Temperature distribution and mechanical properties of FSW medium thickness aluminum alloy 2219

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Abstract
Friction stir welding (FSW) is a solid-state jointing technology, and has the advantages of high joint strength, low residual stress, and small deformation after welding. During FSW, the welding temperature directly influences the quality of the weldment. A heat generation model of FSW medium thickness aluminum alloy 2219 is established considering the friction heat generated at the interface between the tool and the workpiece and the plastic deformation heat of the weldment material near the tool. The heat transfer model is set considering heat conduction, convection, and radiation. Using JMatPro technology, temperature-related material parameters of aluminum alloy 2219 are obtained. The built heat generation model is imported into the simulation software ABAQUS through the DFLUX subroutine, and the simulation of FSW process is achieved. The effectiveness of the simulation is verified by FSW experiments. The simulation has high prediction accuracy. Based on the simulation, the influence of welding parameters on temperature distribution is explored; subsequently the influence of welding temperature on mechanical properties of welded joint is also studied. The research guides the prediction of the temperature distribution and the improvement of the mechanical performance of FSW medium thickness aluminum alloy 2219.

Keywords FSW · Temperature field · Mechanical properties · Aluminum alloy 2219 · Medium thickness

1 Introduction
The diameter of a heavy-lift launch vehicle storage tank is up to 10 m, and the thickness of it is up to 18 mm. Friction stir welding (FSW) is the main welding assembly technique for its advantages such as pollution-free, smoke-free, no radiation, high welding efficiency, small deformation, and excellent weld mechanical properties [1].

FSW is a solid-state jointing technology invented by the British Welding Research Institute in 1991 [2], which can weld flat, cylindrical circular, and spatial curved seams. It is a challenge for FSW to weld 18-mm thick aluminum alloy 2219. The thermal input is large, the temperature difference in weld thickness direction is large, and then the strengthening phase re-dissolution and the microstructure and properties of the weld are different in thickness direction, which makes it difficult to obtain high connection strength. Temperature distribution in the FSW process affects the welding quality [3]. To ensure the connection strength of FSW medium thick 2219, it is important to study the temperature distribution in the welding process.

The research on temperature field during FSW includes experimental, simulation, and analytical methods. In the
FSW process, it is difficult to obtain the temperature distribution over the weldment through experimental methods because of the shielding of the tool shoulder, the flow of the weldment material, and the severe plastic deformation. Simulation methods become a feasible means if analyzing the FSW process, but it cannot reveal the heat generation mechanism of the welding process. The analytical method can only not quickly obtain the temperature distribution of the weldment, but also reveal the heat generation mechanism of the FSW process. Therefore, the analytical method is used in this paper to study the FSW temperature field and further explore the influence of the temperature distribution on the mechanical properties of the FSW process. Relevant experts and scholars have conducted a lot of research on the modeling of FSW temperature using analytical methods. The heat source model of the FSW process was first described by the similar to Rosenthal analytical method of a uniformly moving point heat source or a linear heat source [4, 5]. McClure et al. [4] used Rosenthal analysis method in 1998 to conduct a preliminary analysis of heat transfer in the FSW process. Since the weldment was assumed to be the heat conduction problem of a semi-infinite object, the accuracy of the simulation results was low, but the proposal of this method opened up a new way for the study of the FSW temperature field. Later, Song and Kovacevic [6] also established the FSW heat source model based on the Rosenthal analytical method, but ignored the heat generation by plastic deformation. With the in-depth study of the analytical FSW heat source model, Chang et al. [7] established a heat source model considering the frictional heat generation of the tool shoulder, the tool pin, and the weldment, simulated the temperature field of the 4-mm thick 6061-T6 aluminum alloy FSW, and studied the effect of welding speed on the microhardness and tensile strength of welded joints. Frigaard et al. [8] established a heat source model based on the frictional heat generation of torque, used MATLAB code to simulate the temperature distribution of 6-mm thick AA6082-T6 and AA7108-T79 weldments, and analyzed the microhardness of the weldment material according to the prediction model, but the heat source model ignored the heat generated by plastic deformation. Koral et al. [9] used the same torque heat source model as Frigaard et al. and used ANSYS and HyperXtrude software to simulate the temperature field of the 3.1-mm thick 6061-T6 aluminum alloy FSW and investigated the effect of different rotational speed, welding speed, and dwell time on the peak temperature of the weldments. Schmidt et al. [10] considered the different contact conditions between the tool and the weldment, the concave angle of the shoulder and the cone angle of the tool pin, and modified the heat source model. Gadkah and Adepu [11], Yadayanshi et al. [12], Ghetiya and Patel [13], Bonifaz [14], and Liu et al. [15] based on Schmidt’s heat source model separately studied the effects of rotational speed and welding speed, axial pressure, cone angle of the tool pin, backing plate type, and welding inclination angle on the temperature distribution of thin plates. Among them, Ghetiya’s research showed that the tensile strength and microhardness of joints are affected by temperature.

Analytical FSW heat source models have been studied in great depths, but some FSW heat source models have only considered the frictional heat generation of the tool, while ignoring the heat generated by the plastic deformation of the weldment material during the welding process, which leads to errors in the prediction of the temperature field. Moreover, research studies have been basically carried out around low-strength thin plates, but there are few studies on high-strength medium plates. Compared with low-strength thin plates, the temperature and mechanical properties of high-strength medium thickness plates are more uneven in the FSW process [16], and the welding quality is difficult to guarantee. Therefore, it is necessary to establish a FSW heat source model considering friction heat generation and plastic deformation heat generation to explore the temperature distribution of medium thickness aluminum alloy 2219 plate, to ensure the mechanical properties of the FSW medium thickness aluminum alloy 2219.

2 FSW thermodynamic model

The FSW process generates heat through friction and plastic deformation, softens the welding material, and mixes the material through the stirring action of the tool pin. The main mechanism of the FSW process is the contact interactions between the tool pin and the shoulder and the weldment material. The shoulder is the main source of heat generated by friction. Another function of the shoulder is to keep the material flowing around the tool. The tool pin is located below the shoulder, and its main function is to mix the sheet materials to be welded. In the FSW process, the heat transfer process includes heat conduction, thermal convection, and thermal radiation. In short, the FSW process is a complex heat production and transfer process.

2.1 Heat production model

The tool moves in the processing direction while rotating at a high speed. Frictional heat is generated between the tool and the welded plates due to the existence of frictional resistance, including the friction heat $Q_1$ between the shoulder and the surface of the welded plate, the friction heat $Q_2$ between the side of the tool pin and the welded plate, and
the friction heat $Q_1$ between the bottom surface of the tool pin and the welded plate. The welded plate near the tool will produce plastic deformation under the action of the tool, and these plastic deformations will also generate heat $Q_r$.

The friction heat $Q_1$ between the shoulder and the surface of the welded plate:

$$Q_1 = \omega \int_{R_1}^{R_2} dM_1 = \frac{2\pi \rho \omega}{3} (R_1^2 - R_2^2)$$

(1)

d$M_1$ = r$1$dr = 2\pi \rho \mu r_1^2 dr_1 \quad (R_2 \leq r_1 \leq R_1)

where $\mu$ is the friction coefficient, $\rho$ is the positive pressure, $\omega$ is the rotation speed of the tool, $R_1$ is the shoulder radius, $R_2$ is the large radius of the tool pin, $R_3$ is the small radius of the tool pin, $dM_1$ is the micro-element torque of the shoulder, and $dr_1$ is the micro-element friction.

The frictional heat $Q_2$ between the side of the tool pin and the welded plate:

$$Q_2 = \omega \int_{0}^{H} dM_2 = \frac{2\pi \rho \omega}{3 \sin \alpha} (R_3^2 - R_1^2)$$

(3)

d$M_2$ = r$2$df = 2\pi \rho \mu (R_3 + \tan \alpha)^2 \frac{dh}{\cos \alpha}

(4)

where $H$ is the length of the tool pin, $2\alpha$ is the cone angle of the tool pin, and $dM_2$ is the micro-element torque on the side of the tool pin.

The friction heat $Q_3$ between the bottom surface of the tool pin and the welded plate:

$$Q_3 = \omega \int_{0}^{R_1} dM_3 = \frac{2\pi \rho \omega}{3} R_3^2$$

(5)

d$M_3$ = r$3$df = 2\pi \rho \mu r^2 dr

(6)

where $dM_3$ is the micro-element torque of the bottom surface of the tool pin.

Plastic deformation heat $Q_r$:

$$Q_r = \eta_p \sigma \dot{\varepsilon}_p$$

(7)

where $\eta_p$ is the conversion coefficient of plastic deformation energy into thermal energy, $\sigma$ is the equivalent stress, and $\dot{\varepsilon}_p$ is the equivalent strain rate.

Therefore, the total heat production $Q_{total}$ during the FSW process should equal the sum of the friction heat $Q_1$, $Q_2$, and $Q_3$ and the plastic deformation heat $Q_r$:

$$Q_{total} = Q_1 + Q_2 + Q_3 + Q_r$$

(8)

### 2.2 Heat transfer model

In the FSW process, the temperature of the weldment material changes all the time, so the three-dimensional transient heat transfer problem is analyzed. Assuming that the heat conduction of the material is isotropic, in the Cartesian coordinate system, the transient temperature field $T(x, y, z, t)$ in the deformed body satisfies the differential equation:

$$\rho c \frac{\partial T}{\partial t} - \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \Omega = 0$$

(9)

where $\rho$ is the material density; $c$ is the specific heat capacity of the material; $t$ is the time; $\lambda$ is the thermal conductivity of the material; and $\Omega$ is the heat source density inside the object.

The accuracy of the temperature field in the FSW process is related to heat input on one hand and heat output on the other hand. As the tool presses down to a certain position on the welded plate, tool starts to move in the welding direction. There is a great temperature gradient between the tool and welded plate, so that the heat is transferred from the high-temperature area to the low-temperature area. The main transfer methods are heat conduction, thermal convection, and thermal radiation.

1. **Heat conduction**

The temperature difference within an object or system is a necessary condition for heat conduction. The rate of heat conduction is determined by the distribution of the temperature field in the object. Heat conduction follows Fourier’s law, and its basic form is:

$$q = -\lambda \frac{\partial T}{\partial x}$$

(10)

where $q$ is the heat flux density, $\lambda$ is the thermal conductivity of the material, and $\frac{\partial T}{\partial x}$ is the temperature gradient in the direction of heat conduction.

In the FSW process, there is heat conduction between the tool and the welded plate, the inside of the welded plate, and between the welded plate and the fixture and the backing plate as follows:

1. The heat conduction between the tool and the welded plate.

In FSW process, a lot of heat is generated due to the frictional resistance between the tool and the welded plate. The total heat generated will have a certain distribution ratio between the tool and the welded plate, and the distribution ratio can be different, depending on the model.
2. The heat conduction inside the welded plate.

Heat will first be generated from the area where the tool directly acts on the welded plate. Subsequently, heat will be transferred from the high-temperature area in the welded plate to the low-temperature area because of the temperature difference between this area and the surrounding welded plate. The rate of heat transfer depends on the thermal conductivity of the welded plate.

3. The heat conduction between welded plate and backing plate.

When the thermal boundary conditions are considered, the thermal conductivity of the contact area between the welded plate and the backing plate, that is, the bottom surface of the welded plate, is set to 100 W/(m²·K) [17].

2. Thermal convection

Usually the Newtonian cooling formula is used to describe the thermal convection:

\[ q = h\Delta T \]  

where \( q \) is the heat flux density; \( h \) is the coefficient of heat convection, and \( \Delta T \) is the temperature difference between solid and fluid.

In the FSW process, the coefficient of heat convection on the upper surface and the four sides of the weldment is set as 30 W/(m²·K) [17].

3. Thermal radiation

Thermal radiation refers to the heat exchange process in which an object absorbs electromagnetic energy emitted by other objects and converts it into heat. Thermal radiation does not require a heat transfer medium. The radiant heat flux can be calculated using the empirical correction formula of Stefan-Boltzmann law:

\[ Q = \varepsilon \sigma_b F \Delta T \]  

where \( Q \) is the radiant heat flux, which can quantitatively describe the thermal radiation; \( \Delta T \) is the temperature difference between the object and environment; \( \varepsilon \) is the emissivity; \( F \) is the surface area; and \( \sigma_b \) is the thermal radiation constant.

2.3 Material parameters

XRF-1800 X-ray fluorescence spectrometer is used to determine the material composition of aluminum alloy 2219. The material composition is shown in Table 1. Use JMatPro software to import material composition calculation to obtain material parameters that change with temperature, as shown in Fig. 1.

During the FSW process, the weldment undergoes violent elastoplastic deformation. The strain and strain rate of the weldment change greatly. To accurately describe this characteristic of the weldment in the FSW process, Johnson–Cook constitutive model is adopted as expressed by the following formula:

\[ \sigma = (A + B\varepsilon^n) \left(1 + C\ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) \left[ 1 - \left( \frac{t - t_r}{t_m - t_r} \right)^m \right] \]  

where \( \sigma \) is the flow stress; \( A \) is the plastic strain; \( B \) is the strain rate; \( C \) is the reference plastic strain rate; \( t \) is the
temperature of the weldment; $t_m$ is the melting temperature of the weldment material; and $t_r$ is the room temperature. $A$, $B$, $C$, $m$, and $n$ are material parameters, where $A$ is the yield strength, $B$ is the hardening modulus, $C$ is the strain rate sensitivity coefficient, $n$ is the hardening coefficient, and $m$ is the thermal softening coefficient.

Parameters of Johnson–Cook constitutive model of aluminum alloy 2219 are shown in Table 2 [18].

### 2.4 Coefficient of friction

When the tool pin is in contact with the weldment interface, formulas (1), (3), (5) and (8) fully describe the heat generated by the FSW process, and the use of a rationality of the friction coefficient is to ensure that the heat generation model is a correct foundation. In the FSW process of aluminum alloy, the friction coefficient decreases with the increase of welding temperature. Therefore, it is necessary to adopt temperature-dependent adaptive adjustment of the friction coefficient (as shown in Table 3) to better express the heat generation model. In the numerical calculation, it is realized by adjusting the value of $\mu$ in each time step $dt$, so that the welding temperature will have a steady state, instead of increasing the temperature as the welding progresses.

### 2.5 Implementation of thermodynamic model

Based on the DFLUX subroutine, the heat generation model is imported in the simulation software ABAQUUS, and the FSW thermodynamic model is achieved by combining the heat transfer model, the material parameters of the aluminum alloy 2219, and the friction coefficient. When the rotational speed is 400 rpm and the welding speed is 100 mm/min, the solution of the final temperature field is shown in Fig. 2.

### Table 2 Parameters of Johnson–Cook constitutive model of 2219

| $A$ (MPa) | $B$ (MPa) | $n$  | $C$  | $m$  |
|-----------|-----------|------|------|------|
| 170       | 228       | 0.31 | 0.028| 2.75 |

### 3 Experimental verification of FSW thermodynamic model

The welding temperature in the FSW process is used to experimentally verify the validity of the established thermodynamic model for FSW of aluminum alloy 2219.

#### 3.1 FSW experimental conditions

A gantry type FSW machine tool is used to carry out the FSW experiment, as shown in Fig. 3. The FSW temperature field test system based on K-type thermocouple is used to detect the welding temperature field. The temperature measurement range is 0–1000℃, the measurement error is 0.75%T, and the sampling frequency is 10 Hz. The aluminum alloy 2219 plates are cut into rectangular weldment to the required dimensions (300 mm × 75 mm × 18 mm) by wire cut electric discharge machine. The radius of the shoulder ($R_1$) is 16 mm, the large radius of the tool pin ($R_2$) is 7.5 mm, the small radius of the tool pin ($R_3$) is 3.5 mm, and the length of the tool pin ($H$) is 17.8 mm, as shown in Fig. 4.

The experimental parameters of FSW are set as follows: the welding speed is 100 mm/min, the plunge rate is 20 mm/min, and the rotational speeds are 350 rpm, 400 rpm, and 450 rpm, respectively.

The tensile test is carried out on the electronic universal testing machine DNS-300. The sample size is in accordance with GB/T228.1–2010. The schematic diagram of the sample is shown in Fig. 5, and the tensile rate is set to 2 mm/min. The electronic Brinell hardness tester HBS-3000 is used to measure the microhardness distribution of FSW welded joints. The loading time in the test is 30 s, and the distance between every two measuring points is 10 mm. Use the German MEF-4 metallurgical microscope to observe the microstructure of the joint. A field emission scanning electron microscope (SUPRA55) with energy dispersive spectroscopy (EDS) function is used to scan the tensile fracture.

### Table 3 Friction coefficient related to temperature [17]

| Temperature (℃) | 25 | 300 | 420 | 543 |
|-----------------|----|-----|-----|-----|
| Friction coefficient | 0.3 | 0.25 | 0.2 | 0.01 |
15 mm, 18 mm, and 21 mm from the center of the weldment and 6 mm from the surface of the weldment.

When the rotational speed is 400 rpm and the welding speed is 100 mm/min, the comparison of temperature curves between simulation and experiment at points A1, A2, and A3 is shown in Figs. 7, 8 and 9.

Temperature output of the FSW simulation based on the analytical method is close to the experimentally measured temperature, as shown in Figs. 7, 8 and 9.

Table 4 shows that the maximum relative error of peak temperature is limited to 2%, and the mean relative error of peak temperature is 1.1%, which verifies the validity of the established aluminum alloy 2219 FSW thermodynamic model. However, in the thermodynamic model established by Ghetiya and Patel [13], they considered the heat generated by the friction between the weldment and the tool shoulder as well as between the weldment and the tool pin, but ignored the heat generated by plastic
deformation. The maximum relative error of the predicted welding temperature is within 3.5%.

4 Results and discussion

In the FSW process, the welding speed and the rotational speed of the tool are two important process parameters. The selection of different process parameters affects the temperature distribution of the weldment; subsequently, the distribution of the temperature field has a direct impact on the mechanical properties of the welded joint. Because of the existence of the tool in the FSW process, the temperature of each position of the weld cannot be obtained; the required temperature is obtained through the FSW thermodynamic model as discussed herein.

4.1 Welding temperature

At the center of the joint line and 6 mm away from the upper surface of the weldment, model computations have been performed to capture the effect of different welding speeds on the temperature when rotational speed is 400 rpm, and the effect of different rotational speeds on the temperature when the welding speed is 100 mm/min, as shown in Figs. 10 and 11.

When the rotational speed is 400 rpm and the welding speeds are 60 mm/min, 80 mm/min, 100 mm/min, 120 mm/min, and 140 mm/min, the peak welding value temperature is 503.5 °C, 501.2 °C, 498.9 °C, 496.4 °C, and 494.1 °C, respectively, as shown in Table 5. As shown in Fig. 10, while the welding speed increases, the welding temperature gradually decreases. This is because of the fact that as the welding speed increases, the frictional heat generation time shortens, the unit heat flux density becomes smaller, and the welding temperature decreases.

When the welding speed is 100 mm/min and the rotational speeds are 300 rpm, 350 rpm, 400 rpm, 450 rpm, and 500 rpm, respectively, the welding value temperature is 477.9, 489.8, 498.9, 506.6, and 511.9 °C, as shown in Table 6. As shown in Fig. 11, the welding temperature gradually increases as the rotational speed of the welding tool increases. The physical reason could be understood...
as follows: with the increase of the rotational speeds, the value of $\omega$ increases, the heat generation of $Q_1$, $Q_2$, and $Q_3$ in formulas (1), (3), (5) increases, and so the welding temperature rises.

### 4.2 Mechanical properties of joints

In the FSW process, because the temperature field is not uniformly distributed, the welded joint is subjected to different temperatures, resulting in differences in microhardness. To facilitate the study of the mechanical properties of the welded joint, the heat-affected zone (HAZ), the thermo-mechanically affected zone (TMAZ), and the nugget zone (NZ) [19] are evaluated. The grain-level microstructure of each zone is shown in Fig. 13. As shown in Fig. 12 with the “0” point being the center of the joint line, where NZ is located, the microhardness of the FSW joint of aluminum alloy 2219 with 18-mm thickness is roughly “U” shape. The mean microhardness of NZ is 285HB, which is slightly higher than the mean microhardness of TMAZ (281HB) and HAZ (284HB). This is because in the vertical weld direction, the welding temperature gradually decreases from the joint line center to both sides; that is, the temperature of the NZ is higher than that of the TMAZ and the HAZ, and the grain structure has undergone dynamic recrystallization, forming fine equiaxed grains (as shown in Fig. 13a), which may increase the microhardness. However, as heat input in the TMAZ and HAZ is lower, the crystal grains grow, the microhardness is then slightly lower than that in the NZ.

As can be seen in Fig. 11, the welding temperature of FSW increases with the rotational speed, but the microhardness of the NZ microhardness is 295 HB when the rotational speed is 400 rpm (at the moment, the welding temperature is 498.9 °C). This microhardness value reaches 77% of the microhardness of the base material (383HB).

### Table 4 Comparison of simulation output and experimental results

| Position | Experimental peak temperature (°C) | Simulated peak temperature (°C) | Error (%) |
|----------|-----------------------------------|---------------------------------|-----------|
| A1       | 373.9                             | 376.3                           | 0.6       |
| A2       | 320.9                             | 315.1                           | 2         |
| A3       | 314.5                             | 316.7                           | 0.7       |
The 18-mm thick aluminum alloy 2219 FSW welded joint is cut in the crown, midplane, and root three layers along the vertical direction of the weld, with each layer having a thickness of 6 mm. The welding speed is 100 mm/min, and the rotational speed of the tool is 350 rpm, 400 rpm, and 450 rpm, respectively. Figure 14 shows the results of the tensile test of the welded joint. The tensile strength of each layer increases first and then decreases. The maximum tensile strength of the crown at 400 rpm is 315 MPa, which reaches 72.4% of the base material’s tensile strength (435 MPa), while the elongation rate is 3.3%. When the rotational speed of the tool is 450 rpm, the overall tensile strength decreases. It can be seen from Fig. 15 that the crown has the highest temperature, stronger thermal cycling effect, stronger dynamic recrystallization degree, and significantly improved joint tensile strength; the midplane and root have relatively lower temperatures; and the dynamic recrystallization degree decreases, resulting in a lower tensile strength. The aluminum alloy 6005A-T6, which is also 18-mm thick, has obtained a welded joint with a tensile strength of 81.0% of the base material in the joint tensile performance test [20]. But the tensile strength of the welded joint of 18-mm thick aluminum alloy 2219 is only 72.4% of the base material. This is mainly due to the high strength of aluminum alloy 2219, the large axial force required for welding, the high heat input obtained, and the uneven distribution of the welding temperature of medium plate, which leads to large differences in the internal structure and properties of the joints. These effects are evident in the “S” lines of oxide accumulation in the NZ, as shown in Fig. 16. As the grains of the NZ grow, the oxides in the “S” line hinder the migration of grain boundaries and produce stress concentration, which reduce the tensile strength of the joint.

The macroscopic fracture morphology of the joint is shown in Fig. 17a. The fracture positions of the joints are all located in the NZ. The scanning electron microscope of the fracture surface of the joint is shown in Fig. 17b. It can be seen that the fracture surface of the joint presents dimples of different sizes with deep pores. The average diameter of the large dimples is about 14.2 μm, and the diameter of the small dimples is about 2.1 μm. There are a large number of strengthening phase particles at the bottom of the dimples. In order to analyze the composition of the strengthening phase particles, EDS is performed on the particles. The EDS results show that the particle composition is Al2Cu, and the presence of the strengthening

| Welding Speed (mm/min) | 60 | 80 | 100 | 120 | 140 |
|------------------------|----|----|-----|-----|-----|
| Temperature (°C)       | 503.5 | 501.2 | 498.9 | 496.4 | 494.1 |

| Rotational Speed (rpm) | 300 | 350 | 400 | 450 | 500 |
|------------------------|-----|-----|-----|-----|-----|
| Temperature (°C)       | 477.9 | 489.8 | 498.9 | 506.6 | 511.9 |
phase particles is beneficial to the tensile strength of the joint. It implies that the fracture form of the joint is ductile fracture, indicating that the welded joint has good toughness. However, the tensile test results show that the fracture location is at the NZ, but in the tensile test of the thin aluminum alloy 2219, the fracture position is located at the junction of NZ and TMAZ [21]. The possible reason is that the internal temperature of medium thickness aluminum alloy 2219 is not evenly distributed along the thickness direction during FSW, which leads to the uneven distribution of the strengthening phase Al₂Cu; therefore, the tensile strength of the joint is low.

Fig. 12  Microhardness distribution

Fig. 13  Microstructure of joint. (a) Microstructure of NZ. (b) Microstructure of TMAZ. (c) Microstructure of HAZ

Fig. 14  Tensile test results of welded joints

(a) Microstructure of NZ  (b) Microstructure of TMAZ

(c) Microstructure of HAZ
Fig. 15 Temperature distribution of welded joints

Fig. 16 “S” line distribution of welded joints

Fig. 17 Fracture morphology of joint. (a) Fracture macroscopic morphology. (b) SEM of joint fracture morphology

(a) Fracture macroscopic morphology  (b) SEM of joint fracture morphology
5 Conclusion

In this paper, a heat generation model of FSW medium thickness aluminum alloy 2219 is established considering the friction heat generated at the interface between the tool and the workpiece and the plastic deformation heat of the weldment material near the tool. The heat transfer is set up considering heat conduction, thermal convection, and thermal radiation. The built heat generation model is imported into the simulation software ABAQUS through the DFLUX subroutine, and the simulation of FSW process is achieved. The effectiveness of the simulation is verified by FSW experiments. The maximum relative error between the predicted results and the experimental results is limited to 2%, and the mean relative error is 1.1%. Based on the FSW simulation, the influence of welding parameters on temperature is explored. Results show that the welding temperature decreases with the increase of welding speed, and the welding temperature increases with the increase of rotational speed. In the study of mechanical properties of aluminum alloy 2219 joint, it is found that the tensile strength of the crown is the highest, followed by the midplane and the root. When the rotational speed is 400 rpm (at the moment, the welding temperature is 498.9 °C), the microhardness of the NZ is 295HB, which reaches 77% of the microhardness of the base material. Similarly, when the rotational speed is 400 rpm, the tensile strength of the crown weldment material reaches the maximum value of 315 MPa, which is 72.4% of the base material, and the elongation rate is 3.3%. The fracture form of the joint is observed to be ductile fracture, and Al2Cu is a strengthening phase particle in the dimple. The unevenness distribution of temperature, the unevenness distribution of strengthening phase Al2Cu, and the existence of “S” line during FSW reduce the mechanical properties of the joint. The research guides the prediction of the temperature distribution and the improvement of the mechanical performance of FSW medium thickness aluminum alloy 2219.

Author contribution Xiaohong Lu: Conceptualization, Supervision, Methodology, Funding acquisition, Project administration. Yihan Luan: Conceptualization, Methodology, Software, Validation, Writing-original draft, Investigation, Writing-review and editing. Xiangyue Meng: Formal analysis, Data curation. Yu Zhou: Software, Investigation. Ning Zhao: Formal analysis. Steven Y. Liang: Resources.

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Declarations

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Consent to participate Not applicable.

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