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Numerical simulation of material flow behavior of friction stir welding influenced by rotational tool geometry

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ABSTRACT

Considering the practical geometry of rotational tool and the relation between the material parameters and temperature, the finite volume model of friction stir welding is established on basis of the ANSYS FLUENT software. The effect of shoulder geometry and pin geometry on material plastic flow behavior is studied. The results of numerical simulation show that the flow velocity of material decreases with the increase of the distance away from the weldment surface or the rotational axis of pin. The flow velocity of material inside weldment is increased by decreasing the cone angle of pine or decreasing the width of screw groove. When the rotational tool with the left screw pin rotates clockwise, the flow direction of material near pin is downward while the flow direction near the thermal–mechanical affected zone is upward, which is opposite to that of the right screw pin. From the view of improvement of material flow, the concentric-circles-flute shoulder is better than the inner-concave-flute shoulder or the plane shoulder. Therefore, choosing the reasonable shoulder geometry and the reasonable pin geometry can be good for improving the material flow during the friction stir welding process and avoiding the root defects.

1. Introduction

Friction stir welding (FSW) is a kind of solid-state jointing technology, which owns many advantages, such as low stress, high strength, and non-pollution [1–3]. It is well-known that the material flow behavior during FSW is one of the key factors that influence the quality of FSW joint, so the researchers tried many experimental methods to study the material flow, which include the steel ball tracing technology [4], the stop-action technology [5], the metallography method [6], the marker material method [7] and so on. In fact, it is difficult for the experimental methods to describe the material flow in the stir region, which can be partly solved by using the numerical simulation method [8–10]. Colegrove and Shercliff [8] by the CFD software and Zhang et al. [9] by the ABAQUS software researched how the welding parameters affected the material flow during FSW. Using the numerical simulation method and the experimental method, Nandan et al. [10] showed that the maximum flow velocity of material appeared near the edge of shoulder.

Rotational tool is the most important geometry for FSW and greatly influences the material flow behavior during FSW. A lot of experimental work was done on the effect of rotational tool on material flow and joint property [11–14]. However, little work about the effect of rotational tool on material flow was done by the numerical simulation method [15,16]. Zhang et al. [15] attained the effect of shoulder geometry of tool without pin on material flow on basis of the DEFORM software, but the reason why the concentric-circles-flute shoulder is better than the inner-concave-flute shoulder is not explained. Hirasawa et al. [16] by the particle method analyzed the effect of tool geometry on plastic flow during friction stir spot welding while the tapered pin and the triangular pin are considered. So far, no references introduce the effect of dimensions of flute of rotational tool on the material flow behavior in FSW in detail by FEM or FVM. In this paper, different from the work by the other researchers, the material flow behavior in FSW under varying the rotational tool geometry is investigated in detail by using the finite volume method on basis of the ANSYS FLUENT software. The effect of variations of the shoulder geometry and the pin geometry on material flow velocity is attained.

2. Finite volume model of FSW

2.1. Solid model and mesh generation

Generally speaking, the rotational tool used in FSW is mainly made up of two parts: the shoulder and the pin. At present, the geometries of shoulder are often plane, inner-concave-flute or

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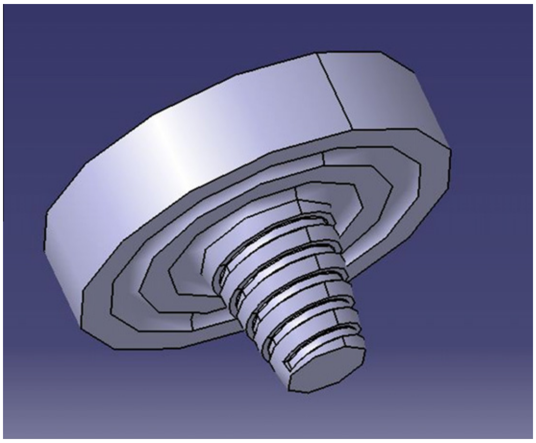


Fig. 1. Solid model of rotational tool.

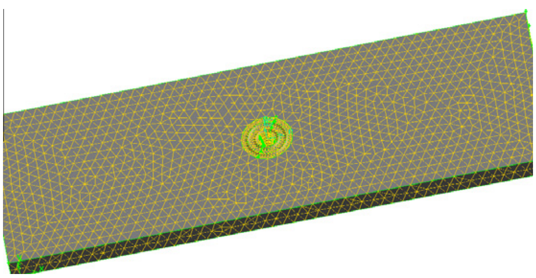


Fig. 2. Mesh generation of model used in simulation.

concentric-circles-flute while the geometry of pin is screw. Fig. 1 shows the solid model of rotational tool with concentric-circles-flute shoulder. Thereinto, the diameter of shoulder is 14 mm, the length of pin with right screw is 5.3 mm, the diameter of pin root is 5.5 mm, the diameter of pin bottom is 3 mm, the width of screw groove is 1 mm and the cone angle of pin is 20°. In the numerical simulation, the dimensions of weldment are 150 mm $\times$ 50 mm $\times$ 6 mm while the mesh generation is shown in Fig. 2.

2.2. Boundary condition

In the simulation process using the FLUENT software, the metal material is considered as fluid, which is stirred by the rotational tool. The surface of weldment, the bottom of weldmnet, the advancing side, the retreating side, the fluid inlet and the fluid outlet are all supposed to be the moving wall while the speed of moving wall is equal to the welding speed and the moving direction is opposite to the welding direction. In the numerical simulation, the welding speed is 100 mm/min

The solid non slip condition is used in the finite volume model to describe the relation between the rotational tool and the metal material contacting with the tool. Therefore, the flow velocity of metal material contacting with the rotational tool is the same as the linear velocity of contacting position of rotational tool. The elements, which are used to represent the shoulder and the pin are supposed to be the rotational wall while the rotational velocity of wall and the rotational direction of wall are both the same as those of rotational tool. In the numerical simulation, the rotational velocity is 800 r/min.

According to the temperature characteristic in FSW, the temperature value near the rotational tool is supposed to be 80% of material melting point [10]. The welding temperature is added to

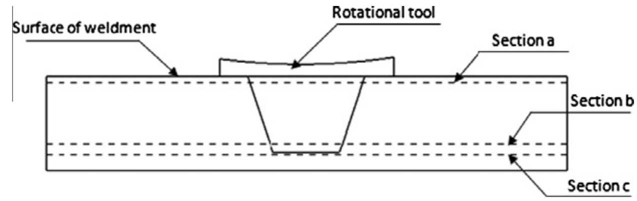
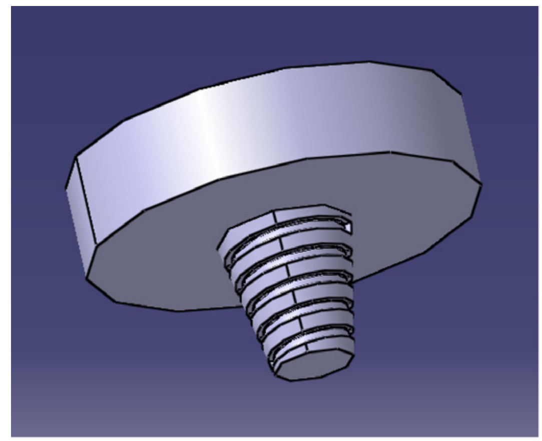
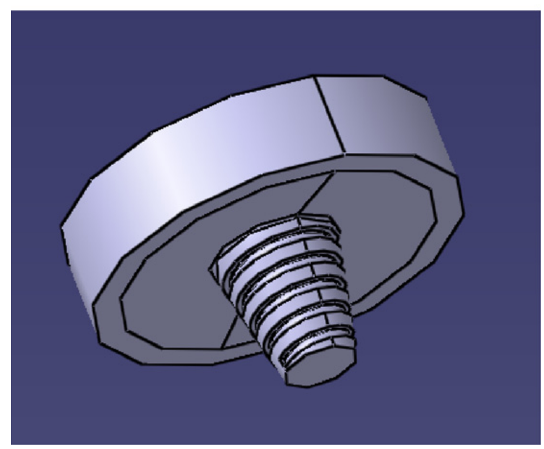


Fig. 3. Position of different sections of weldment.



(a) the plane shoulder



(b) the inner-concave-flute shoulder

Fig. 4. Solid model of rotational tool.

the rotational boundary condition of the model and the coupled thermo-flow method is used to analyze the material flow in FSW.

2.3. Material parameters

To the finite volume model on basis of Euler equation, the material parameters are mainly the specific heat, the thermal conductivity, the coefficient of viscosity and the mass. In the numerical simulation, 2014 aluminum alloy is chosen to be studied and the mass is 2800 Kg/m^3. The values of specific heat (c_p) and thermal conductivity (λ) under different temperature are shown in Eqs. (1) and (2) [17].

$$\lambda = 103.264 + 0.241T \tag{1}$$

$$c_p = 754.08 + 0.3729T + 0.0012T^2 \tag{2}$$

In the process of FSW, the temperature is high near the region of rotational tool while the temperature decreases with the increase