Effect of Process Variable on Temperature Distribution in the Heat-Affected Zone of Temper Bead Welds*

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Stress corrosion cracking (SCC) has recently been observed in Ni-based alloy welds in nuclear power plants, despite countermeasures to prevent it. In the repair welding, temper bead welding (TBW) is applicable when post weld heat treatment (PWHT) is difficult to carry out. In TBW, the welding process variables are appropriately controlled so that the thermal cycles of the subsequent passes provide the area hardened by previous passes with the temper effect, so the hardened area size and thermal cycle tempering parameter (TCTP) are very important. However, very few studies have discussed the quantitative relationships among the hardened area size, TCTP and the welding process variables. In this study, we conducted a combined weld bead surface profile and heat conduction analysis for simulating temper bead welding with Ni-based filler metal to SQV2A plate under various welding conditions. We quantified the hardened area size and TCTP as linear functions of the welding process variable parameter, which was derived from welding heat conduction theory with a moving heat source. Consequently, we concluded that the appropriate welding conditions in temper bead repair welding can be determined based on the welding process variable parameter.

Key Words: Temper bead welding, Process variable, Temperature Distribution, Thermal cycle tempering parameter, Heat conduction analysis, Weld bead surface profile analysis

1. Introduction

Stress corrosion cracking (SCC) has recently been observed in Ni-based alloy welds in nuclear power plants, despite countermeasures to prevent it. In the repair welding, temper bead welding (TBW) is applicable when post weld heat treatment (PWHT) is difficult to carry out. In TBW, the welding process variables are appropriately controlled so that the thermal cycles of the subsequent passes provide the area hardened by previous passes with the temper effect, so the hardened area size and thermal cycle tempering parameter (TCTP) should be controlled appropriately. However, very few studies have discussed the quantitative relationships among the hardened area size, TCTP and the welding process variables.

In this study, through a combined weld bead surface profile and heat conduction analysis, we quantified the hardened area size and TCTP with the process variables in temper bead welding.

2. Combined weld bead surface profile and heat conduction analysis

In this study, we conducted a combined weld bead surface profile and heat conduction analysis to take into account the interaction between bead formation and temperature distribution during welding.

In the profile analysis of the weld bead surface, the proposed curved surface equation shown in Eq. (1) was used, where $x$ is the welding direction, $z$ is the vertically upward direction, $y$ is the direction perpendicular to the x-z plane and $z_{xx}$, $z_{yy}$, $z_{xy}$ and $z_{yx}$ are $\frac{\partial z}{\partial x}\frac{\partial z}{\partial x}$, $\frac{\partial z}{\partial y}\frac{\partial z}{\partial y}$, $\frac{\partial z}{\partial x}\frac{\partial z}{\partial y}$ and $\frac{\partial z}{\partial x}\frac{\partial z}{\partial y}$, respectively. This equation was derived from the equilibrium of the surface tension $\sigma$, gravity and arc pressure $P_{arc}$ by using the density $\rho$ and gravitational acceleration $g$. The Lagrange multiplier $\lambda$ was determined by the bisection method to balance the bead volume increment with the wire supply.

$$
\frac{\sigma}{(1 + z_{xy}^2) z_{xx} - 2 z_{xy} z_{xy} + (1 + z_{yy}^2) z_{yy}} = \rho g z + P_{arc} - \lambda \quad (1)
$$

In the heat conduction analysis, the three-dimensional heat conduction equation shown in Eq. (2) was used, where $t$ is the elapsed time, $\lambda$ is the heat conductivity, $H$ is the specific enthalpy, $T$ is the temperature and $w$ is the heat generation.

$$
\rho \frac{\partial H}{\partial t} = \frac{\partial}{\partial x} \left[ \lambda \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \lambda \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[ \lambda \frac{\partial T}{\partial z} \right] + w \quad (2)
$$

For the combined analysis, Gaussian distributed heat input was provided to the surface of welded plate directly from a traveling welding arc, and then the filler metal elements with enthalpy were added according to the calculated weld bead surface displacement. Then, the bead radius was determined by referring to a previous study. The heat radiation based on the Stefan-Boltzmann law

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and the heat transfer (15 × 10^6 W/mm^2K) on the metal surface were also taken into account.

3. Heat conduction theoretical parameters controlling welding temperature profiles

3.1 Parameter to estimate hardened area size

To estimate the hardened area size based on the process variables in the TBW technique, the parameters associated with the process variables were derived from welding heat conduction theory.

It has been reported that at a distance from the weld zone, the theoretical solution of the temperature rise by a moving point heat source, such as that in TIG welding, is almost equal to the theoretical solution by an instantaneous line heat source. However, it was unclear whether the size of the hardened area, where the peak temperature is over 837 °C, depends on welding heat conduction theory with an instantaneous heat source or a moving heat source. To examine the dependence, we adopted two welding process variable parameters: the parameter derived from welding heat conduction theory with an instantaneous heat source and the parameter with a moving heat source.

Equation (3) shows the theoretical solution of the temperature rise \( T \) by an instantaneous line heat source. In Eq. (3), \( q \) is the heat input per unit time, \( v \) is the welding speed, \( k \) is the heat diffusivity, \( c \) is the specific heat, \( \rho \) is the density, \( r \) is the distance from the welding line and \( t \) is the elapsed time. When the temperature rises to the maximum temperature \( T_{\text{max}} \), or \( \partial T/\partial r = 0 \), Eq. (4) is obtained. According to this equation, \( T_{\text{max}} \) is proportional to \( \sqrt{q/v} \). Therefore, we adopted \( \sqrt{q/v} \) as the welding process variable parameter derived from welding heat conduction theory with an instantaneous heat source.

\[
T = \frac{1}{(2\sqrt{\pi}kt)^2} \frac{1}{c\rho v} \exp \left( -\frac{r^2}{4kt} \right) 
\]

(3)

\[
r = \frac{1}{\pi c \rho} \sqrt{\frac{1}{T_{\text{max}}} \cdot \frac{q}{v}} 
\]

(4)

Equation (5) shows the theoretical solution of the temperature rise \( T \) by a moving point heat source. In Eq. (5), the origin of coordinates is the arc center, \( x \) is the welding direction and \( r \) is the distance from the welding line.

\[
T = \frac{q}{4\pi \rho k} \exp \left( \frac{v}{2k} \left( x - \sqrt{x^2 + r^2} \right) \right) \frac{1}{\sqrt{x^2 + r^2}} 
\]

(5)

In a previous study, it was derived both experimentally and theoretically that under the condition of a constant plate thickness, the maximum temperature near the welded zone \( T_{\text{max}} \) is proportional to \( q/\sqrt{v} \), as given in Expression (6). Therefore, we adopted \( q/\sqrt{v} \) as the welding process variable parameter derived from welding heat conduction theory with a moving heat source.

\[
T_{\text{max}} \propto \frac{q}{\sqrt{v}} 
\]

(6)

3.2 Parameter to estimate the temper effect

It is well known that the Larson-Miller parameter (LMP) \( P \) is generally used for predicting the temper effect during isothermal heat treatment. The parameter, which is a derivative of the Arrhenius equation with an approximation derived from experimental consideration, is represented by Eq. (7), where the holding temperature is \( T \) [K] and the holding time is \( t \) [hr].

\[
P = T(20+\log t) 
\]

(7)

However, LMP is not directly applicable to the TBW technique because TBW is a non-isothermal process. The thermal cycle tempering parameter (TCTP) was proposed as an extended LMP and then applied to estimate the temper effect during a non-isothermal process such as the TBW technique. The parameter was derived from the additivity rule of holding times for multiple PWHT cycles. When LMP at a holding time \( t_{1} \) and a holding temperature \( T_{1} \) is equal to LMP at another holding time \( t_{2} \) and another holding temperature \( T_{2} \), as in Eq. (8), \( t_{2} \) is represented by Eq. (9). In multiple PWHT cycles, to calculate the cumulative holding time, the holding times at the holding temperatures are converted to an equivalent time as shown in Eq. (9).

\[
P = T_{1}(20+\log t_{1}) = T_{2}(20+\log t_{2}) 
\]

(8)

\[
t_{2} = 10^{\frac{T_{1}}{20} - 20} \]

(9)

TCTP is calculated by applying the additivity rule for each efficiently short time segment \( \Delta t \) shown in Eq. (10).

\[
P_{n+1} = T_{n+1}(20+\log(\sum_{i=1}^{n} t_{n} + \Delta t)) 
\]

(10)

Thus, TCTP can be applied to a non-isothermal process. In this study, we adopted TCTP to estimate the temper effect during the TBW technique.
4. Analytical conditions

In this study, we conducted two series of analyses: a first layer welding analysis, and a subsequent layer welding analysis.

In the first layer welding analysis, TIG welding with filler metal was conducted on a low-alloy steel SQV2A plate. The Ni-based alloy electrode ENiCrFe-1 was used for filler metal. The heat conductivity and specific heat of SQV2A and ENiCrFe-1 are shown in Fig. 1. The density was $8.0 \times 10^{-6} \text{ kg/mm}^3$ for both materials. The dimensions of the SQV2A plate were 150 mm×150 mm×50 mm, as shown in Fig. 2. The welding length was 130 mm at the center of the plate except for 10 mm from each plate edge. Table 1 lists the 60 welding process variable conditions that were prepared, and Table 2 lists the total heat input at each welding current based on experimental data.

In the subsequent layer welding analysis, a deposited filler metal layer with a thickness of 1-3 mm was set on a SQV2A plate. A total of 180 welding process variable conditions were prepared in combination with the 60 welding process variable conditions used in the first layer welding analysis. The dimensions of the SQV2A plate were 150 mm×150 mm×50 mm, as shown in Fig. 2. The welding length was 130 mm at the center of the plate except for 10 mm from each plate edge. Table 1 lists the 60 welding process variable conditions that were prepared, and Table 2 lists the total heat input at each welding current based on experimental data.

Both analyses used the appropriate TBW heat source model, which was constructed and experimentally validated in a previous study. The distributions of the heat input and the arc pressure directly provided to the surface of welded plate from a traveling arc are shown in Fig. 3.

![Fig. 1 Material properties.](image1)

![Fig. 2 Dimensions of the SQV2A plate.](image2)

![Fig. 3 Distributions of the weld heat input and the arc pressure (in the case of no wire supply).](image3)

| Table 1 Combinations of welding process variable conditions. |
|---------------------------------------------------------------|
| Welding current, $I$ [A]                                     | 120, 140, 160, 180 |
| Welding speed, $v$ [mm/s]                                     | 1.33, 2.00, 2.67, 3.33, 4.00 |
| The percentage of the enthalpy of the filler metal elements to all weld heat input [%] | 0, 10, 20 |

| Table 2 Total heat inputs.                                      |
|----------------------------------------------------------------|
| Welding current, $I$ [A] | 120 | 140 | 160 | 180 | 120 | 140 | 160 | 180 | 120 | 140 | 160 | 180 |
| The percentage of the enthalpy of the filler metal elements to all weld heat input [%] | 0 | 0 | 0 | 0 | 10 | 10 | 10 | 10 | 20 | 20 | 20 | 20 |
| Weld heat input, $q$ [J/s] | 1116 | 1280 | 1480 | 1692 | 1116 | 1280 | 1480 | 1692 | 1116 | 1280 | 1480 | 1692 |
| Heat input by filler metal [J/s] | 0 | 0 | 0 | 0 | 105 | 125 | 144 | 163 | 211 | 249 | 288 | 326 |
| Heat input by arc [J/s] | 1116 | 1280 | 1480 | 1692 | 1011 | 1155 | 1336 | 1529 | 905 | 1031 | 1192 | 1366 |
5. Results and discussion

5.1 Effect of welding process variables on hardened area in TBW technique

As shown in Fig. 4, the first layer welding indicates a good linear relationship between the hardened area depth and the welding process variable parameter \( q/\sqrt{v} \) for each wire supply condition. In comparison with the relationship between the hardened area depth and the welding process variable parameter \( \sqrt{q/v} \), as shown in Fig. 5, the relationship between the depth and \( q/\sqrt{v} \) indicates better linearity. Hence, the hardened area depth depends on \( q/\sqrt{v} \) more strongly than on \( \sqrt{q/v} \). Likewise, this tendency was observed in the whole area near the weld zone.

Similarly, in the subsequent layer welding, a good linear relationship between the peak temperature and the welding process variable parameter \( q/\sqrt{v} \) was obtained. Moreover, we found that TCTP was strongly dependent on the peak temperature, as shown in Fig. 6. The area where TCTP reaches a certain value can also be controlled by the proposed welding process variable parameter \( q/\sqrt{v} \). Fig. 7 shows an example of the good linear relationship between the depth of area where TCTP is over 14000 and the welding process variable parameter. Additionally, the influence of the filler metal layer thickness on the relationship was hardly observed.

5.2 Discussion about appropriate welding process variable conditions in TBW technique

The quantitative relationships among the hardened area size, TCTP and the welding process variable parameter are expected to be applicable to determining the appropriate welding process variable conditions in the TBW technique.

From the quantitative relationships, the hardened area depth \( d_{873} \) and the depth of the area \( d_{\text{TCTP}} \) where TCTP reaches a certain value are expressed as Eqs. (11) and (12), where the proportionality constants are \( A_{1\text{st}} \) and \( B_{2\text{nd}} \), and the welding process variable parameter is \( q/\sqrt{v} \).

To prevent re-hardening in subsequent layer welding, the maximum welding process variable parameter \( (q/\sqrt{v})_{\text{max of 2nd}} \) can be determined as shown in Eq. (13) to prevent the hardened areas.

![Fig. 4 Relationship between the hardened area depth and the welding process variable parameter \( q/\sqrt{v} \).](image1)

![Fig. 5 Relationship between the hardened area depth and the welding process variable parameter \( \sqrt{q/v} \).](image2)

![Fig. 6 Relationship between TCTP and the peak temperature.](image3)

![Fig. 7 Relationship between the depth of area where TCTP is over 14000 and the welding process variable parameter \( q/\sqrt{v} \).](image4)
of the first layer welding and the subsequent layer welding from overlapping; that is, the parameter is determined so that the depth of the area where the temperature is over $A_{c3}$ of SQV2A in subsequent layer welding $d_{2nd,873}$ does not exceed the filler metal layer thickness $h$ ($d_{2nd,873} < h$), as illustrated in Fig. 8.

Meanwhile, to provide the area hardened by previous passes with a sufficient temper effect, the minimum welding process variable parameter $(q_2v)^{max.,of,2nd}$ can be determined as shown in Eq. (14) to provide the area hardened by previous passes with a sufficient TCTP; that is, the parameter is determined so that the depth of the area where TCTP reaches at a certain value $d_{2nd,TCTP}$ exceeds the sum of the filler metal layer thickness $h$ and the depth of area hardened by previous passes $d_{1st,873}$ ($d_{2nd,TCTP} > h + d_{1st,873}$), as illustrated in Fig. 9.

Fig. 10 shows an example of the range of the appropriate welding process variable parameter. Although the requirements are assumed, the appropriate welding process variable conditions in the TBW technique can be determined based on the welding process variable parameter proposed in this study.

$$d_{873} = A_{873}(q_1/\sqrt{v})_{1st}$$  \hspace{1cm} (11)

$$d_{TCTP} = B_{TCTP}(q_2/\sqrt{v})_{2nd}$$  \hspace{1cm} (12)

$$\left(q_2/\sqrt{v}\right)_{max.,of,2nd} = h/A_{873}$$  \hspace{1cm} (13)

$$\left(q_2/\sqrt{v}\right)_{min.,of,2nd} = (A_{873}q_1/\sqrt{v})_{1st} + h/B_{TCTP}$$  \hspace{1cm} (14)

6. Conclusion

Through the combined temperature and bead surface profile analyses of the TBW technique, we quantified the hardened area size and TCTP, as linear functions of the welding process variables parameter, which was derived from welding heat conduction theory with a moving heat source. Consequently, in the TBW technique, we established a methodology for estimating the appropriate welding conditions based on the welding process variable parameter.

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