Simulation on Temperature Field of Friction Stir Welding of 2A14 Aluminum Alloy Based on Equivalent Film Method

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**Abstract.** Backing plate has an important influence on the temperature field of workpiece during the friction stir welding process. In order to predict the temperature field of workpiece accurately, a thermal-fluid coupled friction stir welding calculation model including workpiece and backing plate was developed. In the model, an equivalent film method was proposed to simplify the contact heat transfer between workpiece and backing plate to a heat conduction problem. The computational fluid dynamic software FLUENT was utilized to simulate the friction stir welding process of 2A14 aluminum alloy. As a result, the steady-state temperature field during the friction stir welding process was predicted and analyzed. The welding process test was carried out to verify the simulation results of temperature field. The compared results show that the simulated temperature and the measured values of all measuring points are in good agreement. Using the simulation method proposed in this paper, the calculation accuracy of temperature field during the friction stir welding process could be relatively high and the maximum error is 4.61%. In addition, there is a good corresponding relationship between the temperature distribution and the various regions of weld cross section.

**Introduction**

Friction stir welding (FSW) is a kind of advanced solid-state joining technique which has been widely applied in aerospace, high-speed train, ship and other fields. In order to understand the welding mechanism of FSW in depth, master the welding rule and guide the actual production, since the invention of FSW, a lot of researches have been completed. Among them, the prediction and analysis of temperature field is the basis. At present, the researchers have developed various models to simulate the temperature field during FSW [1-5]. There is contact heat transfer between workpiece and backing plate during FSW, which has an important influence on the temperature field of workpiece. Due to the complexity of contact heat transfer problem, it’s difficult to measure the thermal contact conductance. Although the vast majority of researchers considered the heat dissipation effect of backing plate in modeling, they simplified the contact heat transfer between workpiece and backing plate to a convective heat transfer problem. In their models, only the workpiece was included, while the backing plate was ignored. Furthermore, the temperature of backing plate was set at room temperature [3-5], which exaggerated the heat dissipation effect of backing plate during welding, but ignored its heat preservation effect during cooling. Consequently, the simulation accuracy of the temperature field of the existing FSW models is relatively low.

In this study, a thermal-fluid coupled calculation model was developed to predict and analyze the steady-state temperature field during FSW using FLUENT. In the model, an equivalent film method was proposed to simplify and solve the contact heat transfer problem between workpiece and backing plate. The welding process test was conducted to verify the simulation results of temperature field.
Thermal-fluid Coupled Model of FSW

According to the material plastic flow characteristics during FSW, workpiece material is assumed as single-phase incompressible non-Newtonian fluid. The coordinate system to describe FSW is shown in Fig. 1. The intersection of the welding tool axis and the bottom surface of workpiece is set as the origin of coordinate. X-axis and the welding direction are accordant, and Z-axis is consistent with the normal direction of the top surface of workpiece.

Fig. 1 Schematic of friction stir welding.

Materials. In this study, the workpiece material is 2A14 Aluminum Alloy and the welding tool material is W6 alloy. Thermal properties used in FSW simulation include thermal conductivity, density and specific heat.

Methods. During FSW, the heat is mainly generated from the friction heat between welding tool and workpiece and the plastic deformation heat. In the study, a welding tool with flat shoulder and conical pin was adopted and the friction heat can be expressed as [6, 7]:

\[
q = \left[ \beta_1 \delta \tau_y + (1 - \delta) \mu_f P \sin \alpha \right] \left( \omega r - U \sin \theta \right)
\]

where, \( q \) is the heat flux density; \( \beta_1 \) is the work to heat conversion efficiency; \( \delta \) is the slip coefficient; \( \mu_f \) is the friction coefficient; \( \alpha \) is the angle between contact interface element and Z-axis; \( \omega \) is the angular velocity of welding tool, \( \omega = \pi n / 180 \), \( n \) is the rotation speed of welding tool; \( r \) is the distance from contact interface element to welding tool axis; \( U \) is the welding speed; \( \theta \) is the angle between the line from contact interface element to welding tool axis and the welding direction; \( \tau_y \) is the shear strength of workpiece material. According to Von Mises yield criterion, \( \tau_y = 0.577 \sigma_y \), and \( \sigma_y \) is the yield stress of workpiece material; \( P \) is the axial pressure acting on contact interface. In the study, \( P = F / (\pi R_S \times R_S) \), \( F \) is the axial force and \( R_S \) is the shoulder radius.

Plastic deformation heat, as the heat released by the plastic deformation of the material within the shear layer near the contact interface between workpiece and welding tool, can be defined as [8]:

\[
\Phi = \beta_2 \gamma [2 \left( \frac{\partial u}{\partial x} \right)^2 + 2 \left( \frac{\partial v}{\partial y} \right)^2 + 2 \left( \frac{\partial w}{\partial z} \right)^2 + \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial x} + \frac{\partial v}{\partial z} \right)^2 + \left( \frac{\partial w}{\partial y} + \frac{\partial v}{\partial x} \right)^2]
\]

where, \( \beta_2 \) is the work to heat conversion efficiency and \( \gamma \) is the viscosity dissipation coefficient.

Different from the previous studies, both workpiece and backing plate were included in the model, as shown in Fig. 2, which is consistent with the actual situation. During FSW, the heat due to convection and radiation can be calculated:

\[
-k \frac{\partial T}{\partial n_S} = \sigma_b \varepsilon_b (T^4 - T_a^4) + h_{\text{con}} (T - T_a)
\]

where, \( n_s \) is the normal direction of heat dissipation surface; \( \sigma_b \) is Steve Boltzmann constant; \( \varepsilon_b \) is the emissivity; \( T_a \) is the ambient temperature; \( h_{\text{con}} \) is the convective heat transfer coefficient.

During FSW, the bottom surface of workpiece and the backing plate are in contact, which has an important influence on the temperature field of workpiece. In fact, because the solid surface is rough, the actual contact area between them is only 1%-2% of the nominal contact area [9], while the other region is filled with air, resulting in thermal contact resistance, as shown in Fig. 3. Due to the
limitation of software FLUENT, there is no interface to set the thermal contact resistance directly, so a new method was proposed to simplify and solve the contact heat transfer problem between workpiece and backing plate. With the method, a layer of thin film material with relatively low thermal conductivity is added at the interface to simulate the contact heat transfer between workpiece and backing plate. The heat can be exchanged between workpiece and backing plate through the thin film. The low thermal conductivity of thin film material plays the same role as the thermal contact resistance and the thermal conductivity of thin film material is defined as:

$$k_{film} = tcc \times \delta_{film}$$  \hspace{1cm} (4)

where, $\delta_{film}$ is the thickness of thin film and $tcc$ is the thermal contact conductance between workpiece and backing plate. Zhu D.C. et al [10] measured the equivalent thermal contact conductance between aluminum alloy and die steel by a self-developed experimental platform, which provides $tcc$ reference values to us.

![Fig. 2 Boundary conditions.](image)

![Fig. 3 Simplification of contact heat transfer problem.](image)

The inlet velocity is set on the side of workpiece as shown in Fig. 2. The value of inlet velocity is equal to the welding speed and its direction is opposite to the welding direction. The outlet pressure is set on another side of workpiece (Fig. 2). In addition, due to the partial slip between workpiece and welding tool, the rotation speed of workpiece material at the contact interface is the product of the rotation speed of welding tool and the slip coefficient.

In this study, the workpiece material was 2A14 Aluminum Alloy, the welding tool material was W6 alloy, and the backing plate material was Q235. Thermal properties used in FSW simulation include thermal conductivity, density and specific heat. According to the above heat source model, in order to accurately calculate the shear friction heat, the yield stress of workpiece material must be provided. Because, the yield stress is approximately equal to the material flow stress [11], the flow stress constitutive model of 2A14 aluminum alloy was established using flow stress instead of yield stress [12]:

$$\sigma(T, \dot{\varepsilon}) = \frac{1}{\eta} \ln \left( \left( \frac{Z(T, \dot{\varepsilon})}{A} \right)^{\frac{1}{n_1}} + 1 + \left( \frac{Z(T, \dot{\varepsilon})}{A} \right)^{\frac{1}{n_1}} \right)^{\frac{1}{2}}$$  \hspace{1cm} (5)

where, $T$ is the temperature; $\dot{\varepsilon}$ is the strain rate; $\eta$, $A$ and $n_1$ are the material constants, and $Z$ refers to Zenner-Hollomon factor:
\[ Z(T, \dot{\varepsilon}) = \varepsilon \cdot \exp \left( \frac{Q}{RT} \right) \]  

(6)

where, \( Q \) refers to the activation energy and \( R \) represents the gas constant.

In addition, the viscosity, flow stress and strain rate of deformed material has the following relationship [7, 8]:

\[ \mu = \frac{\sigma}{3\varepsilon} \]  

(7)

**Results and Analysis**

The steady-state temperature field of 2A14 aluminum alloy plate during FSW was simulated using FLUENT. In the simulation, the size of workpiece is 0.3m×0.15m×0.0063m and the backing plate is simplified to a cuboid with the size of 0.7m×0.55m×0.07m. The meshes are divided using the four node tetrahedral element and a total of 464470 nodes and 2259525 elements are generated. During simulating, the material constants and welding parameters are shown in Table 1.

| Constant/Parameter | Value            | Constant/Parameter | Value            |
|--------------------|------------------|--------------------|------------------|
| \( U \) [m/s]      | 0.00167          | \( n \) [r/min]   | 600              |
| \( F \) [N]        | 10000            | \( \mu_{film} \) [m] | 0.001            |
| \( \delta \)       | 0.20             | \( \mu_f \)       | 0.35             |
| \( \gamma \)       | 0.05             | \( \beta_1, \beta_2 \) | 0.95             |
| \( T_a \) [K]      | 300              | \( \epsilon_b \)  | 0.40             |
| \( h_{con} \) [W/m²K] | 20               | \( \sigma_b \) [J/K⁴m²s] | 5.67×10⁻⁸      |
| \( A \) [s⁻¹]      | 3.25×10⁸         | \( R \) [J/mol K] | 8.314            |
| \( \eta \) [Pa⁻¹]  | 1.6×10⁸          | \( Q \) [J/mol]   | 148880           |
| \( n_1 \)          | 4.27             |                    |                  |

**Table 1 Material constants and welding parameters in the model [5].**

Fig. 4 shows the simulated steady-state temperature field. It can be seen that the highest temperature appears in the vicinity of shoulder, about 700K which is below the melting point (900K) of 2A14 aluminum alloy. At this point, the workpiece material is still solid, indicating that FSW is a solid-state welding process and there exists no melting welding defects, which reflects the advantages of FSW. In addition, in general, the temperature field is distributed symmetrically along the weld center. However, in local small range near the shoulder of welding tool, temperature field is not entirely symmetrical. The temperature on the advancing side is higher than that on the retreating side, and the temperature behind welding tool is higher than that in front of welding tool. Furthermore, the isotherm distribution behind welding tool is sparse and the isotherm in front of welding tool is distributed densely.

![Fig. 4 Steady-state temperature field.](image)
In order to verify the simulation accuracy of temperature field, the welding process test was conducted by a self-developed FSW equipment. Six thermocouples were used to measure the temperature on the advancing side and the retreating side during the welding process, respectively. Table 2 shows the simulated temperature and the measured values. The compared results show that the simulated temperature and the measured one of all measuring points are in good agreement and the maximum relative error is 4.61%, which indicates the simulation results are accurate.

| Measuring Point | Coordinate | Measured Value | Simulated Value | Relative Error |
|-----------------|------------|----------------|-----------------|----------------|
| P1              | 0 -0.013   | 0.0062 565.65  | 541.92          | 4.20           |
| P2              | 0 -0.023   | 0.0062 491.65  | 469.00          | 4.61           |
| P3              | 0 -0.033   | 0.0062 444.25  | 434.65          | 2.16           |
| P4              | 0 0.013    | 0.0062 529.55  | 540.89          | 2.14           |
| P5              | 0 0.023    | 0.0062 468.85  | 468.60          | 0.05           |
| P6              | 0 0.033    | 0.0062 441.55  | 434.43          | 1.61           |

Fig. 5 shows the comparison between the metallographic of weld cross section and the simulated temperature field. It can be seen that, according to the microstructure characteristics, the weld can be divided into the weld nugget zone (WNZ), the thermo mechanically affected zone (TMAZ), the heat affected zone (HAZ) and the parent metal zone (BMZ) away from the weld, which is mainly induced by the different temperature and strain rate in the various regions. In addition, there is a good corresponding relationship between temperature distribution and various regions, which verifies the simulation results indirectly.

**Summary**

(1) In this paper, an equivalent film method was proposed to simply the contact heat transfer between workpiece and backing plate to a simple heat conduction problem, which made the FSW calculation model more close to the real situation.

(2) Using the simulation method proposed in this paper, the calculation accuracy of temperature field during FSW could be relatively high and the maximum error is 4.61%.

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