Numerical simulation of temperature field in multiple-wire submerged arc welding of X80 pipeline steel

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Abstract. Three dimensional (3D) finite element (FE) simulation was implemented to predict the temperature distribution during multiple-wire submerged arc welding (SAW) throughout the welded joint of X80 pipeline steel. A moving heat source model based on Goldak’s double-ellipsoid heat flux distribution was applied in the simulation to capture the heating effect of the welding arc. Effects of welding speed, wire spacing and leading wire current on temperature distribution were further investigated. The simulation results show that both welding speed and wire spacing have significant effects on welding temperature distribution in X80 pipeline steel welded joint.

1. Introduction
Multiple-wire submerged arc welding is widely employed in the construction of ships, pipeline systems, and pressure vessels due to its advantages of deep penetration, high deposition rate, smooth bead appearance, and elevated productivity. Triple-wire SAW has been increasingly used in construction of large diameter pipes, while welded pipes fabricated using four-wire SAW has been employed in several West–East Gas Pipeline Projects. Four-wire tandem SAW process provides simultaneous deposition from four electrodes with one electrode leading the others in the direction of welding [1-3]. The leading, middle and trailing electrodes in four-wire tandem SAW are usually connected respectively to a DC and three AC power supplies so that a large number of welding conditions can be satisfied. These adjustable welding conditions include the leading wire current, the current pulses and the corresponding pulse durations of the trailing wires, the distance between individual wires, the wire diameter, the arc voltage and welding speed. High current and low voltage of the leading wire are employed to obtain high penetration, while low welding current and high voltage of the trailing wire are employed to obtain good appearance. In spite of the many advantages, the large amount of welding parameters results in increasing difficulty in controlling the welding process and the integrity of the welded joint. The temperature distribution during multiple-wire submerged arc welding determines the microstructure, hardness and mechanical properties. However, the typical nature of the multiple-wire SAW makes it difficult to measure the thermal cycles and corresponding peak temperatures in the weld experimentally. Thus, an alternative way to obtain thermal cycles in multiple-wire SAW process based on numerical modeling of the heat transfer was developed in this investigation. Welding temperature field under different welding conditions was
numerically simulated and analyzed. The influence of welding parameters on temperature distribution for X80 pipeline steel was determined from the results obtained.

2. Experimental
The test material used in this study was X80 pipeline steel. Specimens with dimensions of 200mm×140mm×18mm 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 welding parameters along the centerline of the specimen using a four-wire tandem SAW process. The leading electrode was connected to a DC power source, and the middle and trailing electrodes were connected to the AC power sources. Welding parameters adopted in the present investigation are listed in Table 2.

| Sample No. | Electrode No. | Welding current I/A | Welding voltage U/V | Welding speed v/(m min⁻¹) | Inter-wire spacing l/mm |
|------------|---------------|---------------------|---------------------|---------------------------|------------------------|
| 1          | 1             | 950                 | 32                  | 0.03                      | 30                     |
| 1          | 2             | 750                 | 34                  |                           | 30                     |
| 1          | 3             | 550                 | 38                  |                           | 30                     |
| 1          | 4             | 450                 | 40                  |                           | 30                     |
| 1          | 1             | 850                 | 32                  |                           | 30                     |
| 2          | 2             | 750                 | 34                  | 0.03                      | 30                     |
| 2          | 3             | 550                 | 38                  |                           | 30                     |
| 2          | 4             | 450                 | 40                  |                           | 30                     |
| 2          | 1             | 1050                | 32                  |                           | 30                     |
| 3          | 2             | 750                 | 34                  | 0.03                      | 30                     |
| 3          | 3             | 550                 | 38                  |                           | 30                     |
| 3          | 4             | 450                 | 40                  |                           | 30                     |
| 3          | 1             | 950                 | 32                  |                           | 30                     |
| 4          | 2             | 750                 | 34                  | 0.02                      | 30                     |
| 4          | 3             | 550                 | 38                  |                           | 30                     |
| 4          | 4             | 450                 | 40                  |                           | 30                     |
| 4          | 1             | 950                 | 32                  |                           | 30                     |
| 5          | 2             | 750                 | 34                  | 0.04                      | 30                     |
| 5          | 3             | 550                 | 38                  |                           | 30                     |
| 5          | 4             | 450                 | 40                  |                           | 30                     |
| 5          | 1             | 950                 | 32                  |                           | 20                     |
| 6          | 2             | 750                 | 34                  | 0.03                      | 20                     |
| 6          | 3             | 550                 | 38                  |                           | 20                     |
| 6          | 4             | 450                 | 40                  |                           | 20                     |
| 6          | 1             | 950                 | 32                  |                           | 20                     |
| 7          | 2             | 750                 | 34                  | 0.03                      | 40                     |
| 7          | 3             | 550                 | 38                  |                           | 40                     |
| 7          | 4             | 450                 | 40                  |                           | 40                     |
3. Numerical simulation

Using ANSYS FE analysis software, transient heat transfer analysis was carried out and temperature field under different welding conditions were studied to simulate the four-wire tandem SAW process. For each sample, a 3D model was created for the sake of accuracy. In this simulation, the element type Solid 70 and Solid 90 have been considered for the thermal analysis. To decrease CPU time and storage capacity, a finer mesh density was selected for the weld metal and the HAZ. Figure 1 shows the modeling of the welded joint and corresponding meshing.

![Figure 1. FE Mesh of the welded joint.](image)

Since the penetration of the welding arc and the difference between the front and rear part of the heat source is considered in Goldak double ellipsoid heat source, it 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 were determined when the experimental and the numerical microsection of the weld and the weld thermal cycles show a sufficient agreement. The expression of the double ellipsoid heat source [4,5] is as follows:

\[
\begin{align*}
q_f(x, y, z, t) &= \frac{6\sqrt{3}f \cdot Q}{a_1 b c \sqrt{\pi}} \exp\left(\frac{3x^2}{a_1^2}\right) \exp\left(\frac{3y^2}{b^2}\right) \exp\left(\frac{3z^2}{c^2}\right) \\
q_r(x, y, z, t) &= \frac{6\sqrt{3}f \cdot Q}{a_2 b c \sqrt{\pi}} \exp\left(\frac{3x^2}{a_2^2}\right) \exp\left(\frac{3y^2}{b^2}\right) \exp\left(\frac{3z^2}{c^2}\right)
\end{align*}
\]

Where \( q_f \) and \( q_r \) are the heat flux on the anterior and posterior semisphere respectively; \( x, y, z \) are coordinates relative to the heat source center; \( f_f \) and \( f_r \) are the heat distribution fractions and satisfying \( f_f + f_r = 2 \); \( Q \) is the heat input; \( a_1, a_2, b, c \) are parameters relevant to the shape of the molten pool.

The temperature dependent thermo-physical and mechanical properties corresponding to X80 pipeline steel was considered to be similar to the work conducted by Yan et al. [6].

4. Results and discussion

For the sake of illustration, analysis result of specimen No.1 was illustrated for further discussion. The snapshots of the transient temperature fields during the four-wire tandem SAW process are shown in Figure 2. It can be seen from Figure 2 that the temperature distribution in the weld pools are different, peak temperature in the trailing weld pool is higher than the other three weld pools. The peak temperature in the weld pool is about 3200 °C (t=7.8s).

The thermal cycles at different locations on the surface during the four-wire SAW process are plotted in Figure 3. From Figure 3, it is obvious that the peak temperature gradually decreases with increasing distance from the fusion line.
Figure 2. Temperature distribution during the welding process.

Figure 3. Thermal cycles during the welding process in the direction of plate width.

Influence of welding speed and inter wire spacing on the temperature distribution are presented in Figure 4 and Figure 5 respectively. It can be seen from Figure 4 that welding temperature distribution is greatly influenced by the welding speed. With greater welding speed, heat input decreases, causing an obvious decrease in peak temperature in the weld pool. The thermal history showed a maximum deviation of about 500 °C in peak temperature with a difference of 0.6 m/min in welding speed. It is obvious from Figure 5 that inter-wire spacing also plays an important role in controlling the welding
temperature distribution. The maximum deviation of about 400 °C in peak temperature with a difference of 10 mm in inter-wire spacing is observed.

![Figure 4. Temperature distribution with different welding speeds.](image)

Influence of leading wire current on the temperature distribution is presented in Figure 6. It can be seen from Figure 6 that an increase of the leading wire current results in larger heat input and hence an increase in the peak temperature of the welding process is expected. The thermal history showed a maximum deviation of about 30 °C in peak temperature. It is therefore believed that the leading wire current exerts a relatively minor influence on the temperature distribution in four-wire SAW process.

![Figure 5. Temperature distribution with different different inter-wire spacings.](image)
5. Conclusion
Temperature distribution in four-wire tandem SAW process of X80 pipeline steel under different welding conditions was investigated using ANSYS finite element software. Influence of welding speed, inter-wire spacing and leading wire current on the welding temperature distribution was analyzed. It is concluded the welding speed and the inter-wire spacing have significant influence on welding temperature distribution. With increasing welding speed and inter-wire spacing, the global temperature level and peak temperature in the welding process is observed to decrease significantly. However, when the leading wire current is increased, the peak temperature in the welding process is observed to increase slightly.

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