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A numerical model of pin thread effect on material flow and heat generation in shear layer during friction stir welding

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ABSTRACT

A novel method is proposed to analyze the effect of pin thread on the heat generation, temperature distribution and material flow field in friction stir welding (FSW). Based on the analysis of the interaction force between the thread groove and the workpiece material, special equations are derived to describe the effect of pin thread parameters on the material flow velocity inside thread grooves. These equations are combined with a three-dimensional transient CFD model to quantitatively analyze the effect of threaded pin profile on heat transfer and material flow in FSW. The results show that the average flow velocity and the downward z-component of material flow velocity near the pin side surface for threaded pin is higher than that for unthreaded pin. For a threaded pin, heat generation near pin side is a little bit increased, the area of TMAZ (thermo-mechanically affected zone) is broadened, especially the width of TMAZ near the bottom surface of the workpiece, and the pin thread can effectively improve the material flow near the pin tip. The calculated and measured thermal cycles and TMAZ boundary match with each other. Compared with the sliding mesh method, this model is easier to ensure the numerical robustness and save computational time.

1. Introduction

Friction stir welding (FSW) has been successfully used in joining various kinds of metals and alloys [1–3]. Tool geometry is the most influential aspect of the FSW process development [4]. The primary functions of the tool include the localized heating and material flow so that it plays a critical role in affecting the microstructures and mechanical properties of the weld joints [5–7]. A FSW tool typically consists of a rotating round shoulder and a threaded cylindrical pin, which generates heat locally by friction and drives the softened material to flow in the shear layer [8]. Features of the tool such as thread and flat on the pin surface are believed to improve material flow around the tool, promote oxide breakdown, increase the area of nugget zone, produce high quality welds and affect forces on tool [4,9–14].

It is reported that for clockwise rotation, a left-hand thread could push the material downward adjacent to the pin. Besides, it also led to driving an upward motion of material of an equivalent amount far away from the pin surface in the shear layer, and enhance material mixing in the weld vicinity [11,14]. It has been experimentally proven that during FSW, the threaded pin profile can avoid several defects which are likely to occur for an unthreaded pin [6,15,16]. Zhao et al. [6] used four different pins (column threaded pin, taper threaded pin, column pin and taper pin) to make comparison, and concluded that taper pin with thread profile produced the best weld quality compared to others in terms of defect reduction and enhanced grain refinement. It is reported that wormhole defects are minimized or disappeared in weld nugget zone when threaded pin profile is used in place of unthreaded one for FSW [15,16]. The threaded pin promotes the material flow in a downward direction, thereby enhancing material transportation across the weld root. Ouyang et al. [17] found the presence of vortex-like structure formed by concentric flow lines for welding similar alloy and alternative lamellae of alloy components for welding dissimilar alloys, attributing to 'stir action' of a threaded pin. Therefore, a careful consideration of thread profile is vital for FSW tool design. However, for the thread design on pin side, there is a lack of scientific basis in practical application of engineering. Currently, the thread is designed empirically by trial and error. In addition, the underlying mechanism, in context to the variation of flow/thermal behavior with respect to threaded pin, is not properly documented.

In order to obtain dynamic information during FSW process, researchers attempted to observe the real-time plastic material flow around the threaded pin with the aid of sophisticated techniques such as computer tomography (CT) and tracer particles, etc. Schmidt et al. [18] investigated the material flow around the threaded tool by traditional metallography as well as X-ray and CT, and proposed the presence of different flow zones or layers across vicinity of the weldment.

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Morisada et al. [19,20] visualized the material flow around the pin by real-time X-ray radiography using a tiny spherical tungsten tracer, and obtained the three-dimensional material flow path by following the locus of the tracer. They found a comparatively higher material flow velocity at retreating side (RS) compared to advancing side (AS).

Even though great efforts have been made to observe and characterize the difference of heat generation, temperature profile, material flow and joint quality for unthreaded and threaded pins, most of the experiment-based methods just give some qualitative information. A quantitative analysis of pin thread effects on heat generation and material flow behavior during FSW process is essential to interpret the mechanisms involved. Numerical simulation has been widely used in analyzing the thermo-mechanical process and material flow behavior in FSW to explore the physical nature of the process or to guide tool design [21–25]. Generally, researchers employ computational fluid dynamics (CFD) [21–23] and computational solid mechanics (CSM) [24,25] to model FSW process. Due to the advantages in numerical simulation of material flow, the CFD method has been more widely used in modeling FSW process with complex pin shapes [26–29]. In CFD models of FSW, velocity-based boundary condition [22,23] and shear stress-based boundary condition [30,31] are two categories to treat the contact condition at tool-workpiece interface.

In numerical simulation of the thermo-mechanical behavior and material flow in FSW process, some researchers did not take into consideration the thread features because the presence of threads brings the complexity and difficulty of modeling [32–35]. Other investigators indirectly considered the thread feature by simply applying a uniform vertical velocity at pin side [22,36–38]. Such a presetting of vertical material movement may oversimplify the pin thread effect.

On the other hand, some researchers directly dealt with the thread feature in the geometric model of the calculation domain, and applied special boundary conditions at the tool-workpiece interface [31,39–41]. When the contact conditions at tool-workpiece interface were supposed to be full sticking, no obvious movement of material along the vertical direction due to the presence of thread is predicted [39,40]. Atharifar et al. [41] set the contact condition as partial sticking/sliding. Chen et al. established a CFD model of FSW process by considering an alternative frictional boundary condition [31], and took into account the pin thread features by adopting sliding mesh method in their model [42]. The thread feature was treated as an extra fluid volume which rotates with the same speed as that of the tool and is geometrically connected to the surrounding fluid domain by the mesh interface. The simulation results shown that the interfacial sticking is preferable at the inside of the thread groove, and pin thread causes a many-circle flow pattern around the threaded pin. However, the effect of pin thread on the in-process phenomena during FSW has not been completely understood, and there is still a lack of theoretical guidance in thread design and tool manufacture.

In this study, a new method is proposed to consider the pin thread effects on materials flow and heat generation in FSW. Based on the analysis of the interaction force between the thread groove and the workpiece material, special equations are derived to describe the effect of pin thread parameters on the material flow velocity inside thread grooves, which are taken as the boundary conditions for material flow velocity. Then, a three-dimensional transient CFD model is developed to quantitatively analyze the effect of threaded pin profile on the heat generation, temperature field and material flow characteristics in FSW. Finally, the numerical simulation results are verified by experimentally measuring the thermal cycles and the TMAZ boundary.

2. Mathematical modeling

2.1. Governing equations

Fig.1 shows a schematic illustration of FSW process and its geometrical model features for numerical simulation. The origin of the

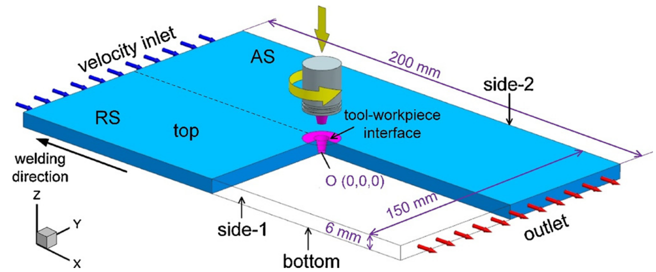

Fig. 1. A schematic of FSW process and its corresponding geometrical model.

Cartesian coordinate system is taken at the intersection point between the tool axis and bottom surface of the workpiece. The workpiece material is assumed as an incompressible single-phase non-Newtonian fluid. In order to simplify the FSW model, effects of tool shoulder concavity and tool tilt angle are ignored. The continuity, momentum and energy conservation equations are used to describe the heat transfer and material flow in FSW process.

The continuity equation,

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\vec{v}) = 0 \tag{1}$$

The momentum equations,

$$\frac{\partial \rho\vec{v}}{\partial t} + \nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla p + \nabla\cdot[\mu(\nabla\vec{v} + \nabla\vec{v}^{T})] \tag{2}$$

The energy equation,

$$\rho c_p\frac{\partial T}{\partial t} + \rho c_p\nabla\cdot(\vec{v}\cdot T) = \nabla\cdot(k\nabla T) + S_v \tag{3}$$

where ρ is the density of material, c_p is the specific heat, $\vec{v}$ is the velocity vector of the plastic material flow, t is the time, p is the pressure, μ is the material viscosity which is temperature and strain rate-dependent, k is the thermal conductivity, T is the temperature, and S_v is the viscous dissipation source due to plastic deformation in the shear layer, which can be expressed as [33,43],

$$S_v=\eta_v\cdot\mu\cdot\dot{\varepsilon}^2 \tag{4}$$

where η_v represents the fraction of the viscous dissipation that is converted to heat, while $\dot{\varepsilon}$ is the effective strain rate, which is calculated as follows,

$$\dot{\varepsilon} = \sqrt{\frac{2}{3}\left(\left(\frac{\partial u_i}{\partial x_i}\right)^2 + \frac{1}{2}\left(\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1}\right)^2 + \frac{1}{2}\left(\frac{\partial u_1}{\partial x_3} + \frac{\partial u_3}{\partial x_1}\right)^2 + \frac{1}{2}\left(\frac{\partial u_3}{\partial x_2} + \frac{\partial u_2}{\partial x_3}\right)^2\right)} \tag{5}$$

where u_i is the velocity component, and x_i is the coordinate-axis directions.

2.2. Material properties

The density of AA6061 material is taken as constant, equals to 2700 kg/m^3, while thermal conductivity and specific heat (c_p) are considered as temperature-dependent properties [43], which are given as below,

$$c_p = 929 - 6.27\times10^{-1}\times T + 1.48\times10^{-3}\times T^2 - 4.33\times10^{-8}\times T^3 \tag{6}$$

$$k = 25.2 + 3.98\times10^{-1}\times T + 7.36\times10^{-6}\times T^2 - 2.52\times10^{-7}\times T^3 \tag{7}$$

The fluid viscosity can be derived in terms of flow stress and effective strain rate [22,39,44],