Numerical Model of Multi-pass Repair Process by Temper Bead Welding*

by Hiroki Murakami**, Shigetaka Okano**, Masahi Kameyama***, Takehiko Sera**** and Masahito Mochizuki**

In this study, a numerical model coupling weld bead formation and thermal conduction was developed for more accurate simulation of the temperature distribution during temper bead welding. Most of the welding parameters used in the analysis were estimated from experimental welding conditions based on experiments and numerical simulations of previous research works. The simulation results were compared with the experimental results under the same welding conditions to confirm the usefulness of the developed numerical model. Except for the weld penetration shape, the analytical results of the bead surface shape and the temperature distribution, such as the $A_{\text{c}1}$ lines, were in good agreement with the experimental results. The developed model has the potential to be effective and more precise in predicting and evaluating properties such as the metallurgical structure and the hardness of the HAZ and the resulting weld residual stress by temper bead welding with the appropriate computational cost.

Key Words: Tempar bead welding, Numerical simulation, Bead shape, Temperature distribution, Welding condition

1. Introduction

In recent years, stress corrosion cracking (SCC) has been observed in the nickel base alloy weld metal of dissimilar pipe joints used in pressurized water reactor plants1). Temper bead welding, which improves the properties of the heat-affected zone (HAZ) or the weld metal located under the temper bead, is proposed as one of the repair processes against SCC when post weld heat treatment (PWHT) is difficult to carry out2-4). However, before temper bead welding is actually used in industrial applications, the weld properties must be verified by property and performance qualification tests. Depending on the results of the property and performance qualification tests, the appropriate welding conditions in temper bead welding must also be determined.

Alternative test procedures requiring lower cost, less time, and a high degree of reliability are desirable. Numerical simulation is regarded as one of the alternative procedures for qualifying the properties of welds. To improve the numerical simulation technique, more precise numerical analysis of the temperature distribution during temper bead welding is required because the properties of the metallurgical structure and the hardness at the welds occur as a result of the thermal cycles during welding.

Laboratory testing has confirmed that it is possible to grow SCC even in Alloy 690, an SCC-resistant welding material used in temper bead welding. So, it is also important to evaluate the residual stress, which is a driving force for the occurrence of SCC, to ensure higher structural soundness and reliability in a part repaired by temper bead welding. If more precise numerical analysis of the temperature distribution during temper bead welding can be developed, the weld residual stress can be predicted and evaluated more accurately.

In this study, a numerical model coupling weld bead formation and thermal conduction was developed for more accurate simulation of the temperature distribution during temper bead welding. The simulation results are compared with the experimental results under the same welding conditions to confirm the usefulness of the developed numerical model.

2. Numerical model of temper bead welding

Since temper bead welding is multi-layer cladding, the temperature distribution is affected by the weld bead formation during welding and the surface shape of the existing weld bead after the previous weld pass. The developed numerical model calculates the coupling between weld bead formation and thermal conduction to consider the change of the bead shape during temper bead welding.

The flow of the numerical calculation is shown in Fig. 1. The temperature distribution is calculated by a thermal conduction analysis that updates the addition or deletion of elements based on the bead formation results at each step. Estimations of most of the welding parameters used in the analysis are based on the experimental welding conditions of previous research works5-7).
In the thermal conduction analysis, the temperature distribution is calculated by solving the heat conduction equation, shown in Eq. (1).

\[
\rho \frac{\partial H}{\partial t} = \frac{\partial}{\partial x} \left[ K \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[ K \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[ K \frac{\partial T}{\partial z} \right]
\]

In Eq. (1), \( \rho \): density, \( H \): enthalpy, \( K \): thermal conductivity, \( T \): temperature.

Within the area of the weld bead, the bead surface shape is calculated based on the quantity of welding wires applied to the base metal and the equilibrium of forces \( \Phi \) by solving Eq. (2).

\[
\alpha \left( \frac{1 + \phi^2_x}{\left( \frac{1}{2} + \phi^2_x + \phi^2_y \right)^{3/2}} \right) = \rho \phi + P - \lambda \tag{2}
\]

3. Conditions for experiment and simulation

3.1 Experimental conditions

The materials used in this study are low alloy steel A533B for the base metal and nickel base alloy Alloy 690 for the weld metal (welding wire). The chemical compositions of these materials are shown in Table 1. The dimensions of the weld plate are length 150 mm, width 100 mm, and thickness 35 mm, as shown in Fig. 2. Multi-pass temper bead welding is performed on the center of the plate. The welding conditions in each pass are shown in Table 2. After welding, the bead surface shape, the weld penetration, and the \( A_{c3} \) lines, as representative examples of the highest temperature distribution, were seen through cross-sectional macro observations. That is, the \( A_{c1} \) and \( A_{c3} \) transformation temperatures of A533B are 670°C and 837°C, respectively.

3.2 Analytical conditions

The plate sizes of the analytical model are the same as those used in the experiment. In the analysis, the minimum size of elements at the melted zone is length 1.0 mm, width 0.5 mm, and thickness 0.5 mm. The density is set to \( 8.0 \times 10^{-6} \text{ [kg/mm}^3] \) and the

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cu</th>
<th>Cr</th>
<th>Mo</th>
<th>Al</th>
<th>Fe</th>
<th>Ti</th>
<th>Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>A533B</td>
<td>0.12</td>
<td>0.26</td>
<td>1.43</td>
<td>0.006</td>
<td>0.002</td>
<td>0.53</td>
<td>0.02</td>
<td>0.01</td>
<td>0.51</td>
<td>0.038</td>
<td>Bal.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alloy 690</td>
<td>0.02</td>
<td>0.15</td>
<td>0.27</td>
<td>0.0021</td>
<td>0.0009</td>
<td></td>
<td>29.59</td>
<td>0.02</td>
<td>0.216</td>
<td>10.13</td>
<td>0.405</td>
<td>0.05</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Welding conditions.
surface tension is 1.0 [N/m]. The acceleration of gravity is set to 9.8 [m/s²]. The material properties of specific heat and thermal conductivity used in the numerical analysis have a temperature dependency, as shown in Fig. 3.

![Thermal conductivity and Specific heat graphs](image)

Fig. 3 Material properties used in numerical analysis.

By using wire feeding rate $V_{Mr}$ and diameter of wire $D$ from the experimental conditions, the supply rate of deposited metal $V_w$ is calculated in Eq. (3). The calculated supply rate of deposited metal $V_w$ in each pass is shown in Table 3.

$$V_w = \pi V_{Mr} \left( \frac{D}{2} \right)^2$$

Table 3 Calculated supply rates of deposited metal.

<table>
<thead>
<tr>
<th>Layer</th>
<th>$V_w$ [cm/min]</th>
<th>$D$ [mm]</th>
<th>$V_c$ [mm³/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>0.9</td>
<td>31.8</td>
</tr>
<tr>
<td>2, 3</td>
<td>150</td>
<td>0.9</td>
<td>15.9</td>
</tr>
</tbody>
</table>

The distributions of the weld heat input and the arc pressure during temper bead welding are estimated based on the numerical simulation results of the welding arc plasma. The welding arc plasma is simulated without welding wires, even though temper bead welding uses welding wires. In this study, it is assumed that both the sum of the weld heat input and the arc pressure given to the welded plate are not influenced by the existence of welding wire in the welding arc. Also, the heat input from the welding wires is estimated under the assumption that the temperature in the metal droplet is 2900 K. Table 4 shows the total amount of weld heat input $q_{total}$ divided between the heat input provided to the surface of welded plate $q_{plate}$ and that possessed in deposited metal $q_{wire}$. The distributions of the weld heat input and the arc pressure provided to the welded plate are shown in Fig. 4 and Fig. 5, respectively.

![Distribution of weld heat input](image)

Fig. 4 Distribution of weld heat input provided to welded plate.

![Distribution of arc pressure](image)

Fig. 5 Distribution of arc pressure provided to welded plate.
4. Results and discussion

The analytical results of the weld bead shape and the maximum temperature distribution after single-layer welding and 3rd-layer welding are shown in Fig. 6 (a) and (b), respectively. In addition, the experimental results of the cross-sectional macro observations after single-layer welding and 3rd-layer welding are shown in Fig. 6 (c) and (d), respectively. As shown in these figures, the shape of the bead surface and the weld penetration in the simulation results, especially in the case of single-layer welding, is a semicircular shape, whereas that in the experimental result is flat. This is because the metal droplet transfer and convective heat transfer in the weld pool are not considered in the calculations. In addition, the effect of the existence of the welding wire in the welding arc plasma on the arc pressure is not negligible. In the condition of a large welding current, the weld pool during welding penetrates deeper due to the intensive arc pressure. However, the global weld bead surface shape and the temperature distribution, such as the $A_{c1}$ lines, in the numerical simulation and the experimental results are in good agreement.

Thus, to simulate the weld bead and the molten pool formation more accurately, more complicated weld phenomena must be considered, even though the computational cost is increased drastically. For reasonable predictive simulation techniques, it is expected that the developed model has the potential to be effective and more precise in simulating properties such as the metallographic structure and the hardness of the HAZ and the resulting weld residual stress by temper bead welding.

5. Conclusions

A numerical model was developed for calculating the coupling between weld bead formation and thermal conduction during temer bead welding. The usefulness of the developed model was validated by comparing the analytical results with the experimental results. Except for the weld penetration shape, the analytical results for the bead surface shape and the temperature distribution were in good agreement with the experimental results. Therefore, the developed model has the potential to be effective and more precise in predicting and evaluating properties such as the metallographic structure and the hardness of the HAZ and the resulting weld residual stress by temper bead welding.

References

394-398.


