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Effects of tool tilt angle on the in-process heat transfer and mass transfer during friction stir welding

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Tool tilt angle in friction stir welding (FSW) is an important factor that influences the joint quality, but the underlying mechanism has not been fully understood due to the lack of in-process observation. In this study, we present a CFD model, in which a geometrical model and an incomplete contact boundary condition are proposed, to investigate the effects of tool tilt angle on the in-process heat transfer and mass transfer during FSW. Three effects of tool tilt angle on heat transfer and mass transfer have been concluded based on the simulation results. First, a higher temperature is generated by the tilt welding tool on the advancing side (AS), which is attributed to the incomplete contact at the shoulder/workpiece interface. Second, the tilt welding tool generates a higher frictional force at the tool/workpiece interface, which significantly improves the interfacial material flow velocity behind the tool. Third, the tilt welding tool generates a stronger stirring action to the material in the vicinity of the welding tool, which is beneficial for the mixing of materials and the formation of friction stir welds. The approaches and concepts in this study can be used for the optimization of the application of tool tilt angle in FSW.

1. Introduction

Friction stir welding [1,2] (FSW) is a kind of solid state welding technology and widely applied in joining of similar/dissimilar alloys [3,4]. It is a thermal-mechanical coupled process, in which the microstructure and properties of the welds is closely related to the in-process heat transfer and mass transfer. FSW process is very sophisticated and affected by many factors including the welding parameters [4,5], tool tilt angle [6,7], tool shape [8–10] and contact states [11,12] at the welding tool/workpiece interface. Among those factors, tool tilt angle can obviously affect the heat transfer and mass transfer in the stir zone and accordingly controls the integrity and the properties of the welds [13]. The performance of the welds prepared at different tool tilt angle is quite different [7,13]. However, the underlying mechanism remains unclear. Thus, it is essential to investigate the effects of tool tilt angle on heat transfer and mass transfer during FSW for the sake of welds quality control and optimization of the process parameters.

Tool tilt angle is defined basing on the positional relationship between the welding tool and the workpiece, where zero denotes the case that the welding tool is perpendicular to the workpiece while a non-zero value denotes the case that the welding tool is tilt to the workpiece [6,7,14–16]. In the past decade, many efforts have been made to study the effects of tool tilt angle on the welds integrity and properties. Early experiments conducted by Chen [13] showed that the welds integrity was closely linked to the tool tilt angle. At a smaller tool tilt angle, material flow behind the pin was insufficient, which resulted in the void defects. At a larger tool tilt angle, void defects might be also generated due to the weld flash generated on the RS and no sufficient material filled up the cavity in the stir zone. Barlas and Ozsarac [17] found that root flaw could be effectively avoided by properly selecting the tool tilt angle. Root flaw would be removed at the tool tilt angle of 2° when the other welding parameters were constants. Zhang et al. [15] reported that the tunnel defect could be eliminated by increasing the tool tilt angle from 0° to 3°, which was attributed to the increase in heat generation and downward forging force at the larger tool tilt angle. On the other hand, welds properties especially dissimilar welds properties were also closely related to the tool tilt angle. Mehta and Badheka [7] investigated the effects of tool tilt angle on the mechanical properties of dissimilar copper-aluminum friction stir welds. The macro hardness increased as the tool tilt angle increased from 0° to 4° and the maximum tensile strength was obtained at the tool tilt angle of 4°. Dehghani [18] reported that the tensile strength of the dissimilar aluminum-mild steel friction stir welds decreased with the increase of tool tilt angle. This was because the thickness of Al_5Fe_2 intermetallic

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compounds (IMCs) increased as the tool tilt angle increased, which was detrimental to the tensile strength of the welds. Kimapong and Watanabe [19] studied the effects of tool tilt angle on the shear strength of the welds. They reported that the thickness of IMCs increased as the tool tilt angle increased, which lead to the reduction of shear strength of the welds. Although lots of experiments had been conducted to investigate the effects of tool tilt angle on the FSW process, the mechanisms were still unclear.

Comparing with experimental approaches, numerical simulation can obtain full-field and full-process information such as material flow and temperature distribution [20,21], which makes it become an effective method to carry out the analysis of the effects of tool tilt angle on FSW process. Computational fluid dynamic (CFD) is an important method in numerical simulation of FSW process [22] and many studies on FSW have been made by using this method. Colegrove et al. [23,24] developed a three-dimensional CFD model to study the temperature distribution and material flow behavior in FSW of aluminum alloys. Tool tilt angle was taken into account in the geometric models, but the effects of tool tilt angle on the FSW process were not elaborated in these papers. Nandan et al. [25] established a CFD model to obtain the 3D temperature distribution and plastic flow fields during FSW and concluded that the plastic flow significantly affected heat transfer within the workpiece. Su et al. [26] proposed a method to gain the values of friction coefficient and contact variable for the optimization of the process parameters and the distribution features of thermal energy density in the vicinity of the tool were elucidated. In recent researches, CFD simulation [22] has been widely and successfully applied in investigating the issues of FSW.

However, till now, very limited work in the literature considers the tool tilt angle in simulation of FSW, as including the tool tilt angle is still of technical difficulty for the CFD simulation. One of the difficulties is that considering the influence of tool tilt angle will make the model excessively complex regarding model establishment, solving equations and simulation results. Thus, tool tilt angle is generally not considered in previous models for the sake of predigestion. In fact, tool tilt angle can influence the in-process heat transfer and mass transfer and thus affect the microstructure and performance of the welds. Therefore, the in-process heat transfer and mass transfer at proximity of the welding tool are not expressed precisely by using the simplified CFD model. In this study, a three-dimensional CFD model is developed to investigate the effects of tool tilt angle on heat transfer and mass transfer during FSW. Especially, tool tilt angle is taken into account in the geometrical model. The incomplete contact boundary condition at the tilt welding tool/workpiece interface is considered. The effects of tool tilt angle on the in-process heat transfer and mass transfer in the vicinity of the welding tool are analyzed based on the simulation results.

2. Experiment

Friction stir butt joining of AA2024-T4 was conducted in this study. The dimensions of each workpiece were 300 × 75 × 5 mm (length × width × thickness), and they were fixed by the fixtures, as shown in Fig. 1(a). The shoulder was flat and the pin was unthreaded. The shoulder diameter was 16 mm, the top and the root diameter of the pin were 6 mm and 4 mm respectively. The length of the pin was 4.8 mm. The rotational speed and the welding speed were 800 rpm and 20 mm/min, respectively. The tool tilt angles were set as 2.5° and 0°, while the other welding parameters were constants.

The temperature history was recorded by eight K-type (CH1-CH8) thermocouples located 10, 14, 20, and 28 mm away

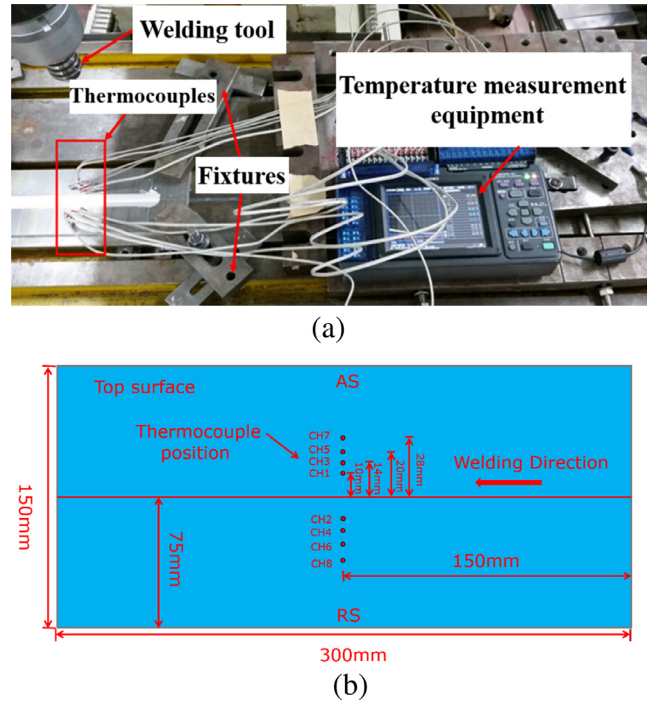

Fig. 1. The experimental setup and the schematic diagram of temperature measurements.

from the welding center line in the top surface on AS and RS, as shown in Fig. 1(b). The thermocouples were mechanically pinned in the holes that were 1 mm underneath the top surface of the workpiece.

3. Description of the CFD model

A CFD model was established in this study to investigate the effects of tool tilt angle on heat transfer and mass transfer during FSW process. Eulerian framework was used in this model. As the tool tilt angle was taken into account in the CFD model, there was a big difference in the geometric model and boundary condition. First, the tilt welding tool had a cutting effect on the workpiece, which would produce a thinner joint. As a result, in the geometric model, the welds surface behind the welding tool was lower than the top surface of the workpiece. Second, the contact area between the shoulder and the workpiece would decrease when the welding tool had a non-zero tilt angle with the top surface of the workpiece, which resulted in an incomplete contact boundary condition at the shoulder/workpiece interface.

In our simulation, ANSYS Fluent [27] was adopted for solving the governing equations. The workpiece was taken as an incompressible non-Newtonian viscous fluid. The heat capacity and thermal conductivity were temperature dependent. The density of the workpiece was set as a constant, which was 2785 kg/m^3 [28].

3.1. Geometric model

The geometric model and mesh schemes at the welding tool/workpiece interface for the tool tilt angle of 2.5° was shown in Fig. 2. In the geometric model, the coordinate origin was set as the intersection point of the welding tool axis and the top surface of the workpiece. When the welding process was carried out with a non-zero tool tilt angle, the welding tool would be tilt to the rear side. The shoulder surface would have 2.5° with the top surface