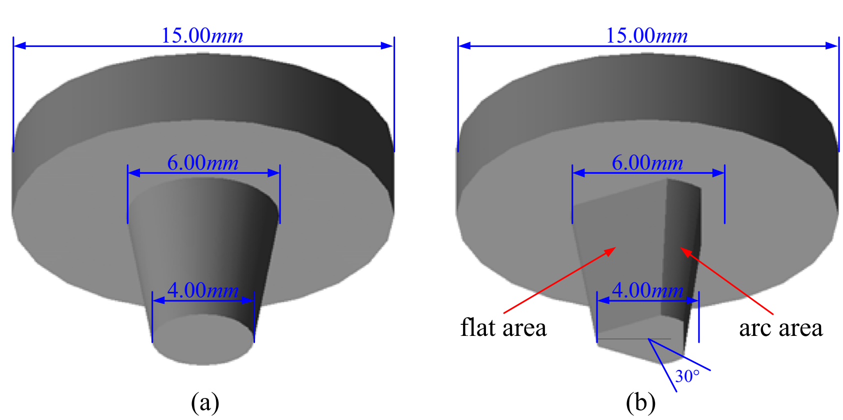

Fig. 1. Schematic sketch of tool profiles: (a) conical tool (CT) and (b) triflat tool (TT).