Estimation of Cooling Rate from 800 °C to 500 °C in the Welding of Intermediate Thickness Plates Based on FEM Simulation

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Abstract: FEM (finite element method) simulation for estimating the cooling rate from 800 °C to 500 °C in welding cycle of plates with intermediate thickness is presented. Moving double ellipsoid heat sources were applied to simulate the thermal field of welding process, and the cooling rates were investigated with different welding parameters including plate thickness, heat input and preheating temperature according to the analysis of heat transfer characteristics. The critical condition for defining intermediate thickness of plates was determined through comparison between FEM results and calculation results from conventional analytical solutions of Rosenthal et al. and prediction equations of cooling rate in welding of plates with intermediate thickness were established based on regression analysis of FEM results using polynomial method. The feasible range of the equations with preheating temperature was discussed. The welding experiments with the same parameters were carried out to verify the effectiveness of the prediction equations. The compared results of thermal cycles and microstructures between experiment and FEM showed that a good agreement was obtained.

Key words: FEM, intermediate thickness plates, cooling rate, microstructure.

1. Introduction

It is well known that there are two processes in thermal cycle of general welding, first of them is the very rapid heating (several hundreds of degrees per second) to a peak temperature, followed by relatively fast cooling (a few tens or hundreds of degrees per second) to ambient temperature after the heat source moving away. The microstructure change in the weld zone and the weld HAZ (heat-affected zone), is greatly dependent on the cooling rate and determining the mechanical performance of the weld joint. Therefore, it is important to predict the thermal cycle characteristics such as cooling rate from 800 °C to 500 °C which is directly related to the microstructure and mechanical properties in HAZ where there is a weak zone usually [1]. This becomes more significant if the effect of heat input on the microstructure changes in the HAZ is to be estimated for a given material, as the heat input is only a rough, simplified parameter specific to a welding process [2].

Analytical solutions for prediction of cooling rate according to the classical heat transfer theory was proposed by Rosenthal [3, 4], which were most widely used and best known. His approach was based on the assumption of a moving point heat source on the plate surface, neglecting any heat transfer from the surface. The physical coefficients were constant independent of temperature, and latent heat of phase change was neglected. Then Ashby and Easterling [5] simplified two limiting solutions derived by Rosenthal’s theory to obtain temperature/time profiles in the HAZ. One set of solutions was derived for thin plates (assuming 2D heat flow) and the other for thick plates (assuming...
3D heat flow). There is an equation to determine a critical thickness for a given heat input (or a critical heat input for a given plate thickness, if used in reverse) at which the 2D condition changes to 3D ones. However, these criteria may be too simplistic, real welds are more likely to lie between the two limiting solutions when different thickness and heat input are applied. Thus 2.5D model that lies with respect to the 2D and 3D conditions was classified by some researchers. The modified formulas for 2.5D model were then deduced with the factors of HAZ width, peak temperature and thickness of plates by K. Poorhaydari [6] and Xiao Li [7]. But their formulas did not consider all the factors including heat input, plate thickness and preheating temperature, which directly affect the cooling rate of the welding.

In this paper, 3D model equivalent to the actual weld size was established by FEM (finite element method), where thermal physical parameters at different temperature were taken into account as well as phase transformation. Moving heat sources described by double ellipsoids were applied to simulate the welding process numerically. Then, the cooling rate from 800 °C to 500 °C (defined as $t_{8/5}$) under different welding conditions (such as heat input, plate thickness and preheating temperature) was discussed by analyzing temperature field. What is more, the critical thickness for defining intermediate plate was determined through comparison between FEM results and calculation results from theoretical formulas. Numerical prediction equations on $t_{8/5}$ of intermediate plate HAZ were established based on regression analysis of FEM using polynomial method. Finally, the welding experiments by the same parameters were applied to verify the effectiveness of prediction equations from FEM.

2. Numerical Model and Welding Conditions

2.1 Welding Model and Thermal Physical Parameters

In order to simulate butt welding process with different plate thickness, three-dimensional finite element model was established with a size of $h \times 100 \times 100$ mm (where $h$ is the thickness of plate) shown in Fig. 1. Refined grids were meshed as 1 mm at WM (weld metal) zone and HAZ with larger temperature gradient, while more sparse grids with as size of 4 mm were applied to regions away from WM.

Considering the processes of fusion and solidification, the phase transforms from solid phase to liquid phase, and finally to solid phase. The thermal physical parameters under different phase state become temperature dependent variables. The influence of the flow in the molten pool on temperature

Fig. 1  The meshed model for numerical simulation.
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Table 1  Thermal conductivity and density of steel varying with temperature.

<table>
<thead>
<tr>
<th>T (°C)</th>
<th>k (W/(m•K))</th>
<th>ρ (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60</td>
<td>7,880</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>7,880</td>
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<td>7,880</td>
</tr>
<tr>
<td>600</td>
<td>30</td>
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<tr>
<td>800</td>
<td>25</td>
<td>7,520</td>
</tr>
<tr>
<td>1,000</td>
<td>26</td>
<td>7,390</td>
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<td>7,180</td>
</tr>
<tr>
<td>3,000</td>
<td>30</td>
<td>7,180</td>
</tr>
</tbody>
</table>

Fig. 2  Model of double ellipsoid heat source.

field should be considered with increasing effective thermal conductivity. Thus, thermal conductivity and density of steel varying with temperature were applied in our model as shown in Table 1.

Latent heat of phase transition was considered with equivalent specific heat capacity:

\[ C_p = \begin{cases} c_s & T < T_s \\ c_s + L_f/(T_l - T_s) & T_s \leq T \leq T_l \\ c_l & T > T_l \end{cases} \]  (1)

where \( T_s \) and \( T_l \) are the temperature of solid and liquid phase in melting differently, \( c_s \) and \( c_l \) are the specific heat capacity of solid and liquid phase, \( c_f = (1-f_f)c_s + f_f c_l \) expresses the specific heat capacity in range of phase transformation, liquid phase quantity \( f_f \) can be expressed:

\[ f_f = \begin{cases} 0 & T < T_s \\ (T - T_s)/(2\Delta T) & T_s \leq T \leq T_l \\ 1 & T > T_l \end{cases} \]  (2)

where \( \Delta T = (T_l - T_s)/2 \) expresses the temperature of half transformation.

In the process of welding, boundary convection and radiation are the major factors of heat loss. The boundary coefficient of cooling can be expressed totally as Ref. [8]:

\[ \alpha_c = 4.536 \times 10^{-8} (293.15 + T)(T^2 + 293.15^2) + 25 \]  (3)

2.2 Model of Heat Source

Different from centralized model of heat source of Rosenthal, double ellipsoid heat source which reflected actual feature of welding heat sources were applied in our model [9]. As shown in Fig. 2, the distance of two heat sources was \( l \). There was 1/4 part ellipsoid of each heat source with a fraction of \( f_f \) and \( f_r \), where \( f_f + f_r = 2 \). The heat sources were distributed as:

\[ q_{\alpha f}(x,y,z,t) = \frac{6\sqrt{3} f_f Q}{a_{if} b_{if} c_{if} \pi} \exp\left(-\frac{3x^2}{a_{if}^2}\right) \exp\left(-\frac{3y^2}{b_{if}^2}\right) \exp\left(-\frac{3z^2}{c_{if}^2}\right) \]  (4)

\[ q_{\alpha r}(x,y,z,t) = \frac{6\sqrt{3} f_r Q}{a_{ir} b_{ir} c_{ir} \pi} \exp\left(-\frac{3x^2}{a_{ir}^2}\right) \exp\left(-\frac{3y^2}{b_{ir}^2}\right) \exp\left(-\frac{3z^2}{c_{ir}^2}\right) \]  (5)

where \( i = 1, 2 \) express numbers of two sources, \( Q_i \) is heat input, \( a_{if}, a_{ir}, b_{if}, c_{if} \) are relevant with electric current, voltage and welding velocity, these parameters are different and independent, which can be determined by depth and width of the molten pool [10]. The characteristic parameters only determine the
heat shape rather than heating power. Therefore, its effect on heat cyclic curve of HAZ is ignored.

2.3 Welding Condition

According to heat transfer theory of weld, thick and thin panel \( t_{8/5} \) formula of weld:

\[
t_{8/5}^{3D} = \frac{E}{2\pi k} \left( \frac{1}{500-T_0} - \frac{1}{800-T_0} \right) \tag{6}
\]

\[
t_{8/5}^{2D} = \frac{E^2}{4\pi kC_p h^2} \left[ \frac{1}{(500-T_0)^2} - \frac{1}{(800-T_0)^2} \right] \tag{7}
\]

the cooling speed of HAZ (\( t_{8/5} \)) is determined by the factors of input \( E \) (including heat power, welding speed and heat efficiency), thickness of plate, as well as the preheat temperature \( T_0 \).

In order to study influence of above three factors on cooling speed, numerical models with different heat inputs, and thickness of plate, preheat temperatures were built to simulate each temperature field of weld. Detailed data of welding conditions are shown in Table 2.

In order to verify the reliability of FEM results, welding thermal cycles are measured using the thermocouples during the process of submerged that are welding. And the parameters of the weld procedure are set according to the heat inputs as Table 2.

3. Results and Discussion

3.1 Effect of Plate Thickness

According to theory of Rosenthal, \( t_{8/5}^{3D} \) was unrelated with the thickness of 3D plates, which was differentiated by critical thickness of plate from 2D models (\( h_{cr} \)):

\[
h_{cr}^{3D} = \sqrt{\frac{E}{2C_p} \left( \frac{1}{500-T_0} + \frac{1}{800-T_0} \right)} \tag{8}
\]

\( t_{8/5}^{3D} \) can be calculated by Eq. (6) when \( h > h_{cr}^{3D} \), while \( t_{8/5}^{2D} \) can be calculated by Eq. (7) when \( h \leq h_{cr}^{2D} \). For example, when heat input is 14.4 kJ/cm, critical thickness of panel can be calculated as 23 mm without being preheated.

The thermal field of welding process was simulated by FEM under the condition of \((E_1 = 14.4 \text{ J}, T_0 = 20 ^\circ \text{C})\), the heat cycle curves for different thickness with 25 mm and 15 mm are shown in Fig. 3. According to theory of Rosenthal’s Eq. (8), they belong to 3D and 2D models, respectively. The \( t_{8/5} \) results can be calculated from theoretical Eqs. (6) and (7), which are compared with FEM results as shown in Table 3. It is evident from the table that data of 3D model are similar between formula results and FEM results, but there is error of 27.8% for 2D model between formula results and FEM results. The main reason that line heat source was applied in 2D model which only considered the heat distribution along the length of line source and the thickness of plates, but surface heat dispersion was ignored. As a result, there is small effect of surface heat dispersion for a thick plate, because the proportion of surface heat dissipation is very small in total energy. But it becomes a higher proportion when the thickness of plate is smaller, which would seriously affect the cooling rate of plates. Thus, Eq. (7) for 2D model in actual welding conditions may result in larger errors, and it is necessary to reevaluate the welding cooling rate \( t_{8/5}^{2D} \) of intermediate thickness plates between 2D and 3D models.
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Thermal field of welding process with different thicknesses plates was simulated by FEM under the condition of \( E_1 = 14.4 \, J \), \( T_0 = 20 \, °C \), the relationship between cooling rate \( t_{8/5} \) and plate thickness is shown as Fig. 4. Comparing the FEM results and theoretical formula results, it is found that the critical thickness for estimation of 3D or 2D is not a fixed value, but rather a transition range between \( h_{cr}^{3D} \) and \( h_{cr}^{2D} \), which can be defined as intermediate thickness plates. It is known that there are two cooling ways after welding including internal heat conduction and surface dissipation, and the efficiency of the former one is larger. For 3D model of thick plate (where \( h \geq h_{cr}^{3D} \)), the effect of heat conduction cools the HAZ area so quickly that surface heat dissipation can almost be ignored. So the cooling rate \( t_{8/5} \) tends to be a constant when the plate thickness exceeds the critical thickness \( h_{cr}^{3D} \), which is consistent with the results of the formula results of 3D model. But for the situation where \( h < h_{cr}^{3D} \), heat conduction is no longer an absolute factor for cooling rate from 800 °C to 500 °C, and the effect of surface heat dissipation becomes more and more significant with thickness reducing. 2D model is only related to the relationship between heat source and thickness of plates, which cause increasing difference between the results of FEM and 2D model. When \( h \leq h_{cr}^{2D} \), the effect of surface heat dissipation exceeds that of heat conduction gradually, and the efficiency of surface heat dissipation increasing with plate thickness decreasing. Therefore, \( t_{8/5} \) decreases with decreasing thickness, the reason for sharp increase of \( t_{8/5} \) for 2D model with the thickness decrease is that theoretical formula just considers thermal conductivity in the thickness direction. As shown in Fig. 4, the 2D critical thickness under this welding condition is \( h_{cr}^{2D} = 7.5mm \), which fits the result from the empirical Eq. (9) based on extensive testing:

\[
  h_{cr}^{2D} = \frac{1}{2} \sqrt{\frac{E}{C_p(T_f - T_0)}} = 7.3mm \tag{9}
\]
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Based on the numerical results in Fig. 4, $t_{8/5}^{2.5D}$ of intermediate thickness plate time under the same welding condition can be expressed with 2D and 3D results using multiple linear regression method, whose equations and the correlation coefficient can be defined as follows:

$$t_{8/5}^{2.5D} = \alpha h_0^{2D} + \beta h_0^{2D}$$

$$\alpha = \frac{h_h^{2D} - h_{cr h}^{2D}}{h_{cr h}^{2D} - h_0^{2D}}; \quad \beta = \frac{h_h^{2D} - h_0^{2D}}{h_{cr h}^{2D} - h_0^{2D}}$$  \hspace{1cm} (10)

3.2 Effect of Heat Input

In order to study the effect of heat input on $t_{8/5}^{2.5D}$, temperature fields of different thickness under condition of ($E_1 = 14.4 \text{kJ/cm}$, $E_2 = 49.8 \text{kJ/cm}$, $T_0 = 20^\circ \text{C}$) were simulated, the results of $t_{8/5}$ changing with thickness are shown in Fig. 5. It can be found that $t_{8/5}$ of same plate thickness becomes higher with the heat input increasing. For larger thickness of 3D model, namely when thicknesses are $h_1 = 23 \text{mm}$, $h_2 = 45 \text{mm}$ respectively, two kinds of heat input time($t_{8/5}^{3D}$ ) tend to be constant: $t_{8/5}^{3D} = 6.8 \text{s}$, $t_{8/5}^{3D} = 25.1 \text{s}$, and $E_2/E_1 \approx t_{8/5}^{3D} / t_{8/5}^{2D}$, which prove that the FEM results fit the theoretical Eq. (6) well. It is important to note that the critical thickness plate changed under different heat input, $h_{cr}^{3D}$ and $h_{cr}^{2D}$ from the FEM results meet Eqs. (8) and (9), thus it can be seen that range of intermediate thickness plates becomes wider with the increase of heat input. Therefore, there are two sides of influence with heat input for $t_{8/5}^{2.5D}$ calculation in Eq. (10): the first is influence of $t_{8/5}^{2.5D}$ and $t_{8/5}^{3D}$, and the second is influence of correlation coefficient $\alpha$ and $\beta$ through changing the critical thickness $h_{cr}^{2D}$ and $h_{cr}^{3D}$.

3.3 Effect of Preheating Temperature

Based on Eqs. (8) and (9) for critical thickness of intermediate thickness plate, temperature fields with different thickness were simulated. The relationship between $t_{8/5}^{2.5D}$ and preheating temperature is shown in Fig. 6, which shows that $t_{8/5}^{2.5D}$ increases at higher preheating temperature. What is more, there is bigger increase of $t_{8/5}^{2.5D}$ under larger heat input, while $t_{8/5}^{2.5D}$ becomes more sensitive for thicker plate under the same heat input. It is also found that the values on curves
t_{85} with different thickness under heat input of 14.4 kJ/cm and 49.8 kJ/cm.

Effect of preheating temperature for $t_{85}^{SD}$.

tend to get closer with the increase of preheating temperature. The main reason is that the higher preheat temperature changes heat dissipation condition on boundary, which reduces the influence of surface cooling and then results in the change of the cooling rate on different thickness plates. In addition, the FEM results are in good agreement with the results from formula calculation under different welding conditions when $T_0 \leq 200^\circ C$, but larger deviation between the results when $T_0 > 200^\circ C$. That is because the critical thickness of the plate is nonlinear when the preheating temperature increases higher, which causes
a nonlinear relationship between $t_{8/5}^{2.5D}$ with $t_{8/5}^{2D}$ and $t_{8/5}^{1D}$.

4. Estimation with Welding Experiment

In order to verify the reliability of FEM results, welding thermal cycles were measured using the method as Ref. [11] which punched on the back of the plate with 20 mm thickness and thermocouples were installed. The actual welding thermal cycle under condition of $T_s = 20^\circ C$, $E = 50kJ/cm$ in the HAZ area is compared with the FEM one, as shown in Fig. 7. It can be found that there is a minor discrepancy between FEM and experiment, but HAZ has the same cold speed ($t_{9/5}$). Overall, they are in good agreement.

According to the cooling curve of thermal cycle and the welding CCT diagram under the same condition,
the microstructure in HAZ area could be predicted [12]. In this paper, cooling curve from FEM results and CCT diagram of Q370 steel are plotted together in Fig. 8. It can be found that the cooling curve passes respectively through F (Ferrite) + P (Perlite) zone and B (Bainite) zone, which explain that the HAZ might contain F, P and B. The welding joint was then tested, and the microstructures on HAZ are shown in Fig. 9, which validated FEM predictions well: GBF (grain boundary ferrite), AF (acicular ferrite), P (perlite) and UB (upper bainite) are found on the coarse grain zone.

5. Conclusion

Based on the finite element method, the welding temperature field was simulated under different conditions. The factors including thickness, heat input, preheat temperature were considered to study the influence of cooling rate which defined with \( t_{8/5} \). The FEM results were compared with the results of formula calculation from traditional heat transfer theory, the conclusions could be draw:

1. In this paper, more suitable formulas were established for \( t_{8/5} \) calculation of intermediate thickness plates, whose critical thickness was also discussed according the FEM results.

2. \( t_{8/5}^{2.5D} \) is proportional to the preheating temperature, which seems more sensitive for the thicker plates. In addition, \( t_{8/5}^{2D} \) has a good correlation with \( t_{8/5}^{3D} \) and \( t_{8/5}^{1D} \) when the preheating temperature is below 200 °C.

3. Both the actual welding thermal cycle curve and the microstructure comparison show that the FEM results agree well with the experimental observation.

References


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