Thermomechanical analysis of friction stir welding 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 interface under different tool rotational speeds. The boundary velocity of the workpiece material was calculated based on the stress state of the material on the interface. An integrated computational fluid dynamics (CFD) model of friction stir welding (FSW) was established based on the coefficient of friction and boundary velocity of matrix 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 decreases. Strain in some regions can be tremendous if the material flows through the rotation flow zone. Wall heat flux on the tool-workpiece interface at RS is more significant than 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

Abbreviations

| Symbol | Description |
|--------|-------------|
| $M_t$ | Tool torque |
| $M_{t,\text{max}}$ | Maximum tool torque |
| $M_w$ | The output torque of the motor |
| $M_{w,0}$ | No-load torque of the motor |
| $\delta$ | Slip rate |
| $\tau_y$ | Shear yield stress |
| $\tau_f$ | Friction stress |
| $\tau_t$ | Deformation stress threshold |
| $\mu_f$ | Coefficient of friction |
| $p_n$ | Normal-pressure |
| $p_{n,\text{max}}$ | Maximum normal pressure |
| $F_n$ | Tool axial force |
| $F_{n,\text{max}}$ | Maximum tool axial force |
| $C$ | The lead of the guide screw |
| $N$ | Tool rotation speed |
| $\nu$ | Welding speed |
| $\omega_m$ | Angular velocity of matrix |
| $\omega_t$ | Angular velocity of the tool |
| $v_m$ | Matrix velocity |
| $v_t$ | Tool velocity |
| $\sigma_y$ | Yield stress |
| $\sigma_f$ | Flow stress |
| $\varepsilon$ | Strain |
| $\dot{\varepsilon}$ | Effective strain rate |
| $t$ | Time |
| $r$ | Radius |
| $R_S$ | Shoulder radius |
| $\eta_M$ | Transmission efficiency |

1 Introduction
Friction stir welding (FSW) is a novel green and sustainable manufacturing technology due to its advantages, including energy efficiency, environmental friendliness, and high weld quality. There is an increasing demand for fabricating critical components using FSW [1, 2]. 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]. The friction and boundary velocity of the workpiece material at the tool-workpiece interface determine the heat generation due to friction and plastic deformation. Therefore, it is crucial to investigate friction behaviour on the tool-workpiece interface and boundary velocity of the workpiece material 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 condition between tool and workpiece. Numerical simulation has been generally recognized to investigate the thermal–mechanical process in FSW quantitatively. 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. It is generally believed that Coulomb’s law of friction can describe the contact friction behaviour between tool and workpiece. 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. Recently, Amini et al. [11] proposed a FEM model of FSW enriched by estimating the coefficient of friction under various system variables like temperature, velocity, atmosphere, and interface geometric properties [24]. 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. These parameters can be used to calculate the coefficient of friction suitable for FSW according to the relationship with the forces of the tool. The predicted coefficient of friction is combined with the CFD model of FSW. The boundary velocity of the workpiece material can be determined based on the friction driving effect of the tool on the workpiece material. The friction and boundary velocity of workpiece material can be applied to our previous three-dimensional CFD model of FSW [25]. Plastic material flow, heat generation, temperature field, and plastic strain are examined with numerical simulation. The predicted temperature profile of specific locations and weld’s macrostructure are verified with corresponding independent experimental results.

2 Determination of the coefficient of friction

2.1 Experimental scheme

A friction stir spot welding (FSSW) experiment was designed and carried out on AA6061-T6 plates with 6 mm in thickness to measure the coefficient of friction under various tool rotational speeds. The chemical composition of the base metal has been detailed in Table 1. A tool with a 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

### Table 1 Chemical composition of workpiece AA6061-T6

| Element | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| Weight% | 0.65| 0.32| 0.29| 0.09| 0.92| 0.09| 0.01| Balanced |
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 shown in Fig. 1. Tool plunges to ensure that the workpiece material and the tool surface are instantaneously fitted when the tool plunges again (stage 1); tool returns to ensure the same temperature on the contact interface before the next contact (stage 2). Tool plunges again to monitor and record the force of the tool when the tool comes into contact with the workpiece (stage 3). The tool rotates in situ to monitor the tool force when temperature increases due to friction (stage 4).

The current FSSW experiments aim to obtain tool torque and 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 conducted to validate the numerical model. The workpiece dimensions are 200 mm (length) \( \times \) 75 mm (width). The plunge depth is 0.1 mm, and the tool tilt angle keeps at 2.5°. The dimension of the tool used in FSW is the same as that used in FSSW. The welding parameters used during FSW are shown in Table 2. The rotational speeds are 400, 600, 800, and 1000 rpm and the welding speeds are 60, 90, and 150 mm/min. K-type thermocouples, which were embedded into the workpiece for temperature measurement, were located at both AS and RS are at a distance of 10, 20, and 30 mm away from the weld centreline. They are located at the middle in a longitudinal direction along \( x \). The end of thermocouples was all at a depth of 3.0 mm from the top surface of the workpiece.

### Table 2

| Rotational speed (rpm) | 400 | 600 | 800 | 1000 |
|------------------------|-----|-----|-----|------|
| Welding speed (mm/min) | 60  | 90  | 150 | 60   |
| Temperature measurement| ✓   | x   | ✓   | x    |

#### 2.2 Coefficient of friction

According to the study of the Arora et al. [26] and Shi and Wu [27], tool torque can be calculated from the shear yield strength of the workpiece material and friction stress on the tool-workpiece interface, which is expressed below:

\[
M_t = \int_A r \times [\delta \tau_y + (1 - \delta) \mu_f p_n] dA
\]

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

\[
p_n = \frac{F_n}{\pi R_s^2}
\]

where \( F_n \) is the measured tool axial force and \( R_s \) 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 simultaneously. The maximum value of axial force \( F_{n_{\text{max}}} \) and torque \( M_{t_{\text{max}}} \) can be obtained by setting the boundary velocity of the workpiece to zero. As a result, the tool torque is determined only by friction on the contact interface. Therefore, tool torque can be expressed as below:

\[
M_{t_{\text{max}}} = \int_A r \times \mu_f p_{n_{\text{max}}} dA = \mu_f p_{n_{\text{max}}} \cdot \frac{2}{3} \pi R_s^3
\]

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

\[
\mu_f = \frac{3M_{t_{\text{max}}}}{2F_{n_{\text{max}}}R_s}
\]
The electric signal of the spindle motor in \( x \), \( y \), and \( z \) are monitored, and the sensor measured the torque of each motor. In the study of Su et al. [28], the method of measuring axial force and torque has been elaborated. The following formula can calculate tool axial force during welding:

\[
F_n = 2\pi \eta_M \cdot \frac{M_w - M_{w0}}{C}
\]  

(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, and \( \eta_M \) 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 3. Tool axial force variation is minimal despite welding parameter change. Therefore, tool axial force was considered a constant in this study. It is the average value under different welding parameters in the experiment. However, the tool torque decreases as rotational speed increases.

Bring the measured data of tool force into Eq. (4), the coefficient of friction under different rotational speeds can be obtained, plotted in Fig. 2. It is easy to find that the coefficient of friction decreases with an increase in rotational speed, which is in line with Nandan et al. [29]. The relationship between the coefficient of friction and rotational speed can be fitted to the following formula according to the experimental results as shown in Fig. 2:

\[
\mu_f = 5.005 \times 10^{-5} \cdot \omega^2 - 0.01109 \cdot \omega + 0.9759
\]  

(6)

### 3 Determination of boundary velocity and strain

#### 3.1 Determination of velocity on tool-workpiece interface

The stress state of the workpiece material adjacent to the tool surface can be considered a pure shear stress 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 [30–33]. The workpiece material at the interface is mainly subjected to two forces. One is the relative movement between the tool and the workpiece. The other is the magnitude of friction stress \( \tau_f \) and deformation stress threshold \( \tau_y \).

For convenience, slip rate, \( \delta \), is defined to describe the contact state at the tool-workpiece interface, which is given by [8, 16]:

\[
v_m = \delta \cdot v_i
\]  

(7)

where \( v_m \) and \( v_i \) are the velocity of the workpiece material and the tool at the contact interface, respectively.

In the study of Schmidt et al. [34], the full sliding, full 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 4.

Material shear yield stress \( (\tau_y) \) is considered equal to the deformation stress threshold. This study shows the method of determining the workpiece boundary velocity in Fig. 3. When the workpiece material velocity is less than the tool velocity and the friction stress is larger than the deformation stress threshold, the workpiece material will be accelerated.

### Table 3 Experimental results of force during FSSW experiments

| Rotational speed \( N \) (rpm) | 400  | 500  | 600  | 700  | 800  | 900  | 1000 |
|-------------------------------|------|------|------|------|------|------|------|
| Maximum tool torque \( M_{t_{max}} \) (N·m) | 38.95 | 37.16 | 33.24 | 27.07 | 22.16 | 19.54 | 16.81 |
| Maximum axial force \( F_{z_{max}} \) (N) | 11,156 |      |      |      |      |      |      |

### Table 4 Definition of contact condition, velocity/shear relationship, and slip rate [34]

| Condition            | Matrix velocity | Tool velocity | Shear stress | Slip rate |
|----------------------|-----------------|---------------|--------------|-----------|
| Full sticking        | \( v_m = v_i \) | \( v_i = \omega r \) | \( \tau_f > \tau_y \) | \( \delta = 1 \) |
| Sticking/sliding     | \( 0 < v_m < v_i\) | \( v_i = \omega r \) | \( \tau_f \geq \tau_y \) | \( 0 < \delta < 1 \) |
| Full sliding         | \( v_m = 0 \)   | \( v_i = \omega r \) | \( \tau_f < \tau_y \) | \( \delta = 0 \) |

Fig. 2 Variation of coefficient of friction with rotational speed
When the friction stress is less than the deformation stress threshold, the workpiece material velocity decreases. Finally, the workpiece material velocity will reach a stable value. 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]:

\( \tau_f = \tau_y \) (8)

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 modelling.

### 3.2 Method to calculate strain based on CFD simulation results

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 [37]. As a result, it is crucial 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 study, the distribution of strain across the transverse cross-section of the weld is calculated, combining the methods proposed by Arora et al. [38] and Zhao and Liu [39] in the simulation of FSW and by Liu et al. [37] and Morisada et al. [40] in experimental analysis.

In the CFD model of FSW, the strain rate of a point in the computational domain is easy to be obtained [25, 41]. If we know the streamline of the point, the strain can be obtained by integrating the strain rate against time along the streamline:

\[
\varepsilon = \int_{t_0}^{t} \dot{\varepsilon} \, dt
\]

(9)

The method to accumulate the strain is shown in Fig. 4. The streamline passing the point should be calculated before the strain was obtained. As shown in Fig. 4, 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 below:

\[
dt = \frac{ds}{v_i}
\]

(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:

\[
d\varepsilon_i = \dot{\varepsilon}_i \cdot dt
\]

(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:
The total strain of this streamline is:

\[ \varepsilon_j = \sum_{i=0}^{i=j} \frac{d\varepsilon}{v_i} \] (12)

The effective strain rate can be given as [40]:

\[ \dot{\varepsilon} = \sum_{i=0}^{i=n} \varepsilon_i \cdot \frac{d\varepsilon}{v_i} \] (13)

The total strain of this streamline is:

\[ \varepsilon = \sum_{i=0}^{i=n} \varepsilon_i \cdot \frac{d\varepsilon}{v_i} \]

The effective strain rate can be given as [40]:

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

4 Mathematical model

Figure 5 shows the schematic of the geometric model of the FSW experiment. The origin of the coordinate locates at the intersection of the tool centre 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 [41].

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 \( \tau \) was assumed to be \( \sqrt{3} \) times of the yield stress \( (\sigma_y) \) which is approximately equal to the flow stress \( (\sigma_f) \) of the material here [42].
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 and Wu [25].

The density of AA6061 is taken as 2700 kg/m³. The mechanical and thermal properties of base metal required during CFD simulation are considered temperature-dependent, shown in Fig. 6. Temperature-dependent mechanical property (yield stress) is shown in Fig. 6a [22], and the thermal properties (thermal conductivity, \( k \), and heat capacity, \( c_p \)) are shown in Fig. 6b [18].
5 Results and discussion

5.1 Material flow velocity field

Figure 7 shows the velocity field on the tool-workpiece interface and into the workpiece near the tool. It is easy to find that velocity on the shoulder is much larger than that on the pin side and bottom surfaces. The maximum velocity value occurs on the shoulder but not at the maximum radius of the shoulder. The 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 low, 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. [23].

To clarify the influence of tool rotational speed on velocity on the tool-workpiece interface, velocity along lines (OA, AB, BC as shown in Fig. 7) in y-direction at AS under different tool rotational speeds are plotted shown in Fig. 8. It is easy to find that the contact condition in almost all regions is partial sticking/sliding ($0 < v_m < v_t$). Full sticking condition ($v_m = v_t$) and full sliding condition ($v_m = 0$) between the tool and the workpiece are challenging to reach. In general, the velocity of the workpiece material increases with an increase in tool rotational speed. On the pin side surface, material velocity near the pin top is very low for all tool rotational speeds, especially when the rotational speed is low. It indicates that material flow here is insufficient and may induce welding defects.

Figure 9 shows the variation of material velocity with angle around tool axis under different tool rotational speeds. As shown in Fig. 9a ($L_{R1}$, $L_{R2}$, 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 rotational speed for all monitoring positions. Velocity distribution near the shoulder surface is almost symmetric to the tool axis and varies little when $\theta$ changes from 0 to 360° for four different tool rotational speeds (Fig. 9b). When tool rotational speed is 800 rpm, the maximum and minimum velocity magnitude are 257.1 mm/s and 249.2 mm/s, respectively.

Interestingly, velocity magnitude at RS is much larger than that at AS near pin side and pin bottom surfaces, as
The rotational of the tool at 800 rpm provides the maximum value of velocity magnitude at the near pin side surface, which is 40.6 mm/s. It occurs at RS and its value is about 1.5 times that at AS (26.0 mm/s), as shown in Fig. 9c. The values in the same meaning near pin bottom surface, as shown in Fig. 9d, are 16.0 mm/s at RS and 7.1 mm/s at AS. The difference in velocity at AS and RS could be induced by the difference in the direction of friction stress. The friction stress of the tool on the workpiece is opposite to the welding direction 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

Figure 10 shows the streamline’s velocity distribution, effective strain rate, and strain. The variation of velocity magnitude is divided into two distinct stages. At the leading side (x < 0), the material is accelerated due to the tool’s drive 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 effective strain rate definition, 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 shown in Fig. 10 is a 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 11 shows the material flow streamlines and strain distribution. As shown in Fig. 11a, 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. 11a, b, it can be found that the strain in the region where the deformation of the streamline is more significant 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. 11a. To deliver a better distribution of the strain, variation of the strain along the y-axis is plotted in Fig. 11c. 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.

Figure 12 shows the effect of tool rotational speed on strain distribution on the transverse cross-section of the weldment. Figure 12a–d shows the strain distribution when the rotational speed is 400, 600, 800, and 1000 rpm, respectively. The strain distribution for different tool rotational 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. 12a). Figure 12e, f shows the strain distribution along \( L_{z1} \) and \( L_{z2} \). The strain increases with an increase in rotational speed, which results from the rise in material flow velocity in the stir zone.

Fig. 9 Variation of material velocity with rotational speed. a Schematic of the positions to monitor data, b near shoulder interface, c near pin side surface, d near pin bottom surface. (\( r = 150 \) mm/min)
Fig. 10 Distribution of strain, material flow velocity, and effective strain rate in x-direction on plane z=4.0 mm (N=600 rpm, v=90 mm/min)

Fig. 11 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)
5.3 Material flow streamlines and plastic strain field

Material softening during the FSW process is mainly due to temperature increase induced by heat generation on the tool-workpiece interface. According to previous studies [29, 43], only about 4.4% of the total heat generation for FSW of aluminium alloy inside the workpiece is viscous heat dissipation. Therefore, the heat generation inside the workpiece is not investigated, and only the heat generation at the tool-workpiece interface is investigated emphatically following this study.

Figure 13 shows the distribution of wall heat flux on the tool-workpiece 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 $9.7 \times 10^6$ W/m$^2$. Figure 13b shows the variation of wall heat flux with distance from tool axis along lines (OA, AB, BC as in Fig. 13a) at AS. Heat production at contact interfaces consists of friction heat generation and plastic deformation heat generation. Heat production of two individual items is also drawn in Fig. 13b. 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 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. Both heat production by friction and sticking increase on pin side surface 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.

Figure 14 shows wall heat flux as a function of tool rotational speed. Figure 14a shows the monitored locations, and Fig. 14b–d shows the effect of direction and tool rotational 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 rotational 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 rotational speed is 800 rpm, the wall heat flux at AS, RS, LS, and TS on the pin side ($L_2$) are $3.45 \times 10^6$, $3.54 \times 10^6$, $3.67 \times 10^6$, and $3.31 \times 10^6$ W/m$^2$, 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 rotational speed due to the more significant...
relative velocity and more extensive plastic deformation. The maximum wall heat flux near pin side surface \((L_2)\) are \(2.6 \times 10^6, 3.3 \times 10^6, 3.7 \times 10^6, \) and \(4.1 \times 10^6\) W/m², when the tool rotational speed is 400, 600, 800, and 1000 rpm, respectively.

Figure 15a 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 15b shows the variation of peak temperature with an increase in distance from weld centreline along line \(MN\), as shown in Fig. 15a. It is clear that peak temperature increases with increased tool rotational speed, but the gradient decreases.

To verify the accuracy of the simulation model, the simulated and measured temperature profiles vs. time are plotted in Fig. 16. It can be found that the predicted temperature profiles agree well with the experimentally measured ones under different welding parameters.
Fig. 15  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 centreline along the line ($MN$) in $y$-direction under different welding parameters. ($v = 150$ mm/min)
Conclusions

1. Friction stir spot welding test was designed and carried out to measure the coefficient of friction on tool-workpiece interface under different tool rotational 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 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 at 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 rotational speed.

5. Wall heat flux on the tool-workpiece 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 sticking. Due to inadequate material flow, defects were susceptible to form at the pin side surface.

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Fig. 16 Comparison between measured and predicted temperature profile under various welding parameters. a $N = 400 \text{ rpm}$, $v = 60 \text{ mm/min}$; b $N = 600 \text{ rpm}$, $v = 60 \text{ mm/min}$; c $N = 800 \text{ rpm}$, $v = 60 \text{ mm/min}$; d $N = 800 \text{ rpm}$, $v = 150 \text{ mm/min}$
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Declarations

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