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Numerical simulation of ultrasonic field and its acoustoplastic influence on friction stir welding

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ABSTRACT

During ultrasonic vibration enhanced friction stir welding (UVeFSW) process, the ultrasonic energy is transmitted directly into a localized area of the workpiece near and ahead of the rotating tool by a specially-designed sonotrode. Understanding the effect of ultrasonic vibration on the thermal and material flow behaviors in friction stir welding (FSW) is of great significance for optimizing the UVeFSW process. In this study, a numerical model of UVeFSW is developed using computational fluid dynamics method coupled with computational ultrasonic field to quantitatively analyze the effect of ultrasonic vibration on thermo-physical phenomena in UVeFSW. Evolution of sound pressure and distribution of ultrasonic energy density during the UVeFSW are calculated by computational ultrasonic field. The effect of ultrasonic vibration on the total heat generation, heat transfer, material flow patterns and deformation regions during the welding process are elucidated in detail. Both the experimental and simulated results show that superimposing ultrasonic vibration on FSW increases the material flow velocity and strain rate; enlarges the flow region and deformation region. The calculated thermal cycles at typical locations and the boundaries of thermo-mechanically affected zone match with those obtained from experiments.

1. Introduction

In recent years, the increasing demand for lightweight and/or high-strength sheet metals such as aluminum and magnesium alloys in manufacturing industries attracts the attention of manufacturers towards friction stir welding (FSW) process [1,2]. As a welding technology being invented by the TWI in 1991 [3], FSW is proved to be an energy efficient, environment friendly and successful method of joining the lightweight materials [4]. During the FSW process, a specially designed non-consumable rotating tool is inserted into the adjoining edges of two workpieces to be welded and then moved all along the abutting edges [5]. Heat due to friction and plastic deformation softens the material near the tool. The tool rotation transports the softened material from the leading side (LS) to the trailing side (TS) to form a joint behind the tool. Being a solid state welding technology, FSW requires sufficient heat generation and material flow to produce defect-free joints with good properties. Thus, very large axial force and tool torque are necessary to soften high strength and high hardness materials, such as high strength aluminum alloy, steels and titanium alloy [6,7]. This poses a risk of rapid tool wear and limits the welding speed and thus the scope of FSW for widespread industries applications [6–8]. To overcome these disadvantages, electrical current [8–11], laser beam [12,13], plasma arc [14], gas tungsten arc [15] and other kinds of heat energy [16] have been used to assisted FSW processes. However, the additional heating from the secondary heat sources may degrade the mechanical properties of the welded joints [16]. Thereby, it is imperative to develop a high efficiency, widely applicable and cost effective secondary energy source for assisting the material softening in FSW.

Blaha and Langenecker [17] found that ultrasonic vibration energy could remarkably soften the metallic materials without significant heating. The effect of reduction in flow stress or yield stress of metallic materials by superimposing high-frequency vibration on a deforming process is usually termed as Blaha or acoustoplastic or acoustic softening effect [18–20]. Since its first observation, the ultrasonic vibration energy has been widely used in metal plastic processing to facilitate material softening for easy process [21,22]. Therefore, the ultrasonic vibration energy, as a mechanical energy, has great potential to assist the plastic deformation, improve the material flow and lower the welding load in FSW. Recently, some researchers have analyzed the using of ultrasonic vibration energy to enhance the plastic material flow and reduce the force and torque needed during FSW process. Park [23] found that superimposing ultrasonic vibration to FSW tool improves the weld quality, reduce the welding force and increase the tool life. Amini and Amiri [24] found that application of ultrasonic vibration on FSW tool reduces the downward force and welding force. Ma et al. [25] found that the ultrasonic vibration improves the properties of the weld, increases the fluidity of plastic material and even reduces the weld defects at improper welding parameters. Rostamiyan et al. [26] found that superimposing ultrasonic vibration on friction stir spot welding of AA6061 increases shear strength of the lap joints. The ultrasonic vibration enhanced FSW (UVeFSW) system, developed at our group,

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transmits ultrasonic vibration energy directly into workpiece near the FSW tool [27]. Our previous experimental studies have found that this novel UVeFSW can improve the weld quality, enhance the plastic material flow and reduce the welding loads [28–31]. However, the above experimental studies were conducted only over narrow process windows. A complete understanding of the underlying mechanisms of UVeFSW requires mathematical modeling and simulation of the process.

The material flow and heat transfer in FSW determine the final microstructure and properties of the welded joints. Thus, both experimental and numerical methods have been used to analyze the plastic material flow in FSW. Guerra et al. [32] investigated the plastic material flow patterns during friction stir welding by using the marker insert technique and stop action technique. Buffa et al. [33] developed a continuum based FEM model for FSW to analyze the plastic material flow during the process. Although, numerous numerical models have been reported to simulate the material flow and heat transfer in conventional FSW [33–38], only a few of them are related to ultrasonic vibration assisted FSW process. Hence, the current understanding of the mechanism of superimposing ultrasonic vibration on FSW is fairly limited. Park [23] has simulated the ultrasonic assisted FSW by applying sinusoidal horizontal ultrasonic vibration on the tip of FSW tool. Lai et al. [39] simulated ultrasonic assisted FSW by considering the additive inertial force generated due to vibration of the FSW tool; the simulation results indicate that superimposed ultrasonic vibration on FSW can provide additional heat energy to soften the material. Montazerolghaem et al. [40] developed an empirical model to investigate the influence of applying vibration on FSW and found that the vibration helps to decrease the welding force. However, these models mentioned above have not considered the acoustoplastic effect of superimposed ultrasonic vibration on FSW process. Recently, Shi et al. [41] have developed a preliminary phenomenological model based on the acoustoplastic effect by introducing a percent ultrasonic softening term to analyze the effect of ultrasonic vibration on FSW process. The simulated results indicate that ultrasonic softening is the primary function of the superimposed ultrasonic vibration in FSW process, while the thermal effect of ultrasonic vibration is relatively small. However, the preliminary phenomenological model is not coupled with the ultrasonic energy field and many artificial correction factors were included in the model. In other words, the ultrasonic energy field during the UVeFSW has not been considered in the reported investigations. Thus, the available information about the influence of acoustoplastic effect on FSW is not sufficient to develop a fundamental science of UVeFSW. In addition, ultrasonic waves have been used to evaluate residual stresses distribution in FSW [42], modeling the ultrasonic field is also needed for better understanding the residual stresses distribution.

In order to investigate the underlying mechanism of UVeFSW process, heat transfer and material flow behaviors during the UVeFSW process has been analyzed using CFD (computational fluid dynamics) method coupled with computational ultrasonic energy field. A modified constitutive equation based on the thermal activation theory has been introduced into the UVeFSW model to account for the acoustoplastic effect at high strain rate and high temperature, as in FSW. Sound pressure evolution and the distribution of ultrasonic vibration energy have been analyzed. The effects of superimposed ultrasonic vibration on heat transfer and material flow in UVeFSW process have been quantitatively analyzed. Experimentally measured thermal cycles are compared with the calculated results to validate the models. The present numerical simulation results are expected to lay foundation for establishing the knowledge base and optimizing the UVeFSW process.

2. Experiment details

Fig. 1 shows the schematic of the experimental set-up in UVeFSW. In the UVeFSW process, a specially-designed sonotrode with a titanium alloy based vibration tool horn directly contacts with the top surface of the workpiece and transmits the ultrasonic vibration energy near and ahead of the rotating tool into a region where severe plastic deformation is inevitable during welding. Thus, during the UVeFSW process, a coupling of the ultrasonic vibration energy with the plastic deformation can produce an enhanced plastic material flow near the tool. In this study, the ultrasonic system operates at frequency (f) 20 kHz and vibration amplitude (λ) 40 μm during the UVeFSW process. The efficient power of the ultrasonic system during the process is about 300 W according to the output of the ultrasonic generator. Considering the adjustable capacity of the self-made locating rack and the efficiency of the ultrasonic energy, the distance between the center of tool horn and the FSW too1 axis is chosen as 20 mm. The inclinations angle (φ, as shown in Fig. 1c) of ultrasonic vibration tool horn with respect to the horizontal axis is 40°. The clamping force of the tool horn is 300 N during the process.

AA6061-T6 alloy plates (length 300 mm, width 80 mm and thickness 6 mm, polished and cleaned by acetone at the top, bottom and abutting surfaces) were welded in a square butt joint configuration using FSW and UVeFSW processes. Compositions of the workpiece are listed in Table 1. Identical process parameters (listed in Table 2) were used for welding by FSW and UVeFSW. The FSW tool comprised of a shoulder of diameter 15 mm, pin of diameter 5.6 mm and 3.2 mm at the root and the tip, respectively. Length of the pin was 5.7 mm. Thermal cycles during both the process were measured by K-type thermocouples. The thermocouples were positioned at transverse distances of 15 mm and 25 mm from the joint line at AS and a depth of 3 mm from the top surface. Thermocouples were placed at a distance of 20 mm away from each other along the joint line. After welding, transverse cross sections of the weld joints were used for microstructure characterization by optical microscopy and electron backscatter diffraction (EBSD). In the EBSD characterization, grain boundaries with misorientation angles lower than 15° were defined as low-angle boundaries (LABs), whereas those with misorientation angles higher than 15° were defined as high-angle boundaries (HABs). The grain size was quantified by determining the area of each grain in the EBSD map and calculating its circle equivalent diameter. The grains were defined as crystallites bordered by a continuous HAB perimeter in the EBSD maps. Detailed description of the EBSD measure and analysis procedure can be found in literatures [29,43].

3. Mathematical model

3.1. Governing equations

A geometrical model for UVeFSW process is shown in Fig. 1a. As shown in this figure, a 3D Cartesian coordinate system was established on the plate with its origin located at the bottom of the workpiece under the axis of the tool. The x-axis is along the weld line, and the z-axis is normal to the top surface of workpiece. For simplification, the tilt angle of the tool was taken as zero, and the tool shoulder was assumed to be flat. The material was assumed to behave as an incompressible and single-phase non-Newtonian visco-plastic fluid, and only the plastic deformation was considered [44,45]. Since it is time-consuming for a transient model to achieve a quasi-steady state, first a quasi-steady state model was developed for the calculation of the thermal and plastic material flow during conventional FSW. After reaching at a converged solution, the computation results of the quasi-steady state model were taken as the initial conditions of transient state model to calculate ultrasonic energy density field, thermal processes and material flow during UVeFSW. The governing continuity equation and momentum conservation equation are given as follows [37]:

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