Numerical analysis of double-electrode gas metal arc welding process

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Abstract

With consideration of process characteristics of the newly developed DE-GMAW (double-electrode gas metal arc welding), a finite element analysis (FEA) model is developed to numerically analyze this novel process. To this end, the authors have extended the functions of SYSWELD, a standard software package for numerical analysis of welding processes; simplified the method for processing the weld reinforcement; and proposed an appropriate mode for the welding heat source in this novel process. Based on the FEA results of temperature profile in DE-GMAW, the weld dimension at cross section and temperature distribution are obtained. The predicted and experimentally measured results match satisfactorily. The results show that DE-GMAW has advantages in terms of increasing deposition rate, lowering heat input to base metal, and reducing residual stress and distortion.

Keywords: DE-GMAW process; Weld dimension; Residual stress and distortion; Prediction; Finite-element analysis

1. Introduction

In the conventional gas metal arc welding (GMAW), the arc is always established between the consumable electrode and the base metal. The base metal is the cathode and the part of the arc heat determined by the product of the welding current and the cathode potential is directly absorbed by the base metal. Because this part of the heat directly melts the base metal contributing to enlarging the weld pool and distortion, the increase of deposition rate via increasing the welding current is limited unless backing is used to support the large weld pool. Due to deposition is the major application of GMAW, the fundamental characteristic of the arcing principle limits the further improvement of productivity in conventional GMAW. For example, for a half inch (12.7 mm) thick joint, five cover passes are typically needed to fill the groove after the root pass [1]. However, if the workpiece is not a terminal of the arc, so that the permitted amperage is not restricted, high current can then be used to achieve high melting rate to fill the groove in a single pass. A novel process, referred to as the double-electrode GMAW, has been developed at the University of Kentucky to decouple the base metal current from the torch current in GMAW [2]. As shown in Fig. 1, adding a GTAW (gas tungsten arc welding) torch to GMAW torch constitutes the double-electrode GMAW system. The current supplied by the bypass control unit flows from the filler wire (GMAW torch) to the GTAW’s tungsten electrode without going through the base metal. The corresponding arc is established between the filler wire and the tungsten electrode. This arc does not directly heat base metal and is referred to as the bypass arc. The corresponding current is referred to as the bypass current \( I_{bp} \). The part of the current which flows from the filler wire to the base metal is referred to as the base metal current \( I_{bm} \). The current which flows through and melts the filler wire will be the sum of the bypass current \( I_{bp} \) and the base metal current \( I_{bm} \) and is referred to as the melting current \( I_{m} \). Because two electrodes are used and the method is basically similar to GMAW except for the current bypass, the method is referred to as the double-electrode GMAW or
DE-GMAW. This modified arc welding process has a few advantages including high deposition rate, low heat input to base metal, and low residual stress and distortion. As illustrated in Fig. 2, this process can be used for high-speed arc welding with good weld bead quality.

In order to better understand the DE-GMAW process and establish the knowledge base and foundations needed to support this novel process, the physical phenomena should be studied by modeling and simulation. In this paper, numerical analysis of the DE-GMAW is conducted to provide guidelines for optimizing the process experimentally.

2. Formulation

SYSWELD, a software package for numerical analysis of welding processes, is applied to simulate the thermal process in DE-GMAW. Though extensive investigations have been conducted on modeling and simulation of conventional GMAW, there still are unsolved problems. For example, the weld reinforcement was not considered [3]; the weld reinforcement was not determined by taking the weld pool surface deformation into account [3–5]; and the procedure for determining the weld reinforcement was too complicated due to the coupling among arc pressure, droplet impact, fluid dynamics, pool surface depression, etc. [6–11]. To obtain an effective method to analyze DE-GMAW process with satisfactory accuracy, the authors have extended SYSWELD’s functions as described below.

2.1. Processing of weld reinforcement

The main arc in DE-GMAW is a gas-metal arc and there thus are phenomena of wire melting, droplet transferring and weld reinforcement forming. To calculate the thermal process more accurately, the model must deal with the weld reinforcement. The cross section area of weld reinforcement can be easily calculated through dividing the melted amount of wire per unit time by the welding speed, i.e.,

\[ A = \frac{\pi d_f^2 v_f}{4 v_w}, \]

where \( A \) is the cross section area of weld reinforcement, \( d_f \) is the wire diameter, \( v_f \) is the wire feed rate, and \( v_w \) is the welding speed. However, the geometry of weld reinforcement at the cross section is determined by combined actions of arc pressure, droplet impact, weld pool gravity, and surface tension. An accurate determination of this geometry needs to deal with the weld pool surface deformation which in turn is affected by complicated fluid dynamics.
inside the weld pool [6–11]. To concentrate on the prediction of weld dimensions in DE-GMAW, a thermal conduction model is developed to calculate the temperature distribution by finite-element-analysis (FEA) so that the fluid convection is only indirectly considered. Hence, a simplified method is employed to compute the weld reinforcement. In this model, the dimension and geometry of weld reinforcement at the cross section are determined first. Second, the weld reinforcement is added to the workpiece in advance. And then the mesh is automatically generated. During FEA, the elements associated with the weld reinforcement are “activated” one by one as the welding proceeds. (2)

As shown in Fig. 3, the contour of weld reinforcement at the cross section is assumed to be parabolic, i.e.,

\[ y = ax^2 \quad (a < 0). \]  

Along the parabola,

\[ y = -h \quad \text{when} \quad x = \pm \sqrt{-\frac{h}{a}}. \]  

Since

\[ \frac{dy}{dx}\bigg|_{y=-h} = 2ax|_{x=-\sqrt{-\frac{h}{a}}} = -2a\sqrt{-\frac{h}{a}} = tg\theta. \]

Then

\[ h = \frac{tg^2\theta}{4a} \]  

where \( \theta \) is the contact angle. When the material properties and welding conditions are known, \( \theta \) may be considered as a constant. Here \( \theta \) and \( h \) are predetermined based on some macrophotograph of DE-GMAW weld cross sections.

Also,

\[ A = 2 \int_0^{\sqrt{-\frac{h}{a}}} (ax^2 + h)dx. \]

Hence,

\[ a^2 = \frac{2v \cdot tg^3\theta}{3\pi d^2 \cdot \nu}. \]  

When \( a, \theta \) and \( h \) are known, the configuration of weld reinforcement at the cross section is completely determined.

2.2. Mesh generation

The workpiece is mild steel sheet of length 120 mm, width 50 mm and thickness 2.5 mm. For mesh generation purpose, the weld reinforcement is added onto the workpiece in advance. For the elements associated with the weld reinforcement ahead of the welding arc, they are “dead”; i.e., they are not considered in FEA. For those elements associated with the weld reinforcement behind the welding arc, they are “activated” and their influence is included in FEA. The whole workpiece is discretized into non-uniform 8-node hexahedrons (Fig. 4).

To include the effect of arc pressure, droplet impact and weld pool surface depression indirectly, a simplified method is used to deal with the mesh structure for the front and rear parts of weld pool. As aforementioned, the weld reinforcement is added to the workpiece in advance. In fact, the whole mesh structure and its cross section are shown in Figs. 4 and 5, respectively. To consider the depressed weld pool surface indirectly, some elements at the front of weld pool are treated as “dead” so that the cross section of mesh structure around the arc centerline is actually like that shown in Fig. 6.

2.3. Heat source mode

Appropriate mode of heat source must be determined to describe the practical physical phenomena in DE-GMAW. In this study, two types of heat sources are combined together to describe DE-GMAW heat input. The wire is melted and transferred into the weld pool so that the pool surface at the rear of weld pool is humped and the weld reinforcement is formed after solidification. Because the transferred droplets are overheated, they deliver some extra heat content into the weld pool [7]. To consider this part of heat input, a volumetric heat source with uniform intensity...
2.4. Governing equations and boundary conditions

Under a moving coordinate system o-xyz with y-axis along the welding direction, z-axis along the workpiece thickness direction (coinciding with the arc centerline), and the origin o at the workpiece surface, the governing equation for the temperature field on the workpiece is as follows:

\[
\rho C_p \left( \frac{\partial T}{\partial t} + (-v_w) \frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + q_V(x, y, z),
\]

where \( \rho \) is the density, \( C_p \) is the specific heat, \( v_w \) is the welding speed, \( T \) is the temperature, \( t \) is the time, \( k \) is the thermal conductivity, and \( q_V(x, y, z) \) is the volumetric heat source term of the weld reinforcement within the effective region of welding arc.

On the upper surface of workpiece,

\[-k \frac{\partial T}{\partial z} = x_c(T - T_\infty) + m_w L_b - q_S(x, y)\]

where \( x_c \) is the heat loss coefficient, \( T_\infty \) is the ambient temperature, \( m_w \) is the evaporation coefficient, \( L_b \) is the latent of evaporation and \( q_S(x, y) \) is the Gaussian heat source term.

On the bottom surface of workpiece,

\[-k \frac{\partial T}{\partial z} = x_c(T - T_\infty).\]

At the symmetry plane \((x = 0)\),

\[\frac{\partial T}{\partial x} = 0\]

Initial condition,

\[t = 0; \quad T(x, y, z, 0) = T_\infty\]

### 3. Results

For a test case \((I_m = 330 A, \quad I_{bm} = 250 A, \quad I_{bp} = 80 A, \quad U_{bm} = 32 V, \quad U_{bp} = 20 V, \quad v_t = 232.83 \text{ mm/s}, \quad v_w = 21.17 \text{ mm/s}, \quad \text{mild steel workpiece of length 120 mm, width 50 mm and thickness 2.5 mm})\), finite-element analysis of temperature field in DE-GMAW has been carried out. The specific heat and thermal conductivity are temperature dependent [12,13]. Some physical properties are listed below, and others are summarized in Table 1.

### Table 1

Other thermo-physical properties and parameters used in the calculation

<table>
<thead>
<tr>
<th>Property or parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>( \rho )</td>
<td>6900 kg m(^{-3} )</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>( T_\infty )</td>
<td>293 K</td>
</tr>
<tr>
<td>Melting point</td>
<td>( T_m )</td>
<td>1773 K</td>
</tr>
<tr>
<td>Latent of evaporation</td>
<td>( L_b )</td>
<td>( 73.43 \times 10^5 \text{ J kg}^{-1} )</td>
</tr>
</tbody>
</table>
Fig. 7. Predicted and measured weld cross section in DE-GMAW. (a) Measured. (b) Predicted and (c) comparison between the predicted and measured results.

Fig. 8. Comparison of weld cross section. Condition 1: With bypass current. Condition 2: No bypass current. (a) Cross section of weld and (b) comparison between predicted and measured weld cross section.
\[
\lg m_\text{cr} = 2.52 + \left( \frac{6.121 - \frac{18.836}{T}}{T} \right) - 0.5 T' (\text{kg s}^{-1}\text{m}^{-2}). \quad (16)
\]

Based on the numerically simulated temperature profile, the geometry and dimension of weld at cross section have been obtained and compared with experimental measurements. In Fig. 7, (a) is the macro-photography of DE-GMAW weld, (b) is the predicted weld cross section, and (c) is the comparison between the predicted and measured weld cross section in DE-GMAW. It can be seen that the predicted and measured weld cross section in DE-GMAW matches well.

Two conditions are used to make a comparison (condition 1: with bypass current, \( I_m = 330 \text{ A}, I_{bm} = 250 \text{ A}, I_{bp} = 80 \text{ A} \); condition 2: no bypass current (i.e., regular GMAW), \( I_m = 330 \text{ A}, I_{bm} = 330 \text{ A}, I_{bp} = 0 \text{ A} \)). As shown in Fig. 8, though the cross-section areas of weld reinforcement are similar because of the same wire feed rate for two conditions, but the workpiece is completely penetrated in condition 2 because of the higher heat input to the base material (\( I_{bm} = 330 \text{ A} \)). For condition 1, the welding current flowing through the workpiece is only 250 A, so the weld penetration and weld volume are much smaller because of the lower heat input (\( I_{bm} = 250 \text{ A} \)).

The heat-affected zone (HAZ) is the portion of the base material that was not melted but whose properties (and,

| Condition 1: Measured | 6.20 | Non-penetration | – | – | 1.80 |
| Condition 1: Computed | 5.96 | Non-penetration | 7.84 | 7.27 | 1.70 |
| Condition 2: Computed | 6.11 | 2.20 | 10.02 | 9.52 | Full penetration |

Fig. 9. Temperature field and weld bead. (a) Condition 1: with bypass current. (b) Condition 2: no bypass current.
usually, structure) were altered by the heat of welding through some phase transformation or reaction [14]. In this study, a peak temperature 1073 K is defined as the temperature at which the structure and properties of the base material are altered by some metallurgical transformation, and then the HAZ width is determined by the temperature profile. As can be seen in Table 2, for condition 2, the front and back widths of heat-affected zone (HAZ) are 28% and 24%, respectively larger than those under condition 1. It is evident that the bypass current decreases the heat input to the base material in DEGMAW, so dimensions of both weld and HAZ are lowered. Figs. 9 and 10, respectively compare their temperature fields on the workpiece and thermal cycles of some points at an upper surface of workpiece under these two conditions. The thermal distribution with bypass current is clearly lower than that without bypass current. Due to the lower temperature profile, the resulted thermal stress, strain, and distortion of the welded workpiece are lower. Fig. 11 demonstrates the thermal stress, strain and distortion on some points at the upper surface of workpiece.
4. Conclusion

(1) Characteristics of DE-GMAW have been combined with function-extended SYSWELD to develop a finite-element model which is capable of simulating this novel process numerically.

(2) A simplified method for processing the weld reinforcement is introduced and the corresponding mode of heat source in DE-GMAW is proposed. The temperature profiles and thermal stress and distortion in DE-GMAW are numerically analyzed.

(3) The computed weld dimensions are found in satisfactory agreement with experimental measurements.

(4) Because of the lower heat input to the base metal, both the weld geometry and HAZ of the welded mild steel in DE-GMAW are much reduced. The thermal distortion is also much reduced.

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References