International Journal of Machine Tools and Manufacture 124 (2018) 12–21

Contents lists available at ScienceDirect

International Journal of Machine Tools and Manufacture

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

# Effects of pin thread on the in-process material flow behavior during friction stir welding: A computational fluid dynamics study

Gaoqiang Chen [a], Han Li [a], Guoqing Wang [b], Zhiqiang Guo [c], Shuai Zhang [a], Qilei Dai [a], Xibo Wang [a], Gong Zhang [a], Qingyu Shi [a,*]

[a] State Key Laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, PR China
[b] China Academy of Launch Vehicle Technology, Beijing 100076, PR China
[c] SAIC Volkswagen Automotive CO. LTD, Shanghai 201805, PR China

ARTICLE INFO

*Keywords:*
Friction stir welding
Material flow
Numerical simulation
Tool design
Pin thread

ABSTRACT

Pin thread is one of the most common geometrical features for the friction stir welding (FSW) tools. The main purpose of employing the pin thread is to improve the in-process material flow behaviors during FSW. However, it has not been fully understood how exactly the pin thread influences the material flow because of the lack of in-process observation. In this study, we aim to analyze the effect of pin thread on the in-process material flow during FSW of an Al-Mg-Zn alloy by using numerical simulation based on computational fluid dynamics (CFD). In our numerical simulation, the transient rotation of the threaded pin is implemented explicitly via fully transient control of the zone motion, and the mechanical interaction at the tool-workpiece interface is considered via the recent developed shear-stress-based frictional boundary condition. The numerical simulation has been validated by the experimental measured temperatures at 8 different locations, the distribution of marker materials and the geometry of deformation zone in the weld. Based on the numerical simulation results, three effects of the pin thread on the material flow have been elucidated. First, accelerated flow velocity and enhanced strain rate is induced owing to the use of the pin thread, which is attributed to the fact that the interfacial sticking is preferable inside the thread groove opening. Second, the pin thread has an effect to trap material in the high-velocity zone inside the thread groove opening, which causes a many-circle flow pattern around the threaded pin. Third, the pin thread contributes to a vertical pressure gradient, which is important for the in-process material transfer from the top to the bottom. The approaches and concepts in this study can be applied for further fundamental investigation of FSW and the computer aided design of the welding tools.

## 1. Introduction

Friction stir welding (FSW) [1] has been successfully applied in fabricating many critical load-bearing structures, e.g. rocket fuel tanks and high speed train bodies. The in-process material flow around the welding tool is of vital importance in the scientific understanding of FSW due to its critical role in governing many underlying processes [2], such dynamic recrystallization [3] and heat generation [4,5], which are closely related to the microstructure [6,7] and performance of the welds [8,9]. Despite its critical importance, the material flow around the welding tool is still one of the yet-least understood phenomenon in FSW. For instance, the effect of the pin thread on the in-process material flow has not been fully understood. The pin thread is one of the most common and basic geometrical features for designing the pin geometry of the FSW tools [10]. Employing thread or thread-like structures on the pin has been considered to be unique to effectively improve the material flow around the welding tool in order to avoid defects and form sound welds. Owing to the important effect of the pin thread, further knowledge is required on how exactly the pin thread influences the material flow behaviors during FSW to support the welding tool design and process optimization. In this study, we report our recent study to quantitatively elucidate the effect of the pin thread on the in-process flow state close to the welding tool during FSW by using three dimensional numerical simulation.

The importance to understand the effect of pin thread on the in-process material flow in FSW has been well recognized in the previous experiment-based researches. Several early studies have tried to reveal the material flow field around a threaded pin during FSW by analyzing the post-welding microstructural features in the welds. It was reported by

* Corresponding author.
*E-mail address:* shqy@tsinghua.edu.cn (Q. Shi).

https://doi.org/10.1016/j.ijmachtools.2017.09.002
Received 24 July 2017; Received in revised form 8 September 2017; Accepted 14 September 2017
Available online 15 September 2017

International Journal of Machine Tools and Manufacture 124 (2018) 12–21

**Table 1**
Nominal chemical composition of the workpiece (AA7A52).

| Elements | Fe | Si | Mn | Cu | Mg | Ni | Cr | Zn | Ti | Zr | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|
| wt % | 0.26 | 0.11 | 0.25 | 0.13 | 2.46 | 0.05 | 0.17 | 4.71 | 0.06 | 0.08 | Bal |

Guerra et al. [11] that the pin thread could contribute to a vertical flow trend. A 'stir effect' of the pin thread is reported by Ouyang et al. [12], which helps to deliver the material to form a sound weld. Besides, Schmidt et al. [13] thought that the thread on the pin could introduce some cyclic flow patterns in the friction stir welds. Actually, it is difficult to understand the influence of the pin thread on the material flow, because quite limited information on the in-process material flow could be gained based on the post-welding analysis of microstructures. Although some recent experiments have employed the X-ray radiography [14] to in situ observe the material flow during FSW, but still very limited information could be obtained due to the limited resolution in the current in-situ experiment.

Due to the difficulties in experimental research, computational methods have been developed to investigate the in-process material flow during FSW [15]. In the literature, the computational methods for studying the material flow during FSW could be divided into two categories, which are the Computational Solid Mechanics (CSM) approach and the Computational fluid dynamics (CFD) approach. Schmidt et al. [16], Buffa et al. [3,17] and Al-Badour et al. [18] have demonstrated that different numerical strategies based on CSM were viable to predict the in-process thermal-mechanical conditions, including the material flow behavior, during FSW. However, few of the CSM-based simulations has explicitly included the pin thread in their geometric model because of the issues of computational cost and numerical robustness. These issues were caused by the large element distortion induced by the rotation of a threaded pin. In the CFD simulation work presented by Colegrave et al. [19], it was demonstrated that the pin thread could be considered explicitly in the three dimensional model. It was concluded that the threaded pin contributed to a larger traversing force than the unthreaded version. In later CFD analysis, Ji et al. [20] reported that the decrease of width of thread groove could result in the increase of material flow velocity in the vicinity of the tool. In CFD simulation by Yu et al. [21], a transient model was proposed to include the transient rotation of the threaded pin. They found that a swirling and upward flow field was caused by the helical thread on the pin while the threads had only a small effect on the temperature distribution. However, the flow velocity and the strain rate were over-predicted in these CFD simulations due to the use of a velocity-based fully sticking boundary condition [20,21]. Although the CFD simulation has been proved to be a very powerful tool for analyzing the in-process material flow behaviors during FSW with a threaded pin, more advanced boundary condition is still needed in the CFD simulation for better understanding how exactly the pin thread influences the in-process material flow behaviors to support the engineering design of FSW.

Our previous modeling work has shown that the CFD simulation with a recent developed shear-stress-based boundary condition is more predictive for the deformation zone shape [22] and defects location [23] in friction stir welds than those with a fully sticking boundary conditions. Therefore, the use of the shear-stress-based boundary condition must make CFD simulation a more useful tool for analyzing the material flow field around a threaded pin. In this study, based on the shear-stress-based boundary condition [22], three dimensional numerical simulation based on the CFD approach is established to analyze the temperature field and the material flow field during friction stir welding of an Al—Mg—Zn alloy. Based on the numerical simulation, the predicted material flow fields around a threaded pin and a smooth pin are predicted and compared. Based on the comparison between the predictions on the smooth and threaded pin, the effects of the pin thread on the in-process material flow behavior are elucidated. Finally, the numerical predictions on temperature and material flow are validated by the experimental measurements.

## 2. FSW condition and experimentation

In this study, bead-on-plate FSW of AA7A52 plates was carried out. The nominal chemical composition of the AA7A52 is given in Table 1. The size of the workpiece was 150 mm (X) × 90 mm (Y) × 6 mm (Z). The rotation rate of the welding tool was 800 rpm and the welding speed was 100 mm/min. A welding tool with threaded pin was used in the experiment. The shoulder of the tool was 20 mm in diameter and had a concave shape. The pin has a conical geometry, which was 8 mm near the shoulder and 6 mm in diameter at the tip. A right-hand thread was employed on the pin. In the welding process, a plunge depth of 0.5 mm was employed, and the tool was tilt at 2°. Eight K-type thermal-couples were pinned on the top surface of the workpiece to record the temperature evolution during the welding process. The locations of the 8 thermal-couples are shown in Fig. 1, which were 15 mm, 20 mm, 25 mm and 30 mm from the welding center line on the advancing side (AS) and retreating side (RS). After welding, the cross section of the weld was examined by optical microscope (OM). In two separate experiments, 0.1 mm-thick copper foil was used to visualize the material flow during welding. Before welding, the copper foil was embedded at the location 2.7 mm from the welding centerline on the AS and RS, which is shown by the colored line in Fig. 1. Owing to its good plasticity of pure copper, the copper foil deforms and flows with the aluminum alloys during FSW. In the experiments with marker material, the welding tool was pulled out of the workpiece without dwelling at the end of tool travel period, so that the state of marker material was frozen as the same as it was during welding. After welding, the welds were examined by computer tomography (CT) in transmission mode to examine the distribution of copper

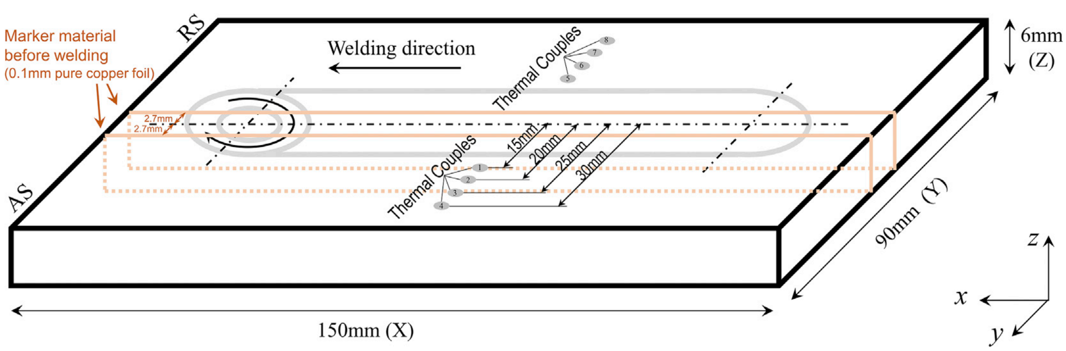


**Fig. 1.** Illustration of the FSW experiment.