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Thermomechanical Analysis of Friction Stir Welding by Using a New Velocity-Based Model for Tool-Workpiece Interaction

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Abstract

The friction stir spot welding test was designed to measure the coefficient of friction on the tool-workpiece contact interface under different tool rotation speeds. The boundary velocity of the workpiece material was calculated based on the stress state of the material on the contact interface. An integrated computational fluid dynamics (CFD) model of friction stir welding (FSW) was established based on the matrix's coefficient of friction and boundary velocity to simulate heat and mass transfer. A more realistic boundary velocity distribution was acquired. A method was introduced to predict strain along a streamline by integrating the strain rate along with the streamline's reverse. The nephogram of strain on the transverse cross-section of weldment displays that strain at the advancing side (AS) is more significant than that at the retreating side (RS), and strain increases as the distance from the shoulder surface decrease. Strain in some regions can be tremendous if the material flows through the rotation flow zone. Wall heat flux on tool-workpiece contact interface at RS is more significant than that at AS. The maximum temperature was observed at the front part of RS. The model is validated since the predicted temperature profile agrees well with corresponding experimental results.

Keywords: Friction stir welding; Boundary velocity; Heat generation; Mass transfer; Computational fluid dynamics

Nomenclature		C	The lead of the guide screw
		N	Tool rotation speed
M_t	Tool torque	v	Welding speed
$M_{t\max}$	Maximum tool torque	ω_m	Angular velocity of matrix
M_w	The output torque of the motor	ω_t	Angular velocity of the tool
M_{w0}	No-load torque of the motor	v_m	Matrix velocity
δ	Slip rate	v_t	Tool velocity
τ_y	Shear yield stress	σ_y	Yield stress
τ_f	Friction stress	σ_f	Flow stress
τ_t	Deformation stress threshold	ε	Strain
μ_f	Coefficient of friction	$\dot{\varepsilon}$	Effective strain rate
p_n	Normal-pressure	t	Time
p_n	Maximum normal pressure	r	Radius
F_n	Tool axial force	R_s	Shoulder radius
$F_{n\max}$	Maximum tool axial force	η_M	Transmission efficiency

1 Introduction

Friction stir welding (FSW) is a novel green and sustainable manufacturing technology due to its advantages, including energy efficiency, environment friendliness, and high weld quality. There is an increasing demand for fabricating critical

components using FSW [1, 2]. Compared with conventional fusion welding techniques, the FSW process requires no shielding gas, flux, or filler metal, and its heat input is relatively low. Therefore, it is an environmentally friendly process. The solid-state nature of FSW yields the fact that the process versatility in welding position, welding orientation, workpiece thickness, and different compositions is greatly extended [2, 3].

In the FSW process, a non-consumable rotating tool with a threaded or unthreaded pin and concave shoulder was inserted into the abutting edges of the workpiece and traversed along the joint line. The heat generated between the tool and workpiece due to friction can soften the material around the tool. Consequently, the softened material moves from the front to the rear of the tool owing to tool rotation. Meanwhile, plastic deformation of the material also generates heat for welding [1]. The friction and boundary velocity of the workpiece material at the tool-workpiece contact interface determine friction heat production and heat generation from plastic deformation. Therefore, it is crucial to investigate friction on the tool-workpiece interface and boundary velocity of workpiece material adjacent to tool surface to study the process mechanism and establish a mathematical model.

Though temperature distribution in the stir zone has been reported, work on direct observation of materials flow during the FSW process is limited due to FSW's solid-state nature. In addition, heat and mass transfer of FSW is challenging to be quantitatively characterized experimentally, especially the contact state between tool and workpiece. Numerical simulation has been generally recognized as a way to quantitatively investigate the thermal-mechanical process in FSW. Good results have been obtained in predicting temperature field and tool forces [4-6].

The computational fluid dynamics (CFD) method has been widely used in the simulation of FSW. Two key parameters, coefficient of friction and boundary velocity of workpiece material, are required for CFD simulation. Estimation of such parameter, however, lacks a theoretical basis. The contact friction between tool and workpiece is generally considered following Coulomb's law of friction. Most researchers set the coefficient of friction as a constant in the simulation model. Throughout literature,

various values of the coefficient of friction are available: 0.25 [7], 0.3 [8], 0.45 [9], 0.5 [10]. Most of them referred to the values of coefficient of friction used in similar processes (rolling, extrusion, turning, etc.) directly or indirectly. The boundary velocity of the workpiece material is usually employed to equal the tool velocity or less than tool velocity. The ratio of workpiece material velocity to tool velocity is a constant which is lower than one. It is reported as: 0.01 [11, 12], 0.09 [13], 0.1-0.3 [14], 0.11-0.2 [15], 1.0 [16]. Determination of boundary velocity of workpiece material often depends on the comparison with the experimental results or refers to the values used in similar processing technology. Arora et al. [17] derived the coefficient of friction and ratio of workpiece material velocity to tool velocity from the trend of the reported data on total accumulated slip during cross-wedge rolling [18]. Liu et al. [19] employed the empirical friction model Maekawa et al. [20, 21] in tool-chip interfacial conditions during the machining process. Chen et al. [22] used a frictional boundary condition at the tool-workpiece interface to obtain a contact state over the tool-workpiece interface. However, the interaction between tool and workpiece material on the contact interface is not clarified.

Rotating speed and travel speed are two main parameters in friction stir welding. The influence of rotating speed on heat generation, welding force, and mechanical properties is much more significant than travel speed. Friction and boundary velocity of workpiece material on the contact interface is inevitably influenced by tool rotating speed. Therefore, it is necessary to investigate the contact condition (friction and boundary velocity of workpiece material) on the tool-workpiece contact interface under different welding parameters for FSW CFD simulation.

The coefficient of friction is a "system property" which depends on various system variables like temperature, velocity, atmosphere, and interface geometric properties [23]. A simple and ingenious friction stir spot welding (FSSW) test was carried out in this study. The torque and axial force of the tool were monitored and recorded in real-time, which can be used to calculate the coefficient of friction suitable for FSW according to the relationship with the forces of the tool. The measured coefficient of

friction is combined with the CFD model of FSSW. The boundary velocity of the workpiece material can be determined based on the friction driving effect of the tool on the workpiece material. The coefficient of friction and boundary velocity of workpiece material can be applied to our previous three-dimensional CFD model of FSW [24]. Plastic material flow, heat generation, temperature field, and plastic strain are examined with numerical simulation. The predicted temperature profile and macrostructure of the weld are verified with corresponding independent experimental results.

2. Determination of the coefficient of friction

2.1. Experimental scheme

Fig. 1 Schematic diagram of the experimental processes (FSSW). (a) Tool plunges the first time; (b) tool returns; (c) tool plunges the second time; (d) tool rotates in situ.

To measure the coefficient of friction under various tool rotation speeds, a friction stir spot welding (FSSW) experiment was designed and carried out on AA6061-T6 plates with 6 mm in thickness. A tool with concave shoulder and a tapered unthreaded pin is employed. The concave angle of the shoulder is 9° , and the diameter of the shoulder is 15.0 mm. The diameter of the tapered pin at the top and root are 3.5 and 6.0 mm, respectively. The pin length is 5.7 mm.

The experimental processes of FSSW are divided into four stages which are shown

in Fig. 1. The aim of each stage is described below.

The first stage (tool plunges the first time): obtain a hole that fits well with the tool to ensure that the workpiece material and the tool surface are instantaneously fitted when the tool plunges again.

The second stage (tool returns): cool the workpiece and the tool to ensure the same temperature on the contact interface before the next contact. Uniform experimental conditions for different welding parameters could be achieved.

Third stage (tool plunges the second time): monitor and record the force of the tool when the tool comes into contact with the workpiece. The tool torque is entirely determined by friction.

Fourth stage (tool rotates in situ): monitor the variation of tool force when temperature increases due to the friction between tool and workpiece.

The current FSSW experiment aims to obtain tool torque and tool axial force when the tool comes into contact with the workpiece. Recorded tool forces can be used to calculate the coefficient of friction which will be combined with the CFD model of FSSW to obtain the boundary velocity of the workpiece.

The FSW experiment of AA-6061-T6 with 6 mm thickness was also carried out to validate the numerical model. The dimensions of the workpiece are 200 mm (length) $\times$ 75 mm (width). The plunge depth is 0.1 mm, and the tool tit angle keeps at 2.5°. The dimension of the tool used in FSW is the same as that used in FSSW. The tool rotation speed used in FSW are 400, 600, 800, and 1000 rpm and the travel speed are 60, 90, 150, and 210 mm/min. During FSW, K-type thermocouples were embedded into the workpiece to measure the temperature profile. Thermocouples located at AS and RS were at a distance of 10, 20, and 30 mm away from the weld centerline. The end of thermocouples was all at a depth of 3.0 mm from the top surface of the workpiece.

2.2. Coefficient of friction

According to the study of the Arora et al. [25] and Shi et al. [26], tool torque can be calculated from the shear yield strength of the workpiece material and friction stress on the contact interface, which is expressed below:

$$M_t = \int_A \tilde{r} \times [\delta \tau_y + (1 - \delta) \mu_f p_n] dA \quad (1)$$

where r is the radius between the point and tool axis, τ_y is the shear yield strength of the workpiece material, μ_f is the coefficient of friction on the contact interface, p_n is the normal contact pressure on the contact interface, which is assumed to be uniform in this study. p_n can be calculated from measured tool axial force,

$$p_n = \frac{F_n}{\pi R_s^2} \quad (2)$$

where F_n is the measured tool axial force, R_s is the radius of the tool shoulder.

In the third stage of the FSSW experiment, the tool is in complete contact with the workpiece. Both axial force and torque of the tool will peak at the same time. The maximum value of axial force F_{nmax} and torque M_{tmax} can be obtained by setting the boundary velocity of the workpiece zero. As a result, the tool torque is determined only by friction on the contact interface. Therefore, tool torque can be expressed as below,

$$M_{tmax} = \int_A \tilde{r} \times \mu_f p_{nmax} dA = \mu_f p_{nmax} \cdot \frac{2}{3} \pi R_s^3 \quad (3)$$

Combining Eqs. (2) and (3), the coefficient of friction can be obtained by following equation,

$$\mu_f = \frac{3M_{tmax}}{2F_{nmax} R_s} \quad (4)$$

The electric signal of the spindle motor in x , y , and z are monitored, and the torque of each motor was measured by the sensor on the motor. In the study of Su et al. [27], the method of measuring axial force and torque has been elaborated. Tool axial force during welding can be calculated by the following formula,

$$F_n = 2\pi\eta_M \cdot \frac{M_w - M_{w0}}{C} \quad (5)$$

where M_w and M_{w0} are output torque of the z -axis motor during welding and without load, respectively, C is the lead of the drive ball screw pair, η_M is the efficiency of the drive ball screw pair.

At least four sets of data were measured under each welding parameter, and the results of average values are shown in Table 1. Tool axial force variation is minimal despite welding parameter change. Therefore, tool axial force was considered a constant in this study, the average value under different welding parameters in the experiment. However, the tool torque decreases as rotation speed increases.

Table 1 Measured results by FSSW experiments.

Rotation speed N (rpm)	Maximum tool torque M_{max} (N·m)	Maximum axial force F_{zmax} (N)
400	38.95	11156
500	37.16	
600	33.24	
700	27.07	
800	22.16	
900	19.54	
1000	16.81	

Bring the measured data of tool force into Eq. (5), the coefficient of friction under different rotation speeds can be obtained, plotted in Fig. 2. It is easy to find that the coefficient of friction decreases with an increase in rotation speed, which is in line with Nandan et al. [28]. The relationship between the coefficient of friction and rotation speed can be fitted to the following formula according to the experimental results shown in Fig. 2,

$$\mu_f = 5.005 \times 10^{-5} \cdot \omega^2 - 0.01109 \cdot \omega + 0.9759 \quad (6)$$

Fig. 2 Variation of coefficient of friction with rotation speed.

3. Determination of velocity boundary of workpiece material

The stress state of the workpiece material adjacent to the tool surface can be considered a pure shear stress state [29]. The workpiece material at the interface is mainly subjected to two forces: friction stress from the tool and the reaction inside the workpiece material. The direction of the two forces is along the tangential direction of tool rotation, respectively. Therefore, the movement of the material can be determined based on the force of the material adjacent to the tool. According to the theoretical study of plastic deformation, the material begins to plastically deform when the driving force is more significant than a certain threshold related to the temperature, pressure, atmosphere, etc. [30, 31].

In the FSW process, the driving force is the friction stress τ_f on the contact interface, and deformation stress threshold τ_t is determined by the shear yield stress of the workpiece material. Friction stress, a function of rotation speed, can be determined based on Coulomb's friction law. At the beginning of welding, the deformation stress threshold is much greater than the friction stress on the contact interface between the tool and the workpiece due to low interface temperature. Thus, the workpiece material is challenging to move, and the contact condition is fully sliding. The entire sliding contact state can be maintained if friction is always less than the deformation stress threshold ($\tau_f < \tau_t$). The temperature of the workpiece material gradually rises due to

frictional heat generation on the contact interface, which results in deformation stress threshold decreases. When the temperature is high enough, the material will start to accelerate under the driving force of friction. The deformation stress threshold is smaller than the friction stress on the contact interface ($\tau_t < \tau_f$). If the boundary velocity of the workpiece material is equal to tool velocity and the deformation stress threshold is also less than the friction stress on the contact interface, the workpiece material velocity will remain similar to the tool velocity, and the contact state is complete sticking. As long as the friction stress exceeds the deformation threshold, the complete sticking contact can be maintained.

The emphasis is to determine the boundary velocity of the workpiece in the partial sliding/sticking contact state. According to von Mises yield criterion, if the external stress is larger than the shear yield stress in case of pure shear stress, the material begins to yield in the direction of external pressure [32, 33]. This theory can be used to decide the relationship between material movement and stress state.

For convenience, slip rate δ (The ratio of material angular velocity to tool angular velocity.) is defined to describe the contact condition at the contact interface – relating the boundary velocity of workpiece material and tool velocity on the contact interface. Therefore, the velocity of the material can be calculated by the following equation,

$$v_m = \delta \cdot v_t \quad (7)$$

where v_m and v_t are the velocity of the workpiece material and the tool at the contact interface.

In the study of Schmidt et al. [34], the sliding, sticking, and partial sliding/sticking conditions were described and the respective heat generation mechanisms for each condition. The final flexible expression for the analytical heat generation suitable for each contact condition was obtained. The relationship between stress state and velocity on the contact interface is shown in Table 2.

Table 2. Definition of contact condition, velocity/shear relationship and slip rate. [34]

Condition	Matrix velocity	Tool velocity	Shear stress	Slip rate
Full sticking	$v_m = v_t$	$v_t = \omega r$	$\tau_f > \tau_y$	$\delta = 1$

Sticking/sliding	$0 < v_m < v_t$	$v_t = \omega r$	$\tau_f \geq \tau_y$	$0 < \delta < 1$
Full sliding	$v_m = 0$	$v_t = \omega r$	$\tau_f < \tau_y$	$\delta = 0$

Material shear yield stress (τ_y) is defined as the deformation stress threshold of workpiece material. For the complete sticking contact condition ($\delta=1.0$), the shear yield stress is lower than the friction stress, and the workpiece material velocity is equal to the tool velocity. For the complete sliding contact condition ($\delta=0$), the shear yield stress is larger than the friction stress, and the boundary velocity of the workpiece material is equal to zero. When the contact condition is a partial sliding/sticking condition, it will be determined by both the shear yield stress and friction stress.

In this study, the deformation stress threshold of the workpiece material is taken as the shear yield stress of the matrix. The method of determining the boundary velocity of the workpiece material is shown in Fig. 3.

When the boundary velocity of the workpiece is equal to tool velocity and friction stress is larger than the shear yield stress of the workpiece material, the friction stress can maintain this contact condition (full sticking). When the boundary velocity of the workpiece material is equal to zero, and the friction stress is less than the shear yield stress of workpiece material, the friction stress cannot drive material movement. Therefore, this contact condition (full sliding) can also be maintained.

When the contact condition is a partial sticking/sliding condition ($0 < v_m < v_t$), the boundary velocity of the workpiece material is between zero and tool velocity. The variation of boundary velocity of workpiece material depends on the relationship between shear yield stress and friction stress. If the friction stress is larger than the shear yield stress, the workpiece material velocity will be accelerated, which will inevitably cause variation in shear yield stress. The relationship between the two forces needs to be re-judged until the two forces reach equilibrium.

When the contact condition reaches a steady state, the friction stress and shear yield stress are a pair of balanced forces, which can be assumed as equal [35, 36],

$$\tau_f \cong \tau_y \quad (8)$$

Fig. 3 Relationship between matrix material velocity and stress state on the contact interface.

It is a quasi-steady-state during the FSW process. As a result, the contact condition at the interface is relatively stable. However, this steady-state comes from the result of the dwelling stage of welding. In this study, the FSSW process model is established first to calculate the boundary velocity of workpiece material. After convergence, the result of boundary velocity of workpiece material in FSSW is then taken as the boundary contact condition in FSW modeling.

4. Mathematical model

Figure 4 shows the schematic of the geometric model of the FSW experiment. The origin of the coordinate locates at the intersection of the tool center axis and workpiece bottom surface. The friction stir tool is regarded as a rigid body that is not involved in the model. Only the contact interface between tool and workpiece is reserved to employ the boundary condition. The translation of tool during welding is replaced by the flow of workpiece material, which flows from the inlet of the model into the calculated region. It flows out from the outlet along the positive x -axis. To ensure accuracy, the dimension of the calculation domain equals that of the actual workpiece used in the experiment. The commercial CFD software ANSYS Fluent was used to conduct the numerical simulation [37].

Some assumptions are made in the current numerical model,

- (1) During FSW, quasi-steady condition is assumed for temperature, material flow, and properties.
- (2) The matrix is treated as non-Newtonian, incompressible, viscoplastic fluid.
- (3) The shear stress for yield in pure shear τ_y was assumed to be $\sqrt{3}$ times of the

yield stress (σ_y) which is approximately equal to the flow stress (σ_f) of the material here [38].

(4) Tool tilt angle is taken as zero, and concave of the tool shoulder is neglected.

(5) Normal stress at the tool-workpiece interface is evenly distributed, regardless of variation in normal pressure due to translation of the tool.

The details of the CFD model in governing equations, formulas used to describe velocity boundary conditions, heat generation boundary conditions, and a volumetric heat source are referred to in our previous work by Sun et al. [24].

Fig. 4 Schematic of geometry model with the boundaries.

5. Results and discussion

5.1. Material flow velocity field

Figure 5 shows the velocity field on the tool-workpiece contact interface and into the workpiece near the tool. It is easy to find that velocity on the shoulder is more significant than on the pin side and bottom surfaces. The maximum value of velocity occurs on the shoulder but not at the maximum radius of the shoulder. The boundary velocity of the workpiece material does not increase monotonously with an increase in radius, which is inconsistent with tool velocity. The reason is that the temperature of the workpiece material near the outer edge of the shoulder is lower, which results in high shear yield stress. Friction stress on the contact interface is challenging to drive

material movement. The result is the same as that obtained with a stress-based model in the study of Chen et al. [22].

Fig.5 The velocity distribution around the tool. ($N=800$ rpm, $v=90$ mm/min)

To compare the boundary velocity of the workpiece material on the contact interface more clearly, Velocity along lines (OA , AB , BC as shown in Fig. 5) in y -direction at AS under different tool rotation speeds are plotted in Fig. 6. It is easy to find that the contact condition in almost all regions is partial sticking/sliding ($0 < v_m < v_t$). Complete sticking condition ($v_m = v_t$) and full sliding condition ($v_m = 0$) between the tool and the workpiece are difficult to reach. Due to low temperature and high shear yield stress, material velocity near the outer shoulder edge is close to zero. In general, the boundary velocity of the workpiece increases with an increase in tool rotation speed. On the pin side surface, material velocity near the pin top is very low for all tool rotation speeds, especially when the rotation speed is low. It indicates that material flow here is not sufficient and may induce welding defects.

Fig. 6 The velocity distribution on the contact interface along lines (OA , AB , BC as shown in Fig. 5) at AS under different welding parameters. ($v=90$ mm/min)

Fig. 7 Variation of material velocity with rotation speed. (a) Schematic of the positions to monitor data, (b) near shoulder interface, (c) near pin side surface, (d) near pin bottom surface. ($v=150$ mm/min)

Figure 7 shows the variation of material velocity with angle around tool axis under

different tool rotation speeds. As shown in Fig. 7(a) (L_{R1} , L_{R2} , and L_{R3}), the monitoring curves are 0.15 mm away from the tool surface. The result shows that velocity magnitude becomes more prominent with increased tool rotation speed for all monitoring positions. Velocity distribution near the shoulder surface is almost symmetric to the tool axis and varies little when θ changes from 0° to 360° for four different tool rotation speeds (Fig. 7b). When tool rotation speed is 800 rpm, the maximum and minimum velocity magnitude values are 257.1 mm/s and 249.2 mm/s, respectively.

Interestingly, velocity magnitude at RS is much larger than at AS near pin side and pin bottom surfaces, as shown in Fig. 7(c) and (d). 800 rpm tool rotation speed yields the maximum value of velocity magnitude near pin side surface is 40.6 mm/s occurring at RS, which is about 1.5 times that at AS (26.0 mm/s) as shown in Fig. 7(c). The values in the same meaning near pin bottom surface, as shown in Fig. 7(d), are 16.0 mm/s at RS and 7.1 mm/s at AS. The difference in velocity at AS and RS could be due to the difference in the direction of friction stress. The friction stress of the tool on the workpiece is opposite to the direction of motion of the workpiece at AS, and the material velocity induced by friction stress decreases when the tool moves forward. On the other side, the direction of friction stress of the tool on the workpiece and movement of the workpiece is the same at RS. Therefore, the material flow induced by friction stress will accelerate when the tool moves in the same direction as the workpiece.

5.2. Material flow streamlines and plastic strain field

The history of strain, strain rate, and temperature during FSW relates to material recrystallization, microstructure evolution, final mechanical properties, etc. The temperature profile can be measured with sensors, but strain and strain rate are difficult to measure directly [39]. As a result, it is of great importance to calculate strain evolution during FSW. However, it is difficult to derive such in the CFD model. As a result, the computational solid mechanics (CSM) method, which can handle strain calculation, is incorporated in the current study with the CFD model. In this section, the distribution of strain across the transverse cross-section of the weld is calculated,

combining the methods proposed by Arora et al. [40], Zhao et al. [41] in the simulation of FSW and by Liu et al. [39], Morisada et al. [42] in experimental analysis.

In the CFD model of FSW, the strain rate of a point in the computational domain is easy to be obtained [24, 37]. If we know the streamline of the point, the strain can be obtained by integrating the strain rate against time along the streamline,

$$\varepsilon = \int_{t_0}^t \dot{\varepsilon} dt \quad (9)$$

The method to accumulate the strain is shown in Fig. 8(b). The streamline passing the point at this moment should be calculated before the strain was obtained. As shown in Fig. 8(b), a streamline is divided into n equal small parts with equal spacing, and the distance of each small part is ds . Meanwhile, $n+1$ point was obtained. Once the convergence is calculated, physical parameters, such as velocity, temperature, and strain rate, can be saved and extracted. Therefore, the time which material flows through a small distance can be expressed as bellow,

$$dt = \frac{ds}{v_i} \quad (10)$$

where i is the number of the point, which varies from 0 to n .

The strain generated in a small distance $d\varepsilon_i$ can be written as,

$$d\varepsilon_i = \dot{\varepsilon}_i dt \quad (11)$$

Therefore, the strain of the point with number j on the streamline can be obtained by accumulating the values in previous small parts along with the reverse of the streamline,

$$\varepsilon_j = \sum_{i=0}^{i=j} \dot{\varepsilon}_i \frac{ds}{v_i} \quad (12)$$

The total strain of this streamline is,

$$\dot{\varepsilon} = \sum_{i=0}^{i=n} \dot{\varepsilon}_i \frac{ds}{v_i} \quad (13)$$

Fig. 8 Method to calculate strain in CFD model. (a) distribution of strain, material flow velocity, and effective strain rate in x-direction on plane $z=4.0$ mm, (b) method to calculate strain. ($N=600$ rpm, $v=90$ mm/min)

The effective strain rate can be given as [37],

$$\dot{\epsilon} = \sqrt{\frac{2}{3} \left(\left(\frac{\partial u_1}{\partial x_1} \right)^2 + \left(\frac{\partial u_2}{\partial x_2} \right)^2 + \left(\frac{\partial u_3}{\partial x_3} \right)^2 + \frac{1}{2} \left(\frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1} \right)^2 + \frac{1}{2} \left(\frac{\partial u_1}{\partial x_3} + \frac{\partial u_3}{\partial x_1} \right)^2 + \frac{1}{2} \left(\frac{\partial u_3}{\partial x_2} + \frac{\partial u_2}{\partial x_3} \right)^2 \right)} \quad (14)$$

Figure 8(a) shows the velocity distribution, effective strain rate, and strain along the streamline. The variation of velocity magnitude is divided into two distinct stages. At the leading side ($x < 0$), the material is accelerated due to the drive of the tool on the workpiece, and the velocity reaches a maximum value of 11.5 mm/s. After it passes the tool axis, the drive effect of the tool on the material weakens, and it begins to decelerate due to adhesive stress inside the material. Eventually, the tool does not affect the workpiece anymore, and the velocity of the workpiece material is equal to the welding speed. It is interesting to find that the trend of strain rate distribution along the streamline is similar to that of velocity. According to the definition of the effective strain

rate, an increase in effective strain rate means that the material is elongated, and a decrease in effective strain rate indicates compression in the material.

The strain is shown in Fig. 8(a) is true strain regardless of whether the material style is deformed (tensile deformation or compression deformation). Therefore, the accumulated strain along the streamline is always positive and presents a stepped shape. Influenced by the combination of material flow velocity and effective strain rate, the strain continues to increase within the scope of the effect of the tool and eventually reaches 18.78. According to the variation of the slope of the strain curve, the place where the strain changes fastest is not the place where the material velocity is the largest, nor the place with the highest effective strain rate, but occurs during the acceleration and deceleration of the material.

Figure 9 shows the material flow streamlines and strain distribution. As shown in Fig. 9(a), the degree of plastic deformation of the material can be seen from the deformation of the streamline. Most streamlines at AS bypass the tool pin from RS to the trailing side of the tool. It can be speculated that the material must be squeezed at RS and sheared at AS according to the deformation of streamlines. Comparing Fig. 9(a) and Fig. 9(b), it can be found that the strain in the region where the deformation of the streamline is obviously greater than one. Therefore, the contour with the strain of one can be defined as the boundary of the deformation zone. It is clear that the strain at AS is more significant than that at RS and becomes more prominent when it is close to the shoulder. The maximum strain value appears close to the tool shoulder at AS, which can also be inferred from the material flow streamlines, as shown in Fig. 9(a). To deliver a better distribution of the strain, variation of the strain along *the* y -axis is plotted in Fig. 9(c). It is clear that the strain at AS is more significant than that at RS, and the strain changes slowly at RS but steeply at AS.

Fig. 9 Material flow streamlines and strain distribution. (a) Streamlines on horizontal plane $z=4.0$ mm, (b) strain distribution on transverse cross-section of the weld, (c) variation of strain and temperature along the y -axis. ($N=600$ rpm, $v=90$ mm/min)

Figure 10 shows the effect of tool rotation speed on strain distribution on the transverse cross-section of the weldment. Fig. 10(a-d) shows the strain distribution when the rotation speed is 400, 600, 800, and 1000 rpm, respectively. The strain distribution for different tool rotation speeds is similar. The strain at AS is more significant than that at RS. The strain distribution close to the pin top and shoulder is extracted for further analysis. L_{z1} and L_{z2} are 0.5 mm and 5.5 mm from the bottom surface of the workpiece, respectively (Fig. 10a). Figures 10(e) and (f) show the distribution of strain along L_{z1} and L_{z2} . The strain increases with an increase in rotation

speed, which results from the rise in material flow velocity in the stir zone.

Fig. 10 Strain distribution under different tool rotation speeds. (a) 400 rpm, (b) 600 rpm, (c) 800 rpm, (d) 1000 rpm, (e) strain along L_{Z1} , (f) strain along L_{Z2} . ($v=90$ mm/min)

5.3. Heat generation and temperature field

Material softening during the FSW process is mainly due to temperature increase induced by frictional heat production. According to previous studies [28, 43], only about 4.4% of the total heat generation for FSW of aluminum alloy inside the workpiece is due to viscous heat dissipation, which is ignored in this study.

Figure 11 shows the distribution of wall heat flux on the tool-workpiece contact interface. It is clear that most heat generates on the shoulder, and the value of heat flux increases with an increase in distance from the tool axis and reaches the maximum value at the shoulder periphery. The heat flux at the leading side (LS) is more significant than that at the trailing side (TS), and the maximum value is 9.7×10^6 W/m². Figure 11(b) shows the variation of wall heat flux with distance from tool axis along lines (OA , AB , BC as in Fig. 11(a)) at AS. Heat production at contact interfaces consists of two parts: friction heat generation and plastic deformation heat generation. Heat production of two individual items is also drawn in Fig. 11(b). The heat generation by friction gradually

increases on the shoulder surface, especially at the shoulder periphery, due to the high relative movement between the tool and the workpiece. The heat generation by sticking gradually increases first, then quickly drops at the shoulder periphery. On the pin side surface, both heat production by friction and sticking increase first and then drop. However, the heat production by friction is significantly larger than that by sticking near the top of the pin, and the heat production by friction is less than that by sticking near the root of the pin. It implies that the sliding contact condition dominates near the pin top, and then the sticking condition dominates near the pin root. At the pin bottom surface, the heat production by friction is much greater than that by sticking, which indicates that the sliding contact condition dominates on the pin bottom surface.

Fig. 11 The distribution of wall heat flux on contact interface. (a) 3-D view, (b) variation of wall heat flux along lines (O - A - B - C , as shown in Fig. 11, (a)) in y -direction at AS. ($N=600$ rpm, $v=150$

mm/min)

Figure 12 shows wall heat flux as a function of tool rotation speeds. Figure 12(a) shows the monitored locations, and Fig. 12(b-d) shows the effect of direction and tool rotation speed on wall heat flux at the shoulder (L_3), the pin side surface (L_2), and the pin bottom surface (L_1), respectively. It is interesting to find that the distribution of wall heat flux is asymmetric around the tool axis. This asymmetry becomes more pronounced with an increase in tool rotation speed. The wall heat flux at RS is more significant than that at AS, and the wall heat flux at LS is more significant than that at TS. When the tool rotation speed is 800 rpm, the wall heat flux at AS, RS, LS, and TS on the pin side (L_2) are 3.45×10^6 , 3.54×10^6 , 3.67×10^6 , and 3.31×10^6 , respectively. The maximum value of wall heat flux occurs at the front part of RS. The value of wall heat flux increases with increased tool rotation speed due to the more significant relative velocity and more extensive plastic deformation. The maximum wall heat flux pin side surface (L_2) are 2.6×10^6 , 3.3×10^6 , 3.7×10^6 , and 4.1×10^6 , when the tool rotation speed is 400, 600, 800, and 1000 rpm, respectively.

Fig. 12 Variation of wall heat flux with rotation speed. (a) Schematic of the positions to monitor data, (b) on shoulder interface, (c) on the pin side surface, (d) on pin bottom surface. ($v=150$ mm/min)

Figure 13 (a) shows the predicted temperature field of the workpiece in 3-D view and transverse cross-section in 2-D view. The temperature field is asymmetric due to the translation and rotation of the tool, and the temperature at AS is slightly larger than that at RS. Figure 13(b) shows the variation of peak temperature with an increase in distance from weld centerline along line MN , as shown in Fig. 13(a). It is clear that peak temperature increases with increased tool rotation speed, but the gradient decreases.

Fig. 13 Predicted temperature field. (a) Temperature distribution in 3-D view ($N=600$ rpm, $v=150$ mm/min), (b) variation of peak temperature at a distance from weld centerline along the line (MN) in y -direction under different welding parameters. ($v=150$ mm/min)

To verify the accuracy of the simulation model, the simulated and measured temperature profiles vs. time are plotted in Fig. 14. It can be found that the predicted temperature profiles agree well with the experimentally measured ones under different welding parameters and pin profiles used in this study.

Fig. 14 Comparison between measured and predicted temperature profile under various welding parameters. (a) $N=400$ rpm, $v=60$ mm/min, (b) $N=600$ rpm, $v=60$ mm/min, (c) $N=800$ rpm, $v=60$ mm/min, (d) $N=800$ rpm, $v=150$ mm/min.

6. Conclusions

(1) Friction stir spot welding test was designed and carried out to measure the coefficient of friction on tool-workpiece contact interface under different tool rotation speeds. The boundary velocity of the workpiece material was obtained based on the stress state on the contact interface. The coefficient of friction and boundary velocity of the matrix were combined with the CFD model of FSW.

(2) On the tool-workpiece contact interface, the material velocity at the shoulder periphery and the lower part of the pin side is very low. Inside the workpiece around the tool, velocity distribution displays that material velocity at RS is more significant than that at AS.

(3) The strain on a particular point was obtained by integrating the strain rate and the streamline's reverse through this point. The actual strain of material represents a stepped shape as it flows from the front of the tool to the rear side.

(4) The nephogram of strain on the transverse cross-section of weldment displays that the strain at AS is more enormous than that RS. It increases as the distance from the shoulder surface decreases. The strain is less than 100 in most regions, but it can be larger than 100 or higher in some areas if the material flows through the rotation flow zone. The strain increases with an increase in tool rotation speed.

(5) Wall heat flux on the tool-workpiece contact interface at RS is more significant than that at AS, and the maximum value occurs at the front part of RS. At the shoulder surface, the heat flux due to sticking is more significant than friction on the inner region and inverse on the periphery. At the pin side surface, the heat flux due to friction is much larger than that of friction. Defects were susceptible to form at the pin side surface owing to inadequate material flow.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and materials

Not applicable

Code availability

Not applicable

Authors Contributions

Zhen Sun: Methodology; Formal analysis; Writing- Original draft preparation; Data Curation; Visualization; Funding acquisition.

Pengfei Liu: Validation; Methodology; Data Curation.

Xinghua Yu: Conceptualization; Validation; Writing - Review & Editing; Project administration.

Ethical Approval

Not applicable

Consent to Participate

Not applicable

Consent for publication

All the authors of the manuscript have read the paper, attested the validity of its contents, and agreed to its submission in *The International Journal of Advanced Manufacturing Technology*.

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References

- [1] Mishra RS, Ma ZY (2005) Friction stir welding and processing. *Materials science and engineering: R: reports* 50(1-2):1-78. <https://doi.org/10.1016/j.mser.2005.07.001>
- [2] Threadgill PL, Leonard AJ, Shercliff HR, Withers PJ (2009) Friction stir welding of aluminium alloys. *International Materials Reviews* 54(2):49-93. <https://doi.org/10.1179/174328009X411136>
- [3] Zhang YN, Cao X, Larose S, Wanjara P (2012) Review of tools for friction stir welding and processing. *Canadian Metallurgical Quarterly* 51(3):250-61. <https://doi.org/10.1179/1879139512Y.0000000015>
- [4] Dialami N, Chiumenti M, Cervera M, Segatori A, Osikowicz W (2017) Enhanced friction model for Friction Stir Welding (FSW) analysis: Simulation and experimental validation. *International Journal of Mechanical Sciences* 133:555-67. <https://doi.org/10.1016/j.ijmecsci.2017.09.022>
- [5] Dialami N, Cervera M, Chiumenti M, de Saracibar CA (2017) A fast and accurate two-stage strategy to evaluate the effect of the pin tool profile on metal flow, torque and forces in friction stir welding. *International Journal of Mechanical Sciences* 122:215-27. <https://doi.org/10.1016/j.ijmecsci.2016.12.016>
- [6] Dialami N, Cervera M, Chiumenti M, Segatori A (2019) Prediction of joint line remnant defect in friction stir welding. *International Journal of Mechanical Sciences* 151:61-9. <https://doi.org/10.1016/j.ijmecsci.2018.11.012>
- [7] Chen G, Li H, Wang G, Guo Z, Zhang S, Dai Q, Wang X, Zhang G, Shi Q (2018) Effects of pin thread on the in-process material flow behavior during friction stir welding: A computational fluid dynamics study. *International Journal of Machine Tools and Manufacture* 124:12-21. <https://doi.org/10.1016/j.ijmachtools.2017.09.002>
- [8] Schmidt H, Hattel J (2004) A local model for the thermomechanical conditions in friction stir welding. *Modelling and simulation in materials science and engineering* 13(1):77.
- [9] Hamilton C, Dymek S, Sommers A (2008) A thermal model of friction stir welding in aluminum alloys. *International journal of machine tools and manufacture* 48(10):1120-30. <https://doi.org/10.1016/j.ijmachtools.2008.02.001>
- [10] Qian JW, Li JL, Xiong JT, Zhang FS, Li WY, Lin X (2012) Periodic variation of torque and its relations to interfacial sticking and slipping during friction stir welding. *Science and Technology of welding and Joining* 17(4):338-41. <https://doi.org/10.1179/1362171812Y.0000000001>
- [11] Heurtier P, Jones M, Desrayaud C, Driver JH, Montheillet F, Allehaux D (2006) Mechanical and thermal modelling of friction stir welding. *Journal of materials processing technology* 171(3):348-57. <https://doi.org/10.1016/j.jmatprotec.2005.07.014>

- [12] Bastier A, Maitournam MH, Dang Van K, Roger F (2006) Steady state thermomechanical modelling of friction stir welding. *Science and Technology of Welding and Joining* 11(3):278-88. <https://doi.org/10.1179/174329306X102093>
- [13] Liechty BC, Webb BW (2008) Modeling the frictional boundary condition in friction stir welding. *International Journal of Machine Tools and Manufacture* 48(12-13):1474-85. <https://doi.org/10.1016/j.ijmachtools.2008.04.005>
- [14] Schmidt HN, Dickerson TL, Hattel JH (2006) Material flow in butt friction stir welds in AA2024-T3. *Acta Materialia* 54(4):1199-209. <https://doi.org/10.1016/j.actamat.2005.10.052>
- [15] Su H, Wu CS, Pittner A, Rethmeier M (2014) Thermal energy generation and distribution in friction stir welding of aluminum alloys. *Energy* 77:720-31. <https://doi.org/10.1016/j.energy.2014.09.045>
- [16] Colegrove PA, Shercliff HR (2005) 3-Dimensional CFD modelling of flow round a threaded friction stir welding tool profile. *Journal of materials processing technology* 169(2):320-7. <https://doi.org/10.1016/j.jmatprotec.2005.03.015>
- [17] Arora A, De A, DebRoy T (2011) Toward optimum friction stir welding tool shoulder diameter. *Scripta materialia* 64(1):9-12. <https://doi.org/10.1016/j.scriptamat.2010.08.052>
- [18] Li Q, Lovell M (2005) On the critical interfacial friction of a two-roll CWR process. *Journal of Materials Processing Technology* 160(2):245-56. <https://doi.org/10.1016/j.jmatprotec.2004.06.022>
- [19] Liu X, Chen G, Ni J, Feng Z (2017) Computational fluid dynamics modeling on steady-state friction stir welding of aluminum alloy 6061 to TRIP steel. *Journal of Manufacturing Science and Engineering* 139(5). <https://doi.org/10.1115/1.4034895>
- [20] Dirikolu MH, Childs TH, Maekawa K (2001) Finite element simulation of chip flow in metal machining. *International Journal of Mechanical Sciences* 43(11):2699-713. [https://doi.org/10.1016/S0020-7403\(01\)00047-9](https://doi.org/10.1016/S0020-7403(01)00047-9)
- [21] Kaufman JG (1999) Properties of aluminum alloys: tensile, creep, and fatigue data at high and low temperatures. ASM international
- [22] Chen G, Feng Z, Zhu Y, Shi Q (2016) An alternative frictional boundary condition for computational fluid dynamics simulation of friction stir welding. *Journal of Materials Engineering and Performance* 25(9):4016-23. <https://doi.org/10.1007/s11665-016-2219-9>
- [23] Hanaor DA, Gan Y, Einav I (2016) Static friction at fractal interfaces. *Tribology International* 93:229-38. <https://doi.org/10.1016/j.triboint.2015.09.016>
- [24] Sun Z, Wu CS (2018) A numerical model of pin thread effect on material flow and heat generation in shear layer during friction stir welding. *Journal of Manufacturing Processes* 36:10-21. <https://doi.org/10.1016/j.jmapro.2018.09.021>
- [25] Arora A, Nandan R, Reynolds AP, DebRoy T (2009) Torque, power requirement and stir zone geometry in friction stir welding through modeling and experiments. *Scripta Materialia* 60(1):13-6. <https://doi.org/10.1016/j.scriptamat.2008.08.015>
- [26] Shi L, Wu CS (2017) Transient model of heat transfer and material flow at different stages of friction stir welding process. *Journal of manufacturing processes* 25:323-39. <https://doi.org/10.1016/j.jmapro.2016.11.008>
- [27] Su H, Wu CS, Pittner A, Rethmeier M (2013) Simultaneous measurement of tool torque, traverse force and axial force in friction stir welding. *Journal of Manufacturing processes* 15(4):495-500. <https://doi.org/10.1016/j.jmapro.2013.09.001>

- [28] Nandan RG, Roy GG, Lienert TJ, Debroy T (2007) Three-dimensional heat and material flow during friction stir welding of mild steel. *Acta materialia* 55(3):883-95. <https://doi.org/10.1016/j.actamat.2006.09.009>
- [29] Sun Z, Wu CS, Kumar S (2018) Determination of heat generation by correlating the interfacial friction stress with temperature in friction stir welding. *Journal of manufacturing processes* 31:801-11. <https://doi.org/10.1016/j.jmapro.2018.01.010>
- [30] Follansbee PS, Kocks UF (1988) A constitutive description of the deformation of copper based on the use of the mechanical threshold stress as an internal state variable. *Acta Metallurgica* 36(1):81-93.
- [31] Aifantis EC (1987) The physics of plastic deformation. *International journal of plasticity* 3(3):211-47. [https://doi.org/10.1016/0749-6419\(87\)90021-0](https://doi.org/10.1016/0749-6419(87)90021-0)
- [32] Mises RV (1913) *Mechanik der festen Körper im plastisch-deformablen Zustand*. Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse (4):582-92.
- [33] Jones RM (2009) Deformation theory of plasticity. Bull Ridge Corporation
- [34] Schmidt H, Hattel J, Wert J (2003) An analytical model for the heat generation in friction stir welding. *Modelling and simulation in materials science and engineering* 12(1):143
- [35] Schmidt HB, Hattel JH (2008) Thermal modelling of friction stir welding. *Scripta Materialia* 58(5):332-7. <https://doi.org/10.1016/j.scriptamat.2007.10.008>
- [36] Schmidt H, Hattel JH (2008) Thermal and material flow modelling of friction stir welding using Comsol. In *Proceedings of the COMSOL Conference Hannover 2008*.
- [37] Nandan R, Roy GG, Debroy T (2006) Numerical simulation of three-dimensional heat transfer and plastic flow during friction stir welding. *Metallurgical and materials transactions A* 37(4):1247-59. <https://doi.org/10.1007/s11661-006-1076-9>
- [38] Groover MP (2020) *Fundamentals of modern manufacturing: materials, processes, and systems*. John Wiley & Sons
- [39] Liu XC, Sun YF, Nagira T, Ushioda K, Fujii H (2019) Experimental evaluation of strain and strain rate during rapid cooling friction stir welding of pure copper. *Science and Technology of Welding and Joining* 24(4):352-9. <https://doi.org/10.1080/13621718.2018.1556436>
- [40] Arora A, Zhang Z, De A, DebRoy T (2009) Strains and strain rates during friction stir welding. *Scripta Materialia* 61(9):863-6. <https://doi.org/10.1016/j.scriptamat.2009.07.015>
- [41] Zhao C, Liu X (2020) Computational Analysis on Weld Formation Mechanism during Self-Reacting Friction Stir Welding. *Journal of Manufacturing Science and Engineering* 1-5. <https://doi.org/10.1115/1.4048856>
- [42] Morisada Y, Imaizumi T, Fujii H (2015) Determination of strain rate in friction stir welding by three-dimensional visualization of material flow using X-ray radiography. *Scripta Materialia* 106:57-60. <https://doi.org/10.1016/j.scriptamat.2015.05.006>
- [43] Carslaw H, Jaeger J (1959) *Conduction of heat in solids*: Oxford Science Publications