Prediction of HAZ width in submerged arc welding of mild steel

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Abstract. A three-dimensional (3D) finite element (FE) model for the submerged arc welding process of medium thick plates was established. The welding temperature distribution for varying heat input was obtained by taking into account nonlinear relationships between temperature and thermal-physical properties. According to the characteristic temperatures of welding thermal cycles, widths of heat-affected zones (HAZs) were obtained. The widths of HAZs were also investigated through combination of metallographic examination and hardness measurements. The simulation prediction results and experimental results were compared and had generally good conformity.

1. Introduction

Submerged arc welding (SAW) is widely employed as one of the major fabrication processes in a wide range of structural applications due to its advantages of deeper penetration, a smooth bead, sound quality, availability in automatic or semi-automatic mode and elevated productivity [1, 2]. Its main drawback, however, is that SAW delivers relative high input into the weld joint, resulting in coarse HAZ microstructures with reduced notch toughness properties. It is evident that welding heat input has significant influence on microstructures and mechanical properties of HAZ. The widths of HAZs are also influenced by the heat input. The sizes of coarse-grained HAZ (CGHAZ), fine-grained HAZ (FGHAZ), and inter-critical HAZ (ICHAZ) are crucial for determining the toughness and strength of the welded joint. Therefore, a detailed quantitative investigation of the influence of heat input on the HAZ width is of vital importance for better understanding of HAZ microstructure distribution and better controlling of heat input to ensure requisite mechanical properties, especially in the welding of medium to high thickness plates. A common practice to obtain the HAZ width is experimental measurement. However, experimental approach is usually time consuming and costly. Some researchers attempted to calculate HAZ width using empirical equations, but these calculated results were not satisfactory especially for relative low heat input. Numerical simulation may be an alternative method of predicting HAZ width. In this research, a method of numerical analysis was adopted to investigate the transient temperature distribution and to evaluate sizes of HAZs.
2. Experimental
The base metal employed is a commercially available mild steel of 10 mm thickness. Specimens with dimensions of 300×100×10mm were prepared. The composition of the base metal used in the present study is given in Table 1. A weld bead was deposited under different heat input along the center-line of the specimen using a SAW process. The welding was performed at an ambient temperature of 20℃. Welding parameters adopted in the present investigation are listed in Table 2.

| Type of material    | C     | Si    | Mn    | P     | S     | Ni    | Fe   |
|---------------------|-------|-------|-------|-------|-------|-------|------|
| Base metal          | 0.14  | 0.13  | 0.44  | 0.015 | 0.031 | 0.251 | Bal. |
| consumable electrode| ≤0.10 | ≤0.07 | 0.80-1.10 | ≤0.030 | ≤0.030 | ≤0.30 | Bal. |

Welded specimens were mechanically polished and etched with 2% natal solution. Microstructures of each test specimen were analyzed by means of optical microscopy. The Vickers microhardness test was performed using a constant load of 200g and 15 seconds dwell time. Based on difference in microstructures and hardness in subzones of HAZ, the widths of HAZs were then determined using metallographic analysis software. Typical microstructures of HAZs in specimen A3 are presented in Figure 1.

It can be seen from Figure 1 that the microstructure in CGHAZ consists of coarse widmanstatten ferrite, grain boundary ferrite and pearlite, while microstructure in FGHAZ consists of uniformly distributed ferrite with small amounts of pearlite. The microstructure in ICHAZ is not uniform throughout the specimens.

3. Numerical simulation
Using SYSWELD FE analysis software, transient heat transfer analysis was carried out and temperature field under different heat input were studied to simulate the SAW process. 3D models were created for accurate simulations. In view of calculating precision and efficiency, different element sizes were used in meshing, with the density being higher for the weld metal and HAZ, and progressively reducing towards the edges of the plates. In performing the simulations, the transient temperature field was simulated using the Element Birth and Death technique. Figure 2 shows the modeling of the welded joint and corresponding meshing.
Goldak double ellipsoid heat source was applied in the simulation to capture the heating effect of the welding arc and achieve high consistency with the practical situations. The Goldak heat source parameters [3] were determined when the experimental and the numerical macrosection of the weld and the weld thermal cycles show a sufficient agreement. The power density distribution within the heat source was determined by the following equations.

\[
q_f = \frac{6\sqrt{3}q_f}{\pi \sqrt{abc_f}} e^{-\frac{(x-a_f)^2}{2\sigma_f^2}}
\]

\[
q_r = \frac{6\sqrt{3}q_f}{\pi \sqrt{abc_r}} e^{-\frac{(x-a_r)^2}{2\sigma_r^2}}
\]

Where \( Q \) is the heat input; \( x, y, z \) are coordinates relative to the heat source center; \( q_f \) and \( q_r \) are the heat flux on the anterior and posterior semisphere respectively; \( f_f \) and \( f_r \) are the heat distribution fractions and satisfying \( f_f + f_r = 2 \); \( a, b, c_f \) and \( c_r \) are parameters relevant to the shape of the molten pool.
For the sake of illustration, analysis result of specimen A3 was illustrated for further discussion. The global temperature field of the welding process in one step of the calculation is shown in Figure 3. It can be seen that the temperature field during welding becomes steady afterwards (t=25s) and the peak temperature is about 2100 °C.

Figure 3. Temperature distribution during the welding process (t=25s)

4. Prediction of HAZ width
In general, weld HAZ has complex distribution of microstructure and mechanical properties because of the welding thermal cycles. Based on peak temperatures of weld thermal cycles, the HAZ can be divided into three zones, viz., coarse-grained HAZ (CGHAZ), fine-grained HAZ (FGHAZ) and intercritical HAZ (ICHAZ). Region close to the fusion line that experiences peak temperatures above 1100°C is called the CGHAZ. Region away from the weld centerline that gets exposed to low peak temperature ($A_{c3}$−1100°C) thermal cycles and is termed as the FGHAZ. Region experiences peak temperature between $A_{c1}$ and $A_{c3}$ is defined as the ICHAZ. In this investigation, the $A_{c1}$ and $A_{c3}$ temperatures of base metal are 730 °C and 825 °C, respectively.

Comparison of simulated and experimental weld bead cross section profiles (specimen A3) is shown in Figure 4. It is evident from the etched cross section of weld that the fusion zone size and sizes of the three HAZs are in good agreement with numerical calculated result. The variations in experimental and numerical simulated HAZ widths with heat input are depicted in Figure 5.

It can be seen from Figure 5 that the predictions from the numerical simulations and the corresponding measured results are in fair agreement for a range of heat inputs from 18 to 28 kJ·cm$^{-1}$. For low heat input of less than 23 kJ·cm$^{-1}$, welding heat input has relatively little influence on the total width of HAZ. The measured total width of HAZ is kept nearly constant at around 2000 μm. For heat input higher than 23 kJ·cm$^{-1}$, an increase of heat input has a significant impact on the sizes of HAZs. This is expected, since the retention time at high temperature and the cooling time increase with increasing heat input. Consequently, the grain sizes and the size of HAZ increase as the heat input per unit length of the weld is increased. The size of CGHAZ does not show larger variations in all the weld specimens considered in this investigation. The grain size of FGHAZ is relative small and grain coarsening happens when activation energy of grain boundary is higher than a critical level. It can be seen from Figure 5(c) that there is a considerable rise in FGHAZ width when heat input is over 23 kJ·cm$^{-1}$.

Figure 4. Comparison of simulated and experimental weld bead cross section profiles
5. Conclusion
A numerical technique of predicting the width of HAZ in submerged arc welding was presented. Transient temperature filed under different heat input was obtained and utilized to calculate respective size of HAZs.

The numerical predicted values of HAZs under different heat input were experimentally validated and the predictions were proved to be very close to the measured actual values. Increase in HAZ width is not significant for heat input less than 23 kJ·cm⁻¹, while HAZ size was observed to increase obviously under relative high heat input.

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