The Numerical Simulation of Temperature Field in Friction Stir Welding of 7075 Aluminium Alloy

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Abstract. Considering friction heat generation between rotating tool and workpiece and plastic deformation heat generation of material, a numerical simulation model of friction stir welding of 7075 aluminium alloy sheet was established. In this study, the temperature field of the welding process was analysed, and the effects of different stirring speeds and welding speeds on the temperature field were compared. The results show that the high temperature region is located below the shoulder and diffuses outward in a ring shape. After the welding is completed, the workpiece center temperature is high and the ambient temperature is low. The stirring speed of the tool has a large effect on the peak temperature during the welding process. The effect of the welding speed on the peak temperature is less than the stirring speed. The comparison shows that the welding temperature is about 478°C at a stirring speed of 800r/min and a welding speed of 120mm/min, which is a suitable welding parameter.

1. Introduction

Friction stir welding (FSW) technology is a new solid phase connection technology invented by the British Welding Research Institute (TWI) in 1991[1]. The frictional heat generated between the rotating tool and the workpiece to be welded during welding causes the material in the vicinity of the rotating tool to be thermoplastic. When the rotating tool moves forward, the dense solid phase connection joint is formed under the forging action of the shoulder.

FSW has been widely used because of its low soldering temperature, low post-weld residual stress, and high joint performance. In recent years, many scholars have analysed the temperature field of FSW welding process. Song et al. [2] established a three-dimensional heat source model based on the tribological principles and the shear rheology theory for FSW in a moving coordinate system. The final temperature field results are in agreement with the experimental results. Fu Ningning [3] obtained a FSW heat source model considering the frictional heat generation of the shoulder and the rotating tool. The results show that the temperature curve is sensitive to the horizontal location of weldment. Based on the heat generation theory of FSW, Wan Shengqiang [4] developed an adaptive moving heat source considering the friction head friction heat generation. He established a finite element model of 2219 aluminium alloy FSW process, and the welding temperature was 532.4°C.

The above research on the temperature field of FSW considers the frictional heat generation of the shoulder and the pin, ignoring the plastic deformation heat generation of the material. Chen [5] used fluid dynamics to simulate material flow to analyse heat production. But he ignored the frictional heat generation due to the potential sliding at the interface between tool and material.
In this study, the heat source model of FSW process is established by considering friction heat generation and material plastic deformation heat generation. A moving heat source is used to instead of the rotating tool to move evenly on the workpiece. The distribution law of the temperature field is obtained, and the effects of different speeds and welding speeds on the welding temperature field are compared.

2. Establishment of heat source model

2.1. Heat generation analysis of the welding process

During the FSW process, the friction between the rotating tool and the material generates heat to raise the temperature of the material to a plastic flow state, then the plastic state material flows backward to the stirring needle. In this process, the heat is also generated due to plastic deformation, so the welding heat is mainly composed of three parts: the heat generated by the friction between the head shoulder and material (shoulder heat generation), the heat generated by the friction between the stirring pin and material (pin heat generation), heat generated by the shearing of material. The location of the heat source is shown in Figure 1.

\[
Q = Q_1 + Q_2 + Q_3 = \frac{2}{3R^2} \mu \omega F (R^3 - R_1^3) + \frac{2}{3R^3 \sin \alpha} \mu \omega F (R_1^3 - R_0^3) + \frac{2}{3} \mu \omega FR_0
\]  

(1)

In equation (1), \(Q_1\), \(Q_2\) and \(Q_3\) are the heat generated by the shoulder, the pin side and the pin bottom, respectively. \(F\) is the shoulder pressure, \(\omega\) is tool stirring speed, \(R\) is the radius of shoulder, \(R_1\) is the radius of pin (bottom), \(R_0\) is the radius of pin (upside), \(\alpha\) is the cone angle of the pin.

2.2. Frictional heat source model

According to the classical friction theory, the interfacial friction heat due to the relative movement between the tool and workpiece is given as follows [6]

\[
q_p = \bar{\sigma} \alpha_p \tilde{\varepsilon}
\]  

(2)

In equation (2), \(q_p\) is heat flux density, \(\bar{\sigma}\) is equivalent stress, \(\alpha_p\) is thermal conversion efficiency, usually between 0.9~0.95, \(\tilde{\varepsilon}\) is equivalent strain rate. The heat generated by plastic deformation can be expressed as

\[
Q_v = \int \bar{\sigma} \alpha_p \tilde{\varepsilon} dV
\]  

(3)

In equation (3), \(V\) is the volume of plastic material.

3. Establishment of finite element model
3.1. Material properties
In this study, the material to be welded is 7075 aluminium alloy, and the material density is 2810kg/m³. Young's modulus is 71.7GPa and Poisson's ratio is 0.3. During the welding process, some material properties such as specific heat capacity and thermal conductivity are sensitive to the temperature. The specific parameters are shown in Table 1.

**Table 1.** The material parameters of 7075 aluminium alloy

| Temperature/°C | Specific heat capacity/(W•m⁻¹°C⁻¹) | Thermal conductivity/(J•kg⁻¹°C⁻¹) |
|----------------|-------------------------------------|----------------------------------|
| 20             | 835.4                               | 166.7                            |
| 100            | 897                                 | 160.8                            |
| 150            | 916.3                               | 152.7                            |
| 200            | 974                                 | 142.2                            |
| 300            | 1012.5                              | 135.7                            |
| 400            | 1128                                | 128.4                            |
| 500            | 1205                                | 114.8                            |

3.2. Boundary conditions
During the FSW process, the ambient temperature and the convective heat transfer coefficient between the workpiece and air are known. This is consistent with the third type of boundary condition for heat conduction problems [8].

The boundary condition can be expressed as

\[-\lambda \frac{\partial t}{\partial n_s} = h(t_w - t_f)\] (4)

In equation (4), subscript $s$ indicates the boundary surface, $\frac{\partial t}{\partial n_s}$ is the normal temperature gradient on the boundary surface of the object.

The temperature field of the workpiece is substantially symmetrical along the sides of the welded joint surface during the welding process. In order to simplify the calculation, the welded joint surface is treated as a symmetry plane. The bottom surface of the weldment that is in contact with the workbench is set as a heat conduction surface, and the remaining surfaces are convective heat transfer surfaces. The boundary conditions are shown in Figure 2.

3.3. Finite element model
The size of the workpiece is 100mm×80mm×6mm. The stirring pin is conical, the radius of shoulder is 20mm, the bottom radius of pin is 5mm, the upside radius of pin is 3mm, and the height of the pin is 5mm. An eight-node linear heat transfer hexahedral element is used to mesh the workpiece. From the centre to the side of the workpiece, the mesh density is gradually reduced.

In the heat source model, the shoulder heat generation is treated as a plane heat source that is axisymmetric with respect to the weld and the heat flux density increases as the shoulder radius increases. In order to facilitate the post-processing analysis, the starting point of the heat source is set to the coordinate origin, and the welding direction is the positive direction of the x-axis. The established finite element model is shown in Figure 3.
4. Numerical simulation results and analysis

4.1. Overall temperature distribution of welding process
Under the condition that the plunge depth of shoulder is 0.1mm, the stirring speed is 800r/min, the welding speed is 120mm/min, the welding and the cooling time are 50s and 300s, respectively. The temperature field of 7075 aluminium alloy FSW was analysed by using the established finite element model. Temperature distribution at different stages are shown in Figure 4.

![Temperature distribution at different times of the welding process.](image)

According to Figure 4(a), the high temperature region is concentrated under the shoulder, which is ellipsoidal and spreads around. As shown in Figure 4(b) and Figure 4(c), as the welding progresses, the heat-affected zone expands and the workpiece temperature rises. At the end of the welding, the rotating tool pulled out quickly to allow the workpiece material to cool naturally. As shown in Figure 4(d), the convection heat exchange around the workpiece with the air and the middle part of the heat is superimposed so that the central temperature is high and the ambient temperature is low.
Figure 5 shows the overall temperature distribution during the welding process. As the heat source moves, the welding temperature gradually rises from 20°C and stabilizes at around 478°C. The stabilization time lasts for about 30 seconds. This is the welding stabilization phase. The points at this stage are representative when performing temperature analysis. The feature point A (0, 50, 0) at the weld stabilization stage of the weld is selected, and the path 1 perpendicular to the weld direction is obtained from point A as shown in Figure 3. As the welding progressed, a temperature rise occurred near the end of the weldment and the peak temperature reached 530°C. At the end of the welding, the heat absorbed by the workpiece in a certain period of time is higher than the amount of heat lost. At the same time, the workpiece temperature accumulation is high when soldered to the end, and the combined effect of these factors causes the temperature to rise. After welding, the rotating tool leaves the workpiece, and the workpiece is rapidly cooled under convection and radiation heat dissipation.

4.2. Effect of stirring speed on temperature field of FSW

The single factor method was used for the simulation analysis in order to study the effect of the rotating tool speed on the welding temperature field. The temperature curve of the path 1 at different speeds is shown in Figure 6 when the plunge depth of the shoulder is 0.1 mm and the welding speed is 120 mm/min.

It can be seen from Figure 6 that the peak temperatures at five speeds are 398°C, 431°C, 478°C, 514°C, 546°C, and the welding temperature increases with the increase of the tool stirring speed. From equation (1), when the welding speed is constant, the higher the stirring speed, the more work the material rubs against the shoulder at the same time, and the higher the heat production. By equation (2), if the temperature is too high, the surface of the weld will be severely oxidized to reduce the quality of the weld. The temperature at 400 r/min is only 398°C, the material fails to reach the thermoplastic state, and it is easy to cause poor soldering.

4.3. Effect of welding speed on temperature field of FSW

The single factor method was used for the simulation analysis in order to study the effect of the rotating tool speed on the welding temperature field. The temperature curve of the path 1 at different speeds is shown in Figure 7.

It can be seen from Figure 7 that the peak temperatures at five welding speeds are 415°C, 458°C, 478°C, 518°C and 538°C, respectively. When the welding speed decreases, the peak temperature increases gradually. This occurs because the temperature accumulation time is so long that the heat input is increased to cause the temperature of the material to rise. If the soldering temperature is too high, void defects affecting the quality of the soldering will occur. When welding speed is 120 mm/min, the peak temperature can reach 478°C, which is 78% of the melting point of the aluminium alloy. This is consistent with the statement that during the FSW welding process, the melting point temperature of the joint generally does not exceed 80% of the melting point of the material to be welded [9].
5. Conclusion
(1) In this study, a heat source model of FSW is established, considering the friction heat generation and plastic deformation heat generation, and the temperature field of the welding process is analysed. The temperature of the workpiece gradually rises first, and then tends to be stable, and the high temperature area is located below the shoulder and spreads outward as a ring shape during the welding process.

(2) The stirring speed has a large effect on the peak temperature during the welding process. The increase of the stirring speed can cause the plastic deformation heat generation and the friction heat generation to be increased greatly, so the peak temperature of the welding changes greatly.

(3) The effect of the welding speed on the peak temperature is smaller than the stirring speed. The welding speed is low, and the heat accumulation time is long so that the temperature rises. So the peak temperature rises as the welding speed decreases. The welding temperature is about 478°C at a stirring speed of 800r/min and a welding speed of 120 mm/min, which is a suitable welding temperature.

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