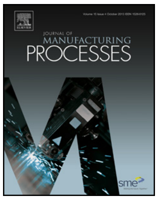
Journal of Manufacturing Processes 25 (2017) 323–339

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro



# Transient model of heat transfer and material flow at different stages of friction stir welding process

L. Shi, C.S. Wu*

*MOE Key Lab for Liquid–Solid Structure Evolution and Materials Processing,and Institute of Materials Joining, Shandong University, Jinan 250061, China*

ARTICLE INFO

*Article history:*
Received 16 June 2016
Received in revised form 19 October 2016
Accepted 8 November 2016

*Keywords:*
Transient model
Friction stir welding
Heat generation
Material flow
Heat transfer

ABSTRACT

A better understanding of heat transfer and material flow for different stages (including plunge stage, dwell stage, welding stage, and cooling stage) of friction stir welding process is critical for the tool design and selecting appropriate welding variables. In this study, a transient model is developed to quantitatively analyze the dynamic variations of the heat generation, temperature profile and material flow for different stages of friction stir welding process, and is used to investigate the dependence of these aspects on the process parameters such as welding speed and the tool rotation speed. It is found that the total heat generation increases persistently during the plunge stage and reaches its peak value when the FSW tool shoulder contacts with the top surface of the workpiece. From the peak value, the total heat generation decreases monotonically during the dwell stage before attaining the quasi-steady state in the welding stage. The materials flow analysis predicts that the plastically deformed material in the front of the tool flows in counter-clockwise direction, passes the tool on the retreating side and gets released behind the tool during the welding stage. The model is experimentally validated by comparing the measured tool torque and peak temperature values with the predicted results, which agree well with each other.

## 1. Introduction

Nowadays a large demand for lightweight, fuel-efficient and low emissive structures has been fulfilled by the widespread application of aluminum and magnesium alloys in manufacturing industries. As a solid-state joining process, friction stir welding (FSW) is considered as an energy efficient, environment friendly and versatile method of joining the lightweight materials than the fusion welding processes [1–4]. The FSW process involves four main stages: plunge stage, dwell stage, welding stage and cooling stage, as shown in Fig. 1. The process is initiated with the plunge stage during which a rotating tool, comprising a shoulder and a pin, is gradually penetrated into the abutting edges of workpieces until the shoulder contacts with their top surfaces. Next is the dwell stage during which the plunged tool is continued to rotate for a while to soften the material near the tool. This is followed by the welding stage during which the rotating tool is translated along the abutting edges, resulting in a weld joint. When the weld distance is covered, the tool is immediately pulled out of the workpiece which results in a rapid decrease in the temperature of the joint. This is referred to as the cooling stage.

During the FSW process, the heat energy is generated by friction between the tool and the workpiece, and plastic deformation of the workpiece [5–7]. While the heat energy softens the material in the shear layer around the tool, the plastic material flow in the shear layer produces localized viscous dissipation heat energy. Combination of the tool rotation and translation leads the softened material to flow from the front of the tool (leading side) to the back of the tool (trailing side), where it is forged into a joint. In FSW process, both the heat generation and material flow have crucial effects on the metallurgical characteristics and mechanical properties of the weld joints [8–10]. Furthermore, the preheating effects of the plunge and dwell stages have significant effect on the welding force and tool wear [11]. Therefore, a complete understanding of both the heat generation and material flow at different stages of FSW process is imperative in optimizing the process, and controlling microstructures and properties of the joints.

Numerical modeling of the FSW phenomena is powerful for understanding different phenomenon [4,12]. Several models have been developed to explore the heat generation and material flow phenomena in FSW process [12–28]. Some of them dealt only with the thermal conduction and ignored the material flow [13–15]. Others rightly emphasized the coupling of heat transfer and mate-

---

* Corresponding author. Fax: +86 531 8839 2711.
*E-mail address:* wucs@sdu.edu.cn (C.S. Wu).

http://dx.doi.org/10.1016/j.jmapro.2016.11.008

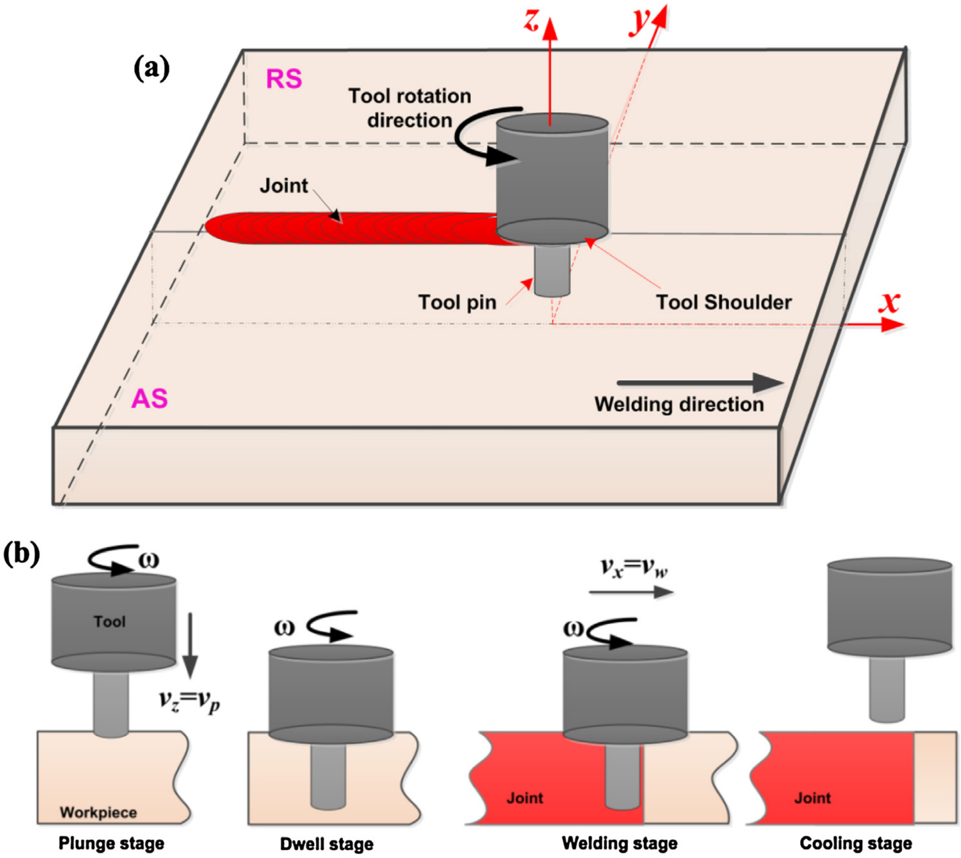


**Fig 1.** Schematic drawings of (a) friction stir welding (FSW) process, (b) different stages in FSW.

rial flow in the FSW process but limited the analysis only to the quasi-steady state of the welding stage and paid no attention to the plunge and dwell stages [16–21]. There are lots of situations where the steady-state conditions cannot be established, for example, at the start and the end of the welding process, or with varying process conditions/workpiece geometry [22]. Furthermore, the heat transfer and material flow during the plunge and dwell stages have significant effects on the properties of the joints and tool wear [11]. A thorough understanding of different stages of FSW process is important in the development of tools and processes for successfully welding of materials with high melting point [4]. Therefore, a transient numerical model is required for those common cases.

Several transient numerical models have recently been proposed to analyze the process mechanism at different stages of FSW [22–25]. Song and Kovacevic [23] and Zhang et al. [24,25] developed 3D transient thermal models which did not account for the convective heat transfer and heat generation from plastic deformation. Recently, Yu et al. [22] proposed a 3D transient model and investigated the heat transfer and material flow in friction stir processing of magnesium alloys. However, this model considered the heat generation only from the plastic deformation by assuming a full sticking condition at the tool-workpiece contact interfaces. In FSW process, the heat generation, the heat transfer and the plastic material flow pattern are fully coupled [26–28], and both friction heat and plastic deformation heat generate in the FSW process [27–30]. However, the transient numerical models mentioned above either only consider friction heat or only consider plastic deformation heat. None of these models adequately accounted for both heat transfer and material flow at different stages of FSW process. In addition, the tool torque is much higher at the start of the process when the tool comes into contact and is inserted into the workpiece at the plunge stage [31–33]. The detailed dynamic variation of tool torque at different stages of FSW is still unrevealed, and the available transient model which could be used to analyze the dynamic variation of tool torque at different stages of FSW is still limited. Therefore, a quantitative analysis of the tool torque, heat generation and material flow at different stages of FSW process is still needed.

In this study, a transient model is developed to quantitatively analyze the heat generation, heat transfer, and material flow during the four stages of the FSW process. Both the friction heat and the plastic deformation heat are considered to determine the heat flux distribution at the tool-workpiece contact interfaces. The effects of process parameters on the contact condition and the friction coefficient between tool-workpiece contact interfaces are examined. The model is validated by comparing the measured tool torque and peak temperature with the predicted results.

## 2. Formulation

### 2.1. Governing equations

Fig. 2 shows the geometric model for the simulation of FSW process. A moving coordinate system is established on the plate. During the plunge stage, the origin of the coordinate system is located at the intersection of the bottom surface of the workpiece and the axis of the tool. The welding direction is parallel to the positive *x*-axis, and the *z*-axis is along the plate thickness (upward). For simplification, the shoulder surface is assumed to be flat, and the thread on the pin side surface is not considered. The influence of the flash produced during the process is ignored. The FSW tool is treated as a rigid body and is not included in the model for saving computation time. The material flow is treated to be non-Newtonian, incompressible, laminar, and visco-plastic in nature [16–18]. The