The Coupled Deformation and Heat Flow Analysis by Finite Element Method During Friction Welding

The information from these numerical calculations will help further develop the theory and application of friction welding

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ABSTRACT. Temperature, stress and strain fields are three main physical parameters of friction welding. With the development of computer and numerical calculation, the theoretical simulation of these three fields has become one of the most important subjects in thermal processing technology, including friction welding. The present paper carries out the analysis of the coupled thermomechanical problem during friction welding by using finite element method, according to the constitutive relation of large elastoplastic deformation and the principle of the virtual work. The heat flow and stress-strain process at the heating stage of friction welding are simulated. The law of variation of temperature, stress and strain fields during friction welding is systematically investigated. Accordingly, the formation of the plastic deformation zone for the welded joint and the uneven distribution of the deformation degree are analyzed. The calculated results of temperature agree well with the experimental data obtained at some measurable points. The calculated axial stress distribution on the frictional surface at different instances is integrated to compare it with the measured results of the axial pressure and shows excellent fit between them.

Introduction

Friction welding is a complicated metallurgical process including the interaction of heat and force. It is accompanied by and coupled with a series of physical phenomena, heat generated by plastic deformation, dynamic stress-strain process and thermal effects for metal behavior, etc. (Ref. 1). To simulate the friction welding process, the coupled thermomechanical analysis of temperature, stress and strain fields should be carried out (Ref. 2).

However, previous studies (Refs. 3-5) primarily concentrated on numerical simulation of temperature field. Most of them were done under the noncoupling condition. In 1990, Andrzej Sluzalec (Ref. 2) first proposed the increment theory for the thermal elastoplastic finite element calculation and adopted the method of the coupled thermomechanical analysis to calculate the temperature field at the heating stage of friction welding. However, he did not report the results of stress and strain fields.

In the present paper, the finite element calculation model of the coupled deformation and heat flow analysis has been established for friction welding. The transient temperature, stress and strain fields for friction welded joint of GH4169 nickel-base superalloy are then calculated under the given boundary conditions. The calculated results are compared with experimental data obtained in our self-designed friction welding apparatus.

Calculation Model

The coupled analysis of deformation and heat flow is realized through the thermal effect generated by plastic deformation. That is to say, the calculated results of the transient temperature field are correspondingly utilized in the calculation of the transient stress-strain field at each instance. In return, the calculated results of the transient stress-strain field are coupled with and incorporated into the calculation of the temperature field through the thermal effect of plastic deformation.

The dimension of frictional weldment for calculation is shown in Fig. 1. The radius of its outer circle is R. The axial direction is Z-axis. The length as shown in Fig. 1 is L. Under the coupled condition of deformation and heat flow, the fundamental nonsteady equation of heat conduction with changeable thermal properties in the solid is as follows:

$$\rho C \frac{dT}{dt} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + \dot{q}$$  \hspace{1cm} (1)

where \( \dot{q} \) is the coupling factor for the thermomechanical action, whose expression is

$$\dot{q} = a \dot{\varepsilon}$$  \hspace{1cm} (2)

where \( \dot{\varepsilon} \) refers to equivalent strain rate and \( a \) is thermal efficiency of plastic deformation. Here we take \( a = 90\% \) as Ref. 2.

Disregarding the heat exchange caused by natural convection and radiation, the boundary condition of the temperature field is determined as follows:
elastoplastic, that is,
\[
\sigma_{ij}^p = \frac{\partial \Sigma_{ij}^p}{\partial \varepsilon_{ij}^p} + \dot{\alpha}_{ij}
\]
(7)

where
\[
\{\sigma_0\} = \frac{[D]_{0}^{-1} \frac{\partial \sigma}{\partial \varepsilon} \frac{\partial H}{\partial \dot{\varepsilon}} + \{P\}_{0} \frac{\partial \sigma}{\partial \varepsilon}}{\frac{\partial \delta}{\partial \varepsilon}}
\]
(for initial stress rate)

The boundary conditions are as follows: The measured variation of the axial shrinkage of the workpiece with time during friction welding is adopted as the displacement boundary condition of the calculation equation; the fixed end of the workpiece is supposed to have zero displacement.

As stated above, the fundamental heat conduction equation and the large deformation thermal elastoplastic equation are systematically reduced by finite element and can be described as in Equations (8) and (9), respectively.

\[
[C] \{\dot{T}\} + [K] \{T\} = \{Q\}
\]
(8)

where
\[
[C] = \text{entropy production rate matrix},
\]
\[
[K] = \text{heat transmission matrix},
\]
\[
\{Q\} = \text{general heat flow vector matrix},
\]
\[
([K_0] + [K_s]) \{\dot{\varepsilon}\} = \{\dot{\varepsilon}\}
\]
(9)

Table 1 — Thermal Properties of the GH4169 Superalloy

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>100</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity, k (W/m · °C)</td>
<td>14.5</td>
<td>15.5</td>
<td>19.0</td>
<td>22.0</td>
<td>14.0</td>
<td>27.5</td>
<td>29.1</td>
</tr>
<tr>
<td>Specific heat, C (J/Kg · °C)</td>
<td>450</td>
<td>480</td>
<td>510</td>
<td>570</td>
<td>660</td>
<td>710</td>
<td>770</td>
</tr>
</tbody>
</table>
Table 2 — Friction Welding Parameters

<table>
<thead>
<tr>
<th>Rotational Speed (rpm)</th>
<th>Friction Pressure (MPa)</th>
<th>Upset Pressure (MPa)</th>
<th>Friction Time (s)</th>
<th>Upset Time (s)</th>
<th>Max. Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1468</td>
<td>360</td>
<td>658</td>
<td>10.2</td>
<td>5</td>
<td>5.9</td>
</tr>
</tbody>
</table>

\[ [K_s] \] = initial stress element rigidity matrix.
\[ \{\alpha\} \] = speed train vector of the panel point of the matter.
\[ \{\dot{r}\} \] = load rate train vector (including thermal load).

The friction bases have a diameter of 18 mm and lengths of 80 mm and 160 mm, respectively. The welding parameters harnessed in both calculation and experiment are listed in Table 2. The instructions both for braking and forging are synchronously sent out by a computer measurement control system. The heat generated and displacement boundary condition are measured by experiment.

Results and Discussions

Temperature Field

Under the conditions (two-dimensions, axial symmetry, nonsteady and temperature dependent thermal properties, etc.) of the calculation, the calculated results of the transient temperature field for the GH4169 superalloy bar are shown in Fig. 2.

As shown in Fig. 2A–C, during the initial frictional stage (0–1.8 s), the temperature distribution along the radial and axial directions of welding heat affected zone (HAZ) appears as a rather complex curved shape. There is a very high heating rate and a steep temperature gradient in this zone. With the frictional heating time increasing, the curved plane of temperature distribution extends, as shown in Fig. 2D–F, due to the heat conduction along the radial and axial directions, and the temperature gradually increases. Consequently, the temperature gradients in both radial and axial directions gradually become smaller. At the breaking and forging instant (10.2 s set in this study), the shape of the temperature distribution almost becomes planar, and the axial width of the zone heated above 700°C reaches 7 mm.

During the period (before 1.8 s) when the frictional torque does not reach its front peak value, the temperature on the frictional surface rises rapidly, and the rate at which the temperature rises at the outer boundary is the fastest, about 980°C/s. At 1.8 s instant, the frictional torque increases to its front peak value. After the peak value, the friction characteristics of the frictional surface transform from the original shearing with many adhesive points to high-temperature plastic metal shearing. Accordingly, the frictional torque decreases gradually to a stable value (balance torque). Corresponding with the variation of the

![Fig. 2 — Dynamical variation process of temperature field during friction welding.](image-url)
frictional torque stated above, the heating rates at each point of the frictional surface become slower and slower. Once the frictional torque reaches its balance value, the heating rates on the frictional surface become uniform and near the constant value, about 25°C/s. The outer circle of the frictional surface has the highest temperature.

Before the frictional torque reaches its front peak value, the highest temperature is about 800°C. At the moment of 10.2 s, the highest temperature is about 1240°C. Apparently, the highest temperature on the frictional surface does not exceed the melting point of the welded material. This is due to the interconstraint relation between the frictional heating power and frictional characteristics on the surface.

The thermal cycle curve at some measurable points in the weldment is detected by armored thermal couple Ni-Cr+Ni-Si. Figure 3 gives the comparison of the detected and calculated results, showing excellent fit between them.

Stress-Strain Field

According to the plastic theory, equivalent strain or plastic work density can be considered as the plastic criterion of the strain strengthening material. Figure 4 shows the variation of the equivalent strain distribution with time during frictional heating stage.

![Fig. 3 - Comparison between the calculated results and measured points of temperature.](image)

![Fig. 4 - Variation of the equivalent strain distribution with time during frictional heating stage.](image)

![Fig. 5 - Variation of the plastic work density distribution in the one quarter of the joint with time.](image)
distribution of the isoline for equivalent strain (isoline is drawn in equal numerical space) on the one quarter of the welded joint during the frictional heating stage. Plastic deformation phenomenon related to the welding process can be observed from this figure:

1) The equivalent strain at the axial zone of the frictional welded joint is larger than that at the other zone.

2) The distribution area for the isoline of the equivalent strain at the outer circle zone of the welded joint is wider than that at the axial zone; that is, the plastic deformation area at the outer circle zone is wider than that at the axial zone.

Figure 4 also reflects the variation of the equivalent strain distribution with welding time. With the frictional time increasing, the temperature rises rapidly and the high-temperature zone along radial and axial directions widens. Accordingly, the equivalent strain gradually increases, and its isoline becomes more and more intensive and tends to distribute near the frictional surface. This phenomenon shows that, with the frictional time increasing, the plastic deformation of the welded joint tends to concentrate on the frictional surface and the zone adjacent to that surface. Moreover, the extent of plastic deformation along axial and radial directions increases unevenly.

The variation of the plastic work density distribution in the one quarter of the joint with time is shown in Fig. 5. The distribution characteristics and variation law of the plastic work density fit well with those of the equivalent strain field shown in Fig. 4.

The isoline distribution of the axial normal stress $\sigma_z$ in the one quarter of the joint calculated at selected moment of 10.2 s is shown in Fig. 6. From this figure,
we find that the frictional surface and the zone adjacent to that surface are compressive stress zones, and that a certain zone far away from the frictional surface is the tensile stress zone, which is surrounded by the zones with larger compressive stress.

Figure 7 shows the variation of $\sigma_z$ distribution at the axis ($r=0$) with time. When $t<4$ s, $\sigma_z$ is a compressive stress. When $t>4$ s, $\sigma_z$ is still a compressive stress in the zone of $z<6$ mm and $z>18$ mm; while in the zone of $6$ mm $<z<18$ mm, $\sigma_z$ becomes a tensile stress. As frictional time increases, the tensile stress zone widens and the value of the tensile stress increases, while the compressive stress zone narrows and its value decreases.

Figure 8 shows the variation of $\sigma_z$ distribution along the radial direction ($z=0$) with time. Here, the axial stress $\sigma_z$ acting on frictional surface is all compressive stresses. As the frictional time increases, the compressive stress rises, then decreases.

The main cause for the variation of stress distribution with time stated above is that the local high temperature of the welded joint leads to its deformation, which will be strongly restricted by the other cooler part of the weldment. Subsequently, the internal stress of the weldment redistributes due to the deformed weldment and ultimately reaches a new balance state in the weldment. Furthermore, metal softening at the frictional surface and the decrease of average compressive stress in the weldment also result in producing tensile stress.

By using the related method of mechanics calculation, the axial stress $\sigma_z$ distribution on the frictional surface at different instances has been integrated. The calculated results are in good agreement with the measured results of variation of axial pressure with time as shown in Fig. 9.

**Summary**

The analysis and calculation carried out in this paper show that the finite element coupled analysis of deformation and heat flow is an effective way for simulating the dynamic variation process of the temperature, stress and strain fields of frictional welding. The calculated results are in good agreement with the experimental points. The information obtained from our numerical calculation work is valuable to further develop the fundamental theory and engineering application research of friction welding.

**References**