Journal of Materials Processing Tech. 255 (2018) 121–128

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

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

# Counter rotating twin-tool system in friction stir welding process: A simulation study

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ARTICLE INFO

*Keywords:*
Twin-tool
Lagrangian method
Friction stir welding
Temperature distribution
Deform 3D
Material flow

ABSTRACT

In the current paper a comparative study between twin-tool and conventional friction stir welding tool by using a numerical method is carried out based on temperature distribution, strain, material flow and material velocity. The model is validated with experimentally measured temperature for both the cases and a good correlation is observed. Twin-tool generates higher maximum and minimum temperatures over the conventional FSW having a single-tool. Lower thermal gradients along transverse and thickness directions are achieved for twin-tool as compared to the conventional FSW. In twin-tool, strain distribution is symmetric contrary to the asymmetry in conventional FSW. Material deposition is closer to its original location in case of twin-tool as compared to conventional FSW leading to lower chances of defects in the former.

## 1. Introduction

Friction stir welding (FSW) is one of the fastest emerging welding techniques since its inception in 1991 (Thomas et al., 1991). FSW possesses several advantages over fusion welding techniques like higher mechanical strength, no defects related to re-solidification, no use of consumables or shielding gas (Jain et al., 2015). Certain defects like worm hole, lack of penetration, kissing bond etc. are reported during FSW due to improper selection of process parameters (Kim et al., 2006). Multi-pass FSW is one of the methods to eliminate the defects. (Brown et al., 2009) have studied the effect of multi-pass (five passes) friction stir welding (MP-FSW) on metallurgical and mechanical properties. They reported reduction of 7% in tensile strength from pass 1–5. Peak residual stress is also reduced with increase in number of pass while there is negligible change in microstructure of nugget zone. (Jie and Jie, 2009) eliminated the groove defect by re-welding. They compared the symmetrical and offset re-welding and found that the latter produces higher strength as compared to the former. In order to produce uniform microstructure, welding direction is reversed during re-welding. (Nakata et al., 2006) carried out MP-FSP to improve the mechanical properties of the sample. They achieved 70% and 22.2% higher strength and hardness, respectively, for MP-FSP as compared to the base metal. Removal of cold flake from the base metal and refinement of microstructure are reasons for improved mechanical properties. Hence, multi-pass/re-welding can be used for elimination of defects and grain refinement, but selection of process parameter for MP-FSW is a challenge. Also, changes in metallurgical and mechanical properties with respect to base material are an area of concern. To overcome the difficulty, the welding institute, Cambridge developed a tandem twin-stir, a variant of FSW having two inline tools, rotating in either same or opposite direction (Thomas et al., 2005). It has several advantages over conventional FSW viz. two counter rotating tool will nullify the forces, lesser clamping force, lower torque, significant reduction of defects etc. (Thomas et al., 2005). (Kumari et al., 2015) have indigenously fabricated a twin-tool setup and compared twin-tool FSW (TT-FSW) with dual-pass single tool FSW in terms of mechanical properties viz. hardness, weld strength, % elongation. Higher hardness is reported for TT-FSW at a rotational speed of 1800 rpm and defect-free weld is achieved at a higher welding speed of 63 mm/min.

Modeling of TT-FSW is essential to understand the mechanism of heat generation, temperature distribution, forces, power, material flow etc., but till date no literature is available in open source. A few notable work for modeling conventional FSW are discussed. (Jain et al., 2016) developed a three dimensional model to simulate FSW based on Lagrangian method in DEFORM-3D. They compared two pin profiles (cylindrical and conical) in terms of force generated and material velocity. Conical pin generates higher material flow in vertical direction as compared to cylindrical pin. They have also shown the asymmetric distribution of plastic strain with higher strain on advancing side (AS) as compared to the retreating side (RS) (Jain et al., 2017a, 2014). (Tutunchilar et al., 2012) simulated material flow for cylindrical pin based on the Lagrangian method. Temperature evolution and axial

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https://doi.org/10.1016/j.jmatprotec.2017.11.043
Received 5 November 2017; Received in revised form 21 November 2017; Accepted 23 November 2017
Available online 24 November 2017
0924-0136/ 

force were used to validate the developed model. They predicted the size of stirred zone by using particle tracking method. (Trimble et al., 2012) predicted axial force and torque through FEM model and validated it with experimental results. The Lagrangian formulation was used with Johnson-Cook material model and sticking friction condition. They compared between smooth and threaded cylindrical pins and found that the latter generates lesser force and higher deformation. (Zhang and Zhang, 2009) developed a 3D model in ABAQUS/Explicit to study the effect of welding speed in FSW. To achieve better convergence, pin height is taken larger than the workpiece thickness. Mass scaling of $10^7$ was defined to reduce computational time. Void was predicted at a higher welding velocity of 4 mm/s.

A good amount of literature is available for modeling of conventional FSW welding by using single tool, but no literature is available on numerical modeling of FSW by using twin-tool, and its comparison with single tool (ST) FSW. Therefore, the current work focuses on the development of three-dimensional, thermo-mechanical model to simulate TT-FSW based on the Lagrangian method. Model predicted temperature, strain, axial force, power and material flow are studied and compared with ST-FSW. Model is validated with experimentally measured temperature for both the cases.

## 2. Experimental procedure

A TT-FSW setup has been indigenously designed and fabricated by the co-authors (Kumari et al., 2015). It consists of a two counter-rotating tools viz. primary and secondary tools. The Former is attached with the main spindle of the machine and rotates in counter clockwise direction. A spur gear assembly with a gear ratio of one is used to transmit power from the primary to the secondary tool. The twin-tool setup is attached to knee type vertical milling machine (BFW, VF3.5) to perform FSW experiment, as shown in Fig. 1.

To compare TT-FSW with ST-FSW, experiments have been performed with the same setup by removing the gear assembly of the secondary tool and performing ST-FSW experiment with the primary tool only. K type thermocouple is used to capture the temperature evolution during the experiment. Thermocouple is attached with a data acquisition system (9211 NI card and LabVIEW software) to capture and store the data. Thermocouple is embedded at a distance of 5 mm from the edge of tool shoulder in transverse direction and at a depth of 1.5 mm from the top surface. Thermocouple was 65 mm away from the edge of the workpiece as shown in Fig. 2.

A 3 mm thick AA1100 is friction stir welded using TT and ST. The workpiece has a total length and width of 150 and 75 mm, respectively. For both the cases, mica sheet is used as a backing plate material to contain the heat within the workpiece and also to avoid sticking of aluminum alloy on the backing plate. Tool steel H13 is used to manufacture the tool with a cylindrical pin of 5 mm diameter and 2.6 mm pin height. Shoulder diameter is 16 mm and plunge depth is defined as 0.1 mm. Experiments for both the cases are performed at a rotational speed of 900 rpm and 80 mm/min welding speed with a tilt angle of zero degree.

## 3. Simulation details

A three-dimensional non-linear thermo-mechanically coupled transient analysis is developed based on the Lagrangian implicit analysis. Simulation parameters and parts dimensions are consistent with the experimental data. All three stages of FSW i.e. plunging, dwelling and welding are simulated. Total plunging, dweling and welding duration are 42, 4 and 54 s, respectively. Following assumptions are made during the modeling to reduce computation time:

1) Dynamic recrystallization of the material and microstructural changes are not considered.
2) Shear factor and mechanical properties of the material are defined as constant values. This assumption avoids the non-linearity and reduces computation time.
3) The workpiece is defined as a single continuum body to avoid contact instabilities at the abutting edge. The tool is defined as a rigid body due to negligible wear during welding of aluminum alloys.

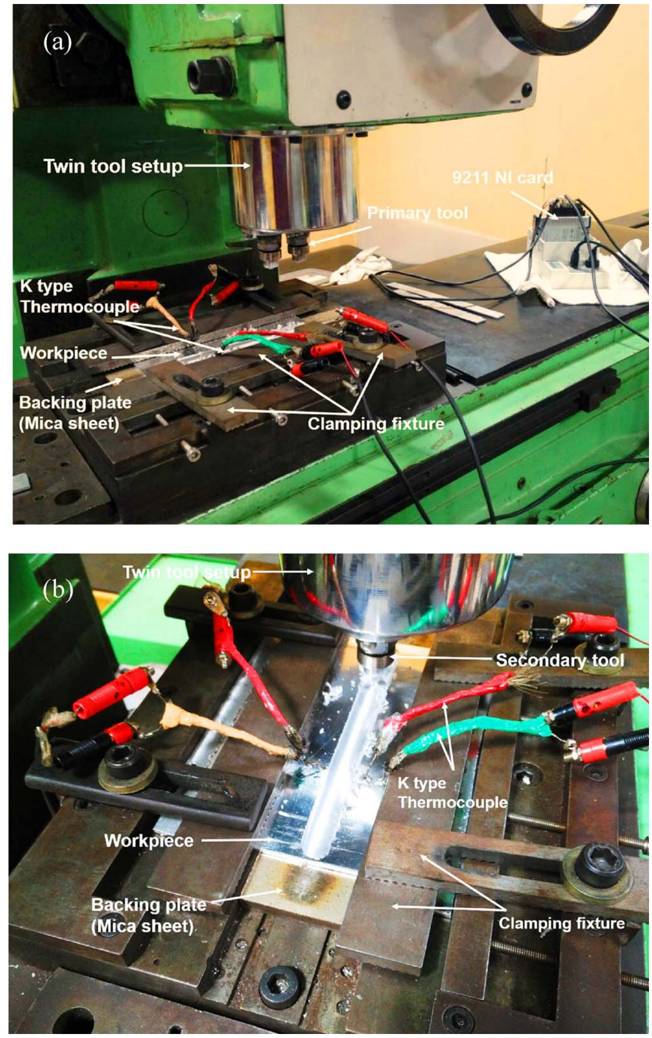


**Fig. 1.** (a) Experimental setup for TT-FSW (b) enlarged view of the fixtures.

### 3.1. Geometric modeling and meshing

Fig. 3 shows the meshed assembly of the workpiece, two tools and backing plate created for the modeling. The workpiece is defined as a rigid visco-plastic material i.e. elastic deformation of the material is neglected and yield point of the material is taken as the inception of deformation. The tool and backing plate are defined as rigid materials. 138720 coupled tetrahedral elements are used to mesh the workpiece with biased meshing as shown in Fig. 3. Mesh size of 0.6 mm is defined on the workpiece near the tool based on the mesh sensitivity analysis, with a minimum element size of 1.5 with a size ratio of 2 elsewhere.

The tool and backing plate are meshed with 7472 and 4062 tetrahedral elements respectively, having thermal degree of freedom only.

#### 3.1.1. Re-meshing technique

FSW is a large deformation process and a strong re-meshing method is required to avoid distortion of the mesh. Re-meshing is triggered based on element size and penetration that are defined by three different criteria as discussed below: