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Numerical analysis and analytical modeling of the spatial distribution of heat flux during friction stir welding

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ABSTRACT

The quantitative characterization of the in-process energy input during friction stir welding (FSW) is crucial for the prediction and the control of microstructure and properties in the welds. In this study, a novel CFD model is established to quantitatively investigate the spatial distribution of frictional heat flux and plastic deformation heat flux during the FSW of AA2024-T4, in which an advanced frictional boundary condition is used to capture the complex interplay between the spatial distribution of heat flux and the contact states at the welding tool/workpiece interface. It is found that the heat flux distribution is closely related to the contact states at the interface. An analytical model of the heat flux distribution is proposed based on the simulation results. The distribution of frictional heat flux at the welding tool/workpiece interface could be represented by a modified Gaussian heat source model and the distribution of plastic deformation heat flux at proximity of the welding tool could be represented by the Two - phase Hill function. The analytical model in this study provides a more realistic mathematical description of the heat flux distribution during FSW, which provides further support for the process optimization and thermal analysis of FSW.

1. Introduction

Friction stir welding [1,2] (FSW) is a unique solid state joining technology for many important light structural materials, such as high strength aluminum alloys [3,4]. It has been widely employed in the fabrication of critical structural components in light-weight vehicles, such as armor structures [5,6]. Recent studies have focused on improving the integrity, the microstructure and the performance of the friction stir welds [7–10], which brings a growing demand for fundamental knowledge on the underlying process in FSW. During FSW, large amount of heat is generated, which creates a localized thermal-mechanical processing zone (TMPZ) in the vicinity of the welding tool. The heat flux into the workpiece during FSW decides the three-dimensional temperature distribution in the TMPZ and thus influences material flow, defects formation and microstructure evolution, which controls the integrity and the performance of the friction stir welds [11]. Therefore, it is of great importance to deeply investigate the heat generation process in FSW and quantitatively characterize the spatial distribution of heat flux in the vicinity of the welding tool. In addition, computer simulation is generally required in the analysis of the residual stress and strain distribution of the welded structure [12–14], in which a reliable heat source model that represents the distribution of heat flux is critical for predicting the transient thermal history and residual stress of the workpiece. This is because the thermal model is the basis of all other models of the FSW process, such as microstructural, computational fluid dynamics (CFD) or thermomechanical [11]. However, the heat flux into the workpiece during FSW has not been fully understood due to the complex, coupled thermal-mechanical nature.

Different from the conventional arc/laser welding, heat generation in FSW is a thermal-mechanical fully coupled process. It is known that, during FSW, heat is generated by friction at the tool/workpiece interface and plastic deformation of workpiece. Thus, in order to determine the heat flux, both the frictional heat flux and plastic deformation heat flux should be taken into account. The previous studies could be grouped regarding their concept in considering the contribution of heat generation from friction and plastic deformation.

In early studies, the heat flux was calculated based on the assumption that the sliding friction occurs at the tool/workpiece interface and the material flow is ignored. This assumption is termed as 'sliding state' as a type of contact state by later literature [15]. Based on this assumption, friction was actually taken as the only process that contributes to the heat generation. Chao et al. [16] investigated heat generation in FSW. Coulomb friction model was used to determine frictional stress at the welding tool/workpiece interface, and a frictional

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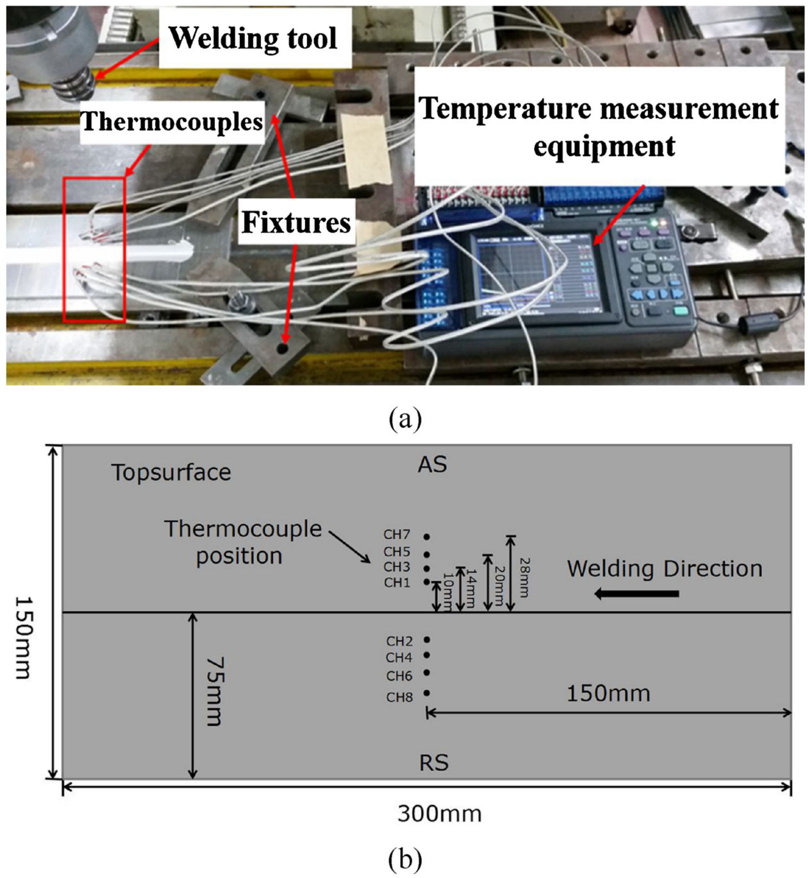

Fig. 1. The device used in the experiment and the schematic diagram of temperature measurements.

heat flux at the top surface of the workpiece was used for the heat flux during welding process. The heat flux was formulated by the product of the frictional shear stress and the tool velocity. Similar formulation was used in later studies [17,18]. Dickerson et al [19], Chen et al [20] and Song [21] recognized the importance of including volumetric heat fluxes to regard the heat generation from the pin-induced plastic deformation in order to predict more realistic temperature field.

In later literatures, computational simulation was used to predict the heat flux based on the assumption of ‘sticking’ contact state, where the tool velocity and the material velocity are assume to be the same at the tool/workpiece interface. By using this assumption, the plastic deformation was taken as the only contributing process to the heat generation during welding process. In simulations conducted by Colegrove et al. [22] and Ulysse [23], the heat generated by plastic deformation was represented by viscous dissipation. The temperature field was simulated based on this heat generation regime. Chen et al [24] employed similar concept and took the volumetric heat flux of plastic deformation as the product of the flow stress and the strain rate to investigate the heat generation in FSW by using computational fluid dynamics (CFD) simulation. They reported the dependency of total heat and the distribution of plastic deformation heat flux on the welding parameters.

In more recent studies, more and more researchers found that contact states at the tool/workpiece interface were neither pure sliding state nor sticking state. As such, the heat generation during FSW has been investigated based on the growing knowledge on the contact state. Schmidt [15] generalized the different contact states at the interface through introducing the parameter δ in their analytical heat generation model. Their analysis showed that the interface was in a partially sliding/sticking state where δ ranges between 0 and 1, where 0 denotes a pure sliding state and 1 denotes a fully sticking state. Nandan et al [25] developed a three dimensional CFD model for material flow and heat transfer during FSW process. In their model, the parameter δ was taken as a function of radial distance, and both the friction heat flux and plastic deformation heat flux were taken into account in the model. Su et al [26] proposed an experimental method to obtain the average value of parameter δ over the tool/workpiece interface. By assuming a constant value of δ over the whole interface, the heat fluxes from friction and plastic deformation were characterized based on CFD simulation. Besides the CFD method, numerical simulation based on computational solid mechanics (CSM) was proved to be able to analyze the temperature and material flow during FSW process. By using adaptive remeshing [27,28], smoothed particle hydrodynamics (SPH) [29], and eulerian analysis [30], the approaches based on CSM had been applied in the numerical simulation of FSW, which predicted the complex distribution of the contact states between welding tool and the workpiece. Comparing with the CSM-based methods, a higher spatial resolution (corresponding to smaller mesh sizes) in the vicinity of the welding tool could be achieved in the CFD simulation, which was crucial for the analysis of the heat flux distribution. Although it was more suitable to investigate heat generation in FSW process based on CFD simulation, the current studies might not completely reflect the real contact state at the interface and thus limited the analysis of the heat generation. This is because, in the real FSW process, contact state could depend on many factors such as temperature, material flow and friction, which is non-uniformly distributed over the tool/workpiece interface [31–33]. Therefore, a more advanced interfacial model is still needed for better elucidating the contact state at the tool/workpiece interface in order to better understand the heat generation during FSW.

In this paper, a three-dimensional CFD simulation of FSW is established to analyze the heat generation during FSW regarding the complex interplay between the spatial distribution of heat flux and the thermal-mechanical processing, in which a more advanced interfacial friction model [31] is adopted to characterize the interaction between