Welding parameters optimization during plunging and dwelling phase of FSW 2219 aluminum alloy thick plate

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Received: 6 October 2021 / Accepted: 22 March 2022 / Published online: 6 April 2022
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Abstract

The influence of welding parameters on temperature distribution during plunging and dwelling phase of friction stir welding (FSW) 2219 aluminum alloy thick plate has not been studied. Improper selection of welding parameters will result in uneven temperature distribution along with the thickness of the weldment, leading to welding defects and ultimately affecting the mechanical properties of the weldment. To achieve the prediction of temperature distribution and the optimization of welding parameters, a simulation process model of FSW 18-mm-thick 2219 aluminum alloy is established based on DEFORM. The validity of the simulation is verified by experiments. With the minimum temperature difference in the core area of the weldment as the target value and weldable temperature range of 2219 aluminum alloy as the constraint conditions, orthogonal experiments are conducted considering the rotational speed, the press amount, the tool tilt angle, the plunging traverse speed and the dwelling time. The results of variance analysis show that the rotational speed and the dwelling time are significant factors affecting the temperature field during the plunging and dwelling phase. Through single factor simulation, the welding parameters during the plunging and dwelling phase are optimized. This study guides the selection of welding parameters of the FSW 2219 aluminum alloy thick plate.

Keywords Friction stir welding (FSW) · 2219 aluminum alloy · Thick plate · DEFORM · Temperature distribution · Optimization of welding parameters

1 Introduction

A heavy-lift launch rocket is a key part of spaceflight and deep space exploration [1]. A rocket fuel tank is the drive component of a rocket, which has extremely high requirements for manufacturing quality and reliability [2]. The advanced rocket fuel tank is made of 2219 high-strength aluminum alloy with a thickness of 18 mm. Friction stir welding (FSW) has the advantages of no need to add welding wire, no shielding gas, no pollution, no smoke, no radiation, high welding efficiency, small product deformation after welding, and excellent weld mechanical properties and has become the main connection process for the rocket fuel tanks [3].

The whole process of FSW includes plunging and dwelling, welding, and tool withdrawal phases. The plunging and dwelling phase is the initial phase, which affects the subsequent welding phase. In this phase, the pin is slowly pressed into the weldment. The plasticization and flow behavior of the weldment material near the pin is the basis for forming the joint. Improper selection of welding parameters during plunging and dwelling phase will result in high-temperature...
gradient and uneven temperature distribution along with the thickness of the weldment and thus leads to defects in welded joints, such as flashes, holes, incomplete penetration, etc. Welding defects directly affects the mechanical properties of the weldment. The thermomechanical affect zone and weld nugget zone of the weldment are defined as the welding core area. It is difficult to measure the temperature distribution in the welding core area due to the tool rotation, shielding of the shoulder, material flow, and severe plastic deformation in the welding zone. Therefore, the finite element method (FEM) has become an important means to study the temperature distribution in the welding core area. At present, software such as ANSYS, MSC. Marc, FLUENT, ABAQUS, and DEFORM are widely adopted to simulate the FSW process.

Scholars have simulated temperature distribution in the welding phase of FSW based on the heat source model. McClure et al. [4] and Jiang et al. [5] used the Rosenthal analytical method to analyze the transient temperature distribution in the FSW process and obtained the thermal cycle curve of each feature point in the welding zone. He et al. [6] and Wan et al. [7] adopted MSC. Marc established FSW simulation models, analyzed the ultrasonic-assisted FSW and FSW, and studied the temperature distribution during the welding process. Ren et al. [8] and Xu et al. [9] established the FSW heat source model based on the torque heat source model and used ANSYS to study the temperature distribution of the welding process and the residual stress after welding. Complex nonlinear friction and plastic deformation in the FSW process make analytical methods difficult to describe temperature distribution.

Some scholars studied the temperature distribution of FSW based on FLUENT and ABAQUS. Eyvazian et al. [10] and Feng et al. [11] used FLUENT to simulate the FSW process of dissimilar and the same materials and studied the temperature distribution of weldments. Yang et al. [12] utilized FLUENT to simulate friction stir lap welding of dissimilar materials Q235 steel and 6061 aluminum alloy and studied the influence of welding parameters on the temperature distribution. Su and Wu [13] established simulation models of different stir pin shapes based on the CFD method and studied the effects of stir pin shape, shoulder radius, rotational speed, and welding speed on temperature distribution in the welding process. Some scholars adopted ABAQUS to simulate the FSW process and studied the influence of tool size and welding parameters on the temperature distribution of the weldment. Zhang et al. [14], Iordache et al. [15], and Liu et al. [16] used the arbitrary Lagrangian-Euler (ALE) method in ABAQUS to avoid mesh loss, established FSW simulation model, and studied temperature distribution. While ALE method usually ignores the plunging and dwelling phase to reduce the deformation of the mesh.

DEFORM attracted the attention of many scholars due to its powerful automatic re-meshing function. Zhou et al. [17] and Han et al. [18] simulated the FSW process using local mesh refinement and adaptive following technology and studied the influence of the rotational speed, welding speed, and down pressure on the temperature distribution. Asadi et al. [19] used DEFORM to study the FSW process of magnesium alloy and adopted a point tracking method to study the temperature distribution. DEFORM has strong mesh refinement capability. When the mesh deformation reaches a certain degree, DEFORM will automatically re-divide the global meshes to make the model easier to converge. Most notably, DEFORM can simulate the whole phase of FSW.

There are few studies that have been done on the optimization of welding parameters during the plunging and dwelling phase. There are many welding parameters during the plunging and dwelling phase, such as the rotational speed, the press amount, the tool tilt angle, the plunging traverse speed, and the dwelling time. The influence law of the above-mentioned factors on temperature has not been studied. Different welding parameters are suitable for weldments of different materials and sizes. Therefore, it is necessary to study the influence of welding parameters on the temperature field of FSW 2219 aluminum alloy thick plate during the plunging and dwelling phase and to optimize the welding parameters.

To realize the prediction of temperature distribution of FSW 2219 aluminum alloy thick plate and the optimization of the welding parameters, a simulation model of FSW is built based on DEFORM. The effectiveness of the simulation is verified by experiments. With the minimum temperature difference in the core area of the weldment as the target value and the weldable temperature range of 2219 aluminum alloy as the constraint conditions, orthogonal experiments and variance analyses are carried out. The research determines the significant influence factors of the temperature difference and achieves the optimization of welding parameters during the plunging and dwelling phase of the FSW 2219 aluminum alloy thick plate.

2 Simulation of FSW 2219 aluminum alloy thick plate based on DEFORM

A simulation model of FSW 18-mm-thick aluminum alloy is realized based on DEFORM. To reduce the complexity of the simulation model, the following assumptions are made: (1) the weldment is modeled as a visco-plastic material; (2)
the tool is rigid; (3) the material properties of weldment are temperature dependent; (4) the friction coefficients between the weldment and the tool are temperature dependent.

2.1 Geometrical model and meshing

The tool is composed of a shoulder with a concave angle and a conical stir pin, as shown in Fig. 1a. The radius of the shoulder is 16 mm. The root radius and length of the conical stir pin are 7.5 and 17.8 mm, respectively. The weldment is 100 × 150 × 18 mm³. The three-dimensional model after assembly is shown in Fig. 1b.

The mesh needs to be refined in the interaction area between the weldment and the tool to improve the simulation accuracy and coarsen on the outside of the interaction area to shorten the computation time. The position of mesh windows is shown in Fig. 2a. The size ratio is set to 4 to avoid the mesh outside the mesh windows from being too large to affect simulation accuracy. The mesh window density is set as 1 mm. The simulation model after meshing is shown in Fig. 2b.

2.2 Material properties

XRF-1800 X-ray fluorescence spectrometer is used to determine the chemical composition of 2219 aluminum alloy. The chemical composition is shown in Table 1. JMatPro software is used to obtain the temperature-dependent material properties of 2219 aluminum alloy by importing chemical composition, as shown in Fig. 3.

Define the material of the weldment as visco-plastic material [20, 21]. Johnson–Cook material model describes the effect of strain rate and temperature on flow stress and is used in FSW simulation. Johnson–Cook constitutive equation is written as

\[
\sigma = (A + B\varepsilon^n)(1 + C \ln \dot{\varepsilon}^* \left(1 - \left(\frac{T^*}{T_m}\right)^m\right))
\]

(1)

\[
T^* = \begin{cases} 
0 & T < T_{room} \\
\frac{T - T_{room}}{T_m - T_{room}} & T_{room} \leq T \leq T_m \\
1 & T > T_m
\end{cases}
\]

(2)

where \(\varepsilon\) presents the effective plastic strain; \(\dot{\varepsilon}^*\) presents the relative plastic strain rate, \(\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0\); \(\dot{\varepsilon}_0\) presents the effective plastic strain rate; \(T_m\) presents the reference plastic strain rate. Zhang et al. [22] used split-Hopkinson pressure bar (SHPB) equipment to test the dynamic compression mechanical properties of 2219 aluminum alloy under high temperature and high strain rate processing conditions and used an electronic universal testing machine for quasi-static compression. The Johnson–Cook material model used to predict
the flow stress of the 2219 aluminum alloy was obtained by fitting. The constants of the constitutive equation of 2219 aluminum alloy are shown in Table 2.

### 2.3 Boundary conditions and frictional model

Boundary conditions are divided into mechanical and thermal boundary conditions. Mechanical boundary conditions limit the degree of freedom of the weldment to ensure that the weldment is fixed during the simulation process. That is, limit the degree of freedom of movement in the $Z$ direction of the bottom surface of the weldment, and limit the degree of freedom of movement in $X$ and $Y$ directions of the side surface of the weldment.

Thermal boundary condition setting mainly includes setting heat transfer mode and coefficient between the tool, weldment, and backing plate. To shorten simulation time, the heat convection coefficient of the bottom surface of the weldment and the air is used to simulate the heat conduction between the bottom surface of the weldment and the backing plate. Room temperature is set to 15 °C, heat convection coefficient of the bottom surface of the weldment and the air is set to 5 N/mm·s·°C, and heat convection coefficient of the remaining surface of the weldment, the surface of the tool, and the air is set to 0.025 N/mm·s·°C [23].

During the welding process, the temperature of the contact area between the weldment and the tool increases, and the surface of the weldment material with lower strength is partially sheared. Under the action of friction, part of the weldment material will be stuck to the surface of the tool. To describe the state of the contact area between the weldment and tool during the welding process accurately, a shear friction model is adopted [24].

During FSW heat generation, the choice of friction coefficients between the tool and weldment plays an important role. However, the friction coefficients are dependent on several factors, e.g., temperature, relative motion, and contact geometry. Zhang et al. [25] conducted extensive studies on the factors affecting the friction coefficient of the FSW process and found that the friction coefficients largely depend on temperature. Therefore, the temperature-dependent coefficients of friction are used in this study to analyze the FSW process. The equation is expressed as

$$\tau = mk$$

where $\tau$ is the contact stress at the interface of the weldment and tool; $m$ is the shear factor; $k$ is the shear strength. The coefficients of friction are defined as temperature-dependent, as shown in Table 3.

### 2.4 Implementation of simulation

Simulation of FSW 18-mm-thick 2219 aluminum alloy is finally realized, and the temperature distribution of the weldment in the three phases, i.e., plunging and dwelling, welding, and tool withdrawal is obtained and is shown in Fig. 4a–c, respectively.

### 3 Verification of the simulation results

Temperature measurement experiments based on K-type thermocouples are carried out in Capital Aerospace Machinery Company, and a temperature measurement system based on LabVIEW developed by our research group is used to collect the temperature data of the sampling points in the
The measurement range of the system is −200 to 1250 °C. The FSW equipment is a large gantry FSW equipment, as shown in Fig. 5.

The plunging traverse speed is 20 mm/min, the welding speed is 100 mm/min, the tool tilt angle is 2.5°, the press amount is 0.2 mm, and the rotational speed is set as 350, 400, and 450 r/min, respectively. Sampling points on the advancing side (AS) and the retreating side (RS) are obtained for temperature comparison to verify the validity of the built simulation model, as shown in Fig. 6.

Figure 7 shows the comparison of experimental and simulated temperature curves of sampling points on the AS and RS when the rotational speed is 400 r/min. The measured peak temperature on the AS and RS are 458.3 and 429.9 °C, respectively. The simulated peak temperature on the AS and RS are 464.1 and 434.5 °C, respectively. The relative errors between the simulation and experimental peak temperature of the sampling points on the AS and RS are 1.27 and 1.07%, respectively.

Figure 8 shows the comparison of experimental and simulated temperature curves of feature points on the AS with the rotational speed of 350, 400, and 450 r/min. The temperature change law of experimental and simulated results is basically the same, and both experience the process of heating-peak-cooling. The measured peak temperatures on the AS are 413.2, 424.2, and 417.9 °C, respectively, and the simulated peak temperatures on the AS are 426.1, 429.9, and 431.7 °C, respectively. The relative errors of the simulation and experimental peak temperature on the AS are 3.12, 1.34, and 3.30%, respectively. The effectiveness of the entire welding process of the established simulation model is verified.

### 4 Optimization of welding parameters during plunging and dwelling phase

To determine the optimal welding parameters of FSW 18-mm-thick 2219 aluminum alloy during the plunging and dwelling phase. This strategy based on the FEM simulation of FSW process is proposed, and the influence of welding parameters on temperature is explored. The optimal welding parameters during the plunging and dwelling phase are obtained.

It has been proven that the friction heat generated by the friction between the shoulder and the weldment is higher than the friction heat generated by the stir pin [5, 7]. In addition, the heat generated by the friction between the bottom surface of the tool and the weldment is transferred to the backing plate under the weldment, resulting in uneven heat input along with the thickness of the weldment. The temperature difference in the core area of the weldment directly affects the joint structure, which ultimately affects the mechanical properties of the welded joint. Scholars have found that the tensile strength at the bottom of the joint was low [26, 27]. If the bottom temperature increases, the dynamic recrystallization degree increases, the grain boundary angle increases, and...

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**Table 2** Johnson–Cook constants of 2219 aluminum alloy

| A (MPa) | B (MPa) | n | C | m | T_C (°C) | T_m (°C) |
|---------|---------|---|---|---|---------|---------|
| 170     | 228     | 0.31 | 0.028 | 2.75 | 15       | 590     |

**Table 3** Temperature-dependent coefficients of friction

| Temperature (°C) | 25 | 100 | 200 | 300 | 400 | 500 |
|------------------|----|-----|-----|-----|-----|-----|
| m                | 0.61 | 0.51 | 0.21 | 0.07 | 0.47 | 0   |

**Fig. 4** Temperature distribution: a the plunging and dwelling phase; b the welding phase; c the tool withdrawal phase
the tensile strength of the joint increases. Therefore, the minimum temperature difference in the core area of the weldment is selected as the optimization goal.

Ma et al. [28] established a simulation model of FSW 4-mm-thick 2219 aluminum alloy and studied the influence of the shoulder radius on the maximum temperature and tensile strength of the weldment. The study found that when the maximum temperature of the weldment was about 80% of the liquidus temperature, the tensile strength of the welded joint was highest, which is 82.5% of the base metal. Fehrenbacher et al. [29] buried a thermocouple in the stir pin, built a wireless temperature measurement system based on the thermocouple, and performed FSW temperature measurement experiments of 4.76-mm-thick 6061 aluminum alloy and 5-mm-thick 5083 aluminum alloy. They found that when the temperature at the stir pin was lower than 80% of the solidus temperature of the aluminum alloy, the tensile strength of the joint was significantly reduced.

It has been proven [30] that there exists the optimal welding temperature for obtaining a joint of high tensile strength. Iordache et al. [31] took pure copper as the research object, assumed 550°C as the optimal welding temperature according to references, carried out finite element simulations and experiments, and realized the optimization of rotational and welding speed.

To optimize the welding parameters of FSW 18-mm-thick 2219 aluminum alloy during the plunging and dwelling phase, 80% of the solidus and liquidus temperature of 2219 aluminum alloy is assumed to be the optimal temperature range. For 2219 aluminum alloy, its solidus and liquidus temperature measured by DSC (differential scanning calorimeter) is 548 and 649°C, respectively.

4.1 Influence of welding parameters on temperature

The welding parameters of the plunging and dwelling phase include the rotational speed, the press amount, the tool tilt angle, the plunging traverse speed, and the dwelling time. Orthogonal experiments are conducted to study the influence of the above parameters on the temperature differences in the core area of the weldment. The orthogonal table is shown in Table 4.

The sum of the freedom degrees of each factor is the number of factors × (number of levels − 1) = 5 × (3 − 1) = 10, which is less than the total freedom degree of L18(3⁷). The orthogonal table is selected as L18(3⁷).

The temperature differences between the maximum and the minimum temperatures in the core area are extracted through the post-processing module. The orthogonal experiment scheme and the temperature differences results are shown in Table 5.

The maximum and minimum temperatures in the core area of the 18 groups of models are shown in Fig. 9.
maximum temperature of the 18 groups of models does not exceed the upper limit of the temperature in the core area of the weldment. Only the minimum temperature of the 7th group model is within the weldable temperature range of 2219 aluminum alloy.

Then the mean square is calculated with the sum of squares and degrees of freedom to calculate the $F$ test value. The analysis of the variance table is shown in Table 6. It shows that the rotational speed and dwelling time have a significant effect on the temperature difference in the core area of the weldment. Among them, the dwelling time has the greatest influence on the temperature difference, followed by the rotational speed.

The results of variance analysis show that the dwelling time and the rotational speed have a significant influence on the temperature difference. Next, comprehensive research on the influence of the rotational speed and dwelling time on temperature differences is conducted.

The plunging traverse speed is set as 20 mm/min, the welding speed is set as 100 mm/min, the tool tilt angle is set as 2.5°, the press amount is set as 0.2 mm, the rotational speed is set as 300, 400, 500, and 600 r/min, respectively, and the dwelling time is set as 0, 2.5, 5, 7.5, 10, 12.5, and 15 s, respectively. The completion time of the plunging phase is 52.8 s. The maximum temperature of weldment with different rotational speeds and dwelling times is shown in Fig. 10. The maximum temperature shows a certain upward trend during the dwelling phase under different rotational speeds. When the rotational speed is 600 r/min, the maximum temperature exceeds the upper limit of the weldable temperature of the weldment after dwelling for 2.5 s. When the rotational speed is less than or equal to 500 r/min, the maximum temperature within 15 s is lower than the upper limit of the weldable temperature of the weldment.

The maximum and the minimum temperature in the core area of weldment with different rotational speeds and dwelling times are shown in Fig. 11. When the rotational speeds are 300 and 400 r/min, the minimum temperature in the core area of weldment is lower than the lower limit of the weldable temperature of the weldment. When the rotational speed is 500 r/min and the dwelling time is from 5 to 15 s, the maximum and the minimum temperature in the core area of weldment are both within the weldable temperature range of 2219 aluminum alloy. When the rotational speed is 600 r/min, the maximum temperature exceeds the upper limit of the weldable temperature of the weldment.

The temperature differences in the core area of the weldment with different rotational speeds and dwelling times are shown in Fig. 12. It shows that the higher the rotational speed, the smaller the temperature difference. There is no significant difference in the temperature difference when the dwelling time is in the 5–15 s range at the rotational speed of 500 and 600 r/min. The reason may be that with the increase of rotational speed, the temperature of the contact area between the tool and the weldment increases, and the surface of the weldment material with lower strength is partially sheared. Under the action of friction, part of the weldment material will be stuck to the surface of the tool, reducing the friction coefficient, which is manifested by the fact that there is no significant change in the temperature difference when the rotational speed increases to a certain extent.
When the dwelling time is 5 s, the temperature difference of the weldment decreases sharply, and when the dwelling time is 15 s, the temperature difference of the weldment decreases insignificantly. The reason may be that after dwelling for 5 s, the frictional heat, plastic deformation heat, and heat dissipation reach a stable state.

Table 4 Five factors and three levels of the orthogonal table

| Level | Rotational speed (A) | Press amount (B) | Tool tilt angle (C) | Plunging traverse speed (D) | Dwelling time (E) |
|-------|----------------------|------------------|---------------------|----------------------------|------------------|
| 1     | 300 r/min (A₁)       | 0.2 mm (B₁)      | 1° (C₁)             | 20 mm/min (D₁)             | 0 s (E₁)         |
| 2     | 400 r/min (A₂)       | 0.3 mm (B₂)      | 2° (C₂)             | 40 mm/min (D₂)             | 2.5 s (E₂)       |
| 3     | 500 r/min (A₃)       | 0.4 mm (B₃)      | 4° (C₃)             | 60 mm/min (D₃)             | 5 s (E₃)         |

Table 5 Orthogonal experimental results

| Number | Factor | Rotational speed (A) | Press amount (B) | Tool tilt angle (C) | Plunging traverse speed (D) | Dwelling time (E) | Temperature difference 𝑦ᵢ (°C) |
|--------|--------|----------------------|------------------|---------------------|----------------------------|------------------|-------------------------------|
| 1      | 1      | 1                    | 1                | 1                   | 1                           | 1                | 187.63                        |
| 2      | 1      | 2                    | 2                | 2                   | 2                           | 2                | 138.84                        |
| 3      | 1      | 3                    | 3                | 3                   | 3                           | 3                | 117.34                        |
| 4      | 2      | 1                    | 1                | 1                   | 2                           | 2                | 116.55                        |
| 5      | 2      | 2                    | 2                | 2                   | 3                           | 3                | 102.92                        |
| 6      | 2      | 3                    | 3                | 3                   | 1                           | 1                | 151.22                        |
| 7      | 3      | 1                    | 1                | 2                   | 1                           | 3                | 65.08                         |
| 8      | 3      | 2                    | 3                | 2                   | 1                           | 2                | 130.89                        |
| 9      | 3      | 3                    | 3                | 3                   | 2                           | 2                | 98.08                         |
| 10     | 1      | 1                    | 3                | 3                   | 3                           | 2                | 159.56                        |
| 11     | 1      | 2                    | 1                | 1                   | 1                           | 3                | 114.74                        |
| 12     | 1      | 3                    | 2                | 2                   | 1                           | 2                | 221.86                        |
| 13     | 2      | 1                    | 2                | 3                   | 1                           | 1                | 159.47                        |
| 14     | 2      | 2                    | 3                | 3                   | 1                           | 2                | 112.03                        |
| 15     | 2      | 3                    | 1                | 2                   | 3                           | 3                | 95.15                         |
| 16     | 3      | 1                    | 3                | 2                   | 3                           | 2                | 74.20                         |
| 17     | 3      | 2                    | 1                | 3                   | 1                           | 1                | 135.17                        |
| 18     | 3      | 3                    | 2                | 1                   | 2                           | 2                | 85.85                         |

Fig. 9 The maximum and the minimum temperatures in the core area of the weldment

When the dwelling time is 5 s, the temperature difference of the weldment decreases sharply, and when the dwelling time is 15 s, the temperature difference of the weldment decreases insignificantly. The reason may be that after dwelling for 5 s, the frictional heat, plastic deformation heat, and heat dissipation reach a stable state.

Table 6 Results of analysis of variance

| Source of variation | SS     | df  | MS     | F      | F₀₀₅(2,7) |
|---------------------|--------|-----|--------|--------|-----------|
| Rotational speed (A)| 10331.9| 2   | 5165.95| 35.77  | 9.55      |
| Press amount (B)    | 113.68 | 2   | 56.84  | 0.39   |           |
| Tool tilt angle (C) | 85.86  | 2   | 42.93  | 0.3    |           |
| Plunging traverse speed (D) | 381.84 | 2 | 190.92 | 1.32   |           |
| Dwelling time (E)   | 14975.21 | 2 | 7487.61 | 51.85  |           |
| Error               | 1010.91 | 7  | 144.42 |        |           |
| Total variation     | 26899.4 | 17 |        |        |           |
From the above analyses, when the rotational speed is 500 r/min, the dwelling time is 5 s, the tool tilt angle is 2.5°, the plunging traverse speed is 20 mm/min, and the press amount is 0.2 mm, the temperature difference of the weldment is relatively small. The optimal welding parameters during the plunging and dwelling phase are obtained.

**5 Conclusion**

To predict the temperature of FSW 2219 aluminum alloy thick plate and optimize the welding parameters, a simulation model of FSW 18-mm-thick 2219 aluminum alloy is established based on DEFORM, and the simulation during the plunging and dwelling, welding, and tool withdrawal phases is realized. The effectiveness of the simulation model is verified by temperature measurement experiments. The maximum relative error of the peak temperature of the sampling points is 3.30%, and the average relative error is 2.02%.

With the minimum temperature difference in the core area of the weldment as the target value and the weldable temperature range of 2219 aluminum alloy as the constraint conditions, orthogonal experiments are carried out considering the rotational speed, the press amount, the tool tilt angle, the plunging traverse speed and the dwelling time. The results of variance analysis show that the rotational speed and dwelling time exert great influence on the temperature field during the plunging and dwelling phase.

The simulation results show that when the rotational speed is 600 r/min, the maximum temperature exceeds the upper limit of the weldable temperature of the weldment after dwelling for 2.5 s. When the rotational speeds are 300 and 400 r/min, the minimum temperature in the core
area of weldment is lower than the lower limit of the weldable temperature of the weldment. When the dwelling time is 5 s, the temperature difference in the core area of the weldment decreases sharply, and when the dwelling time is further extended, there is no significant change in the temperature difference in the core area of the weldment.

Considering the processing efficiency and temperature difference comprehensively, the optimal welding parameters combination of FSW 18 mm 2219 aluminum alloy during the plunging and dwelling phase is obtained: the rotational speed is 500 r/min, the dwelling time is 5 s, the tool tilt angle is 2.5°, the plunging traverse speed is 20 mm/min, and the press amount is 0.2 mm.

**Author contribution** Xiaohong Lu: conceptualization, supervision, methodology, funding acquisition, project administration, writing—review, and editing. Jinhui Qiao: conceptualization, methodology, software, validation, writing—original draft, investigation, writing—review, and editing. Junyu Qian: formal analysis, data curation. Shixuan Sun: software, investigation, and formal analysis. Steven Y. Liang: supervision, methodology, and resources.

**Funding** The research was supported by the National Key Research and Development Program of China (grant no. 2019YFA0709003), Dalian Science and Technology Innovation Fund (grant no. 2020J26GX041), and the Fundamental Research Funds for the Central Universities (grant no. DUTZ20ZD204). The financial contributions are gratefully acknowledged.

**Availability of data and material** All data generated or analyzed during this study are included in this manuscript.

**Code availability** The code is available on request.

**Declarations**

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** The authors consent that the work entitled “Welding parameters optimization during plunging and dwelling phase of FSW 2219 aluminum alloy thick plate” for possible publication in the International Journal of Advanced Manufacturing Technology.

**Conflict of interest** The authors declare no competing interests.

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