Engineering Model of Metal Active Gas Welding Process for Efficient Distortion Analysis

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This study presents a computational framework for an efficient distortion analysis based on coupled process-mechanics modeling of metal active gas (MAG) welding. For coupled process-mechanics analysis, an integrated simulation model between bead formation, thermal conduction, and thermo-mechanical behaviors during MAG welding was developed. A combined bead formation and thermal conduction model provided bead surface and temperature profiles during welding from welding process conditions. Then, heat source parameters estimated based on welding process conditions enabled a predictive simulation of MAG welding process. The bead surface and temperature profiles obtained were used for a large deformation thermal elastic–plastic analysis of weld angular distortion. The calculations were compared with the measurements, which were obtained in a previous study, under the same welding process conditions to validate the developed analysis model. From the comparison results, we concluded that the developed model has great potential to be efficient distortion analysis that estimate weld angular distortion from welding process conditions with a high degree of accuracy. Additionally, the effect of welding process conditions on weld bead morphology, temperature profiles, and angular distortion were discussed through the developed analysis model to obtain a more detailed understanding of dominant factor influencing the weld angular distortion of MAG welded structural steel plates.

KEY WORDS: metal active gas welding; angular distortion; coupled process-mechanics modeling; welding process conditions; heat source parameters.

1. Introduction

The importance of fusion welding process has been widely recognized in the manufacturing process of various steel structures such as ships, bridges, construction machines, power plants, and automobiles. However, the fusion welding process has a significant disadvantage that often generates unacceptable levels of geometric imperfections such as shrinkage and distortion. The excessive weld distortion deteriorates the dimensions and performances of the structures and influences the appearance of the finished products. Then, weld distortion is typically controlled by prevention or correction using mechanical and thermal techniques, which involves costly processing in addition to the welding process. Recently, highly accurate prediction and control of weld distortion are becoming increasingly important for improving efficiency and productivity in manufacturing.

In the 1970s, thermal elastic–plastic analysis techniques with finite element methods were first applied to welding thermo-mechanical problems.1,2) Since then, advanced modeling and simulation techniques have variously been developed for calculating welding-induced residual stress and deformation. Computational solutions have enabled the temperature dependence of a material’s properties and microstructure effects to be considered;3–5) moreover, the double-ellipsoidal moving heat source model6,7) enhanced the mathematical theory of heat distribution during welding8) and of the resulting residual stress and deformations.9–11) Thus, computer methods that perform calculations of the time evolution of thermo-mechanical behavior during welding have already shown great potential for estimating weld residual stress and deformation. However, predictive simulation techniques for weld residual stress and deformation have not yet been established. One of the main reasons is the difficulty in constructing a welding process condition-based heat source model that does not require preliminarily observed weld bead morphology and measured temperature profiles obtained by welding experiments.

Recently, a methodology for arc physics-based heat source modeling has been proposed for predictively simulating weld angular distortion.12,13) For gas metal arc (GMA) welding, an integrated simulation model between arc plasma, bead formation, thermal conduction, and thermo-mechanical behaviors was developed. A computational simulation based on electromagnetic thermal fluid modeling of arc plasma provided the distribution of the heat transfer and the arc pressure from the arc plasma to the surface of a welded plate; it also provided the quantity of the mass and heat involved with metal transfer in GMA welding. These heat source properties estimated based on considering the
physics of the welding arc has successfully enabled an accurate simulation of weld bead morphology, temperature distribution, and angular distortion through the developed simulation technique. However, it tends not to be a methodology that anyone can use because of the difficulty in constructing a complicated model of welding arc plasma. To further extend the application of the coupled process-mechanics analysis, an engineering model of GMA welding process will be beneficial.

This study presents a computational framework for an efficient distortion analysis based on coupled process-mechanics modeling of metal active gas (MAG) welding. For the coupled process-mechanics analysis, we developed an integrated simulation model between bead formation, thermal conduction, and thermo-mechanical behaviors during welding to accurately predict weld bead morphology, temperature profiles, and angular distortion, respectively. A combined bead formation and thermal conduction model provides bead surface and temperature profiles during welding from welding process conditions. The bead surface and temperature profiles obtained are used for a large deformation thermal elastic-plastic analysis of weld angular distortion. In the developed analysis model, heat source parameters are estimated based on welding process conditions. The calculations were compared with the measurements, which were obtained in the previous study, under the same welding process conditions to validate the developed analysis model. On the basis of the developed analysis model, the effect of welding process conditions on the weldability of MAG welded structural steel plates was further discussed to obtain a more detailed understanding of a dominant factor influencing the weld angular distortion.

2. Numerical Simulation Procedure

2.1. Methods of Coupled Process-mechanics Modeling of MAG Welding

In this study, a general purpose finite element code ABAQUS ver. 6.9.1 was adopted for the thermal elastic-plastic analysis of weld angular distortion. In the finite element analysis, the welded plate and weld-deposited metal were considered as solid deformable bodies. Figure 1 shows the finite element model of a bead-on-plate welding joint. The plate to be welded had a length of 200 mm, a width of 500 mm, and a thickness of 12 mm. The weld length was 150 mm, which left unwelded sections of 25 mm at both ends of a plate. These are exactly the same as those of the previous experiments. A fine mesh was used around the melted zone to accurately simulate the temperature distribution that determined the thermo-mechanical behavior during welding. The dimensions of the minimum mesh size were 1.0 mm in the longitudinal direction and 0.5 mm in both the transverse and the thickness directions. There were no restraints considered to prevent the thermal deformation due to welding in the thermal elastic-plastic analysis.

The bead surface and temperature profiles during welding, which are input data for the thermal elastic-plastic analysis, were calculated through a combined bead formation and thermal conduction analysis with finite difference methods. In MAG welding, the electrode wire is melted and supplied into the molten pool intermittently, and the welding process is dynamic and irregular. Since it is troublesome to develop a phenomenologically rigorous simulation model of the metal transfer and related processes, it seems reasonable to develop a simplified engineering model for the MAG welding process. In the present model, the following two fundamental assumptions have been introduced: the heat flow in the weld pool is assumed to be conductive, and the weld pool surface is assumed to be in static equilibrium under gravity, arc pressure, and surface tension. In the thermal conduction model, the transient temperature distribution during welding is numerically analyzed and the molten pool size was estimated by using a finite difference method. The equation of three-dimensional thermal conduction is

\[ \rho \varepsilon H = \frac{\partial (K \varepsilon T)}{\partial x} + \frac{\partial (K \varepsilon T)}{\partial y} + \frac{\partial (K \varepsilon T)}{\partial z} + \frac{\partial}{\partial t} \left( \frac{\partial \varepsilon T}{\partial x} + \frac{\partial \varepsilon T}{\partial y} + \frac{\partial \varepsilon T}{\partial z} \right) + w, \]  

where \( t \) is time, \( \rho, K \) and \( \varepsilon \) are density and thermal conductivity of material, respectively. \( H \) is enthalpy and can also be expressed as \( cT \) by using specific heat of material, \( c \), and temperature, \( T \), and \( w \) is the heat generation for simulating the welding heat source. In the present model, welding heat input is comprised of two processes; (1) the melted electrode wire is supplied into the molten pool, and (2) the pool is directly heated by the arc plasma. Within the bead surface displacement calculation area, which approximately corresponds to the melted area of the base metal obtained using the thermal conduction model, the molten pool surface profile is numerically analyzed using a finite difference method that takes the molten pool balance into account. The equation for the molten pool balance is

\[ \tau \left( (1 + \varepsilon_x^2) \phi_{x} - 2 \varepsilon_x \varepsilon_y \phi_{xy} + (1 + \varepsilon_y^2) \phi_{y} + (1 + \varepsilon_x^2) \phi_{x}^2 + \phi_{y}^2 \right) = \rho \varepsilon T + P - \lambda, \]

where \( \tau \) is surface tension (\( \tau = 1.0 \text{ N m}^{-1} \)), \( g \) is the acceleration due to gravity, \( P \) is arc pressure, \( \phi \) is surface displacement, \( \lambda \) is the Lagrange multiplier, and \( \phi_x, \phi_y, \phi_{xx}, \phi_{xy}, \phi_{yy} \) and \( \phi_{xy} \) are \( \partial \phi / \partial x, \partial \phi / \partial y, \partial^2 \phi / \partial x^2, \partial^2 \phi / \partial x \partial y, \partial \phi / \partial x \partial y, \) and \( \partial^2 \phi / \partial y^2 \), respectively. These governing and auxiliary equations are solved iteratively for a combined bead formation and thermal conduction analysis. The grids for the thermal conduction analysis were added within the specified area of weld reinforcement, which was previously calculated based on the molten pool surface profile analysis. The initial temperature of the material to be welded and the atmospheric temperature were estimated to be 20°C. Heat transfer and thermal emission from the surface of the material to the air.

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Fig. 1. Configuration of specimen to be welded and its finite element model.
heat source, such as the distributions of heat input and arc pressure from the arc plasma and the wire melting rate, estimated from welding process conditions. The present model assumes the MAG welding using a mixed gas composed of 80% Argon and 20% CO2 as shielding gas. To promote practical application of the coupled process-mechanics modeling for an efficient distortion analysis, an engineering model of heat source for MAG welding was developed based on welding process conditions as follows.

The quantity of net heat input per unit welding time \( q_{\text{weld}} \) is expressed as \( \eta IV \) by using welding current, \( I \), arc voltage, \( V \), and arc efficiency, \( \eta \). In the present model, arc efficiency was estimated to be constant of 0.85 approximately for MAG welding.\(^{19}\) Then, the total net welding heat input is divided into heat input provided directly from the arc plasma, \( q_{\text{arc}} \), and that involved with the melting wire, \( q_{\text{wire}} \). The heat input energy involved with the melting wire is expressed as \( \rho Hv_{\text{wire}} \) by using density and enthalpy of welding wire, and wire melting rate, \( v_{\text{wire}} \). The wire melting rate was approximately estimated as:

\[
 v_{\text{wire}} = a + bL_e I^2 
\]

where \( L_e \) is wire extension (15 mm), and \( a \) and \( b \) are estimated to 0.00198 mm s\(^{-1} \) A\(^{-1} \) and 0.0054 mm\(^2\) s\(^{-1} \) A\(^{-2} \), respectively, based on the experimental data.\(^{14}\) For heat input provided directly from the arc plasma in a traveling welding arc, the radial distribution of heat transfer from the arc plasma to a welded plate is expressed as:

\[
 w_{\text{arc}} = \frac{(q_{\text{arc}} / \pi R_{\text{arc}}^2) \exp\left[-(x-vt)^2 / R_{\text{arc}}^2\right] \exp\left[-y^2 / R_{\text{arc}}^2\right]}{\sqrt{2\pi}} \]

where \( q_{\text{arc}} \) can be calculated as \( q_{\text{arc}} = q_{\text{weld}} - q_{\text{wire}} \). \( R_{\text{arc}} \) is the radius of the Gaussian distribution and \( v \) is welding speed, respectively. \( R_{\text{arc}} \) was expressed as:

\[
 R_{\text{arc}} = kIV + 2.56 
\]

where \( k \) is estimated to 0.00024 mm A\(^{-1} \) V\(^{-1} \) based on the numerical data.\(^{21}\) Similarly, the radial distribution of arc pressure on the surface of welded plate is expressed as:

\[
 P = P_{\text{max}} \exp\left[-(x-vt)^2 / R_{\text{pres}}^2\right] \exp\left[-y^2 / R_{\text{pres}}^2\right] 
\]

where \( P_{\text{max}} \) is maximum value of arc pressure at the center of a traveling welding arc, and \( R_{\text{pres}} \) is the radius of the Gaussian distribution, respectively. The maximum value of arc pressure at the center of a traveling welding arc was expressed as:

\[
 P_{\text{max}} = sf^2V^{-2} 
\]

where \( s \) is estimated to 19.8 Pa A\(^{-2} \) V\(^{-2} \) based on the numerical data.\(^{21}\) Meanwhile, \( R_{\text{pres}} \) was expressed as:

\[
 R_{\text{pres}} = mL_1 V^{-1} + 1.60 
\]

where \( m \) is estimated to 791.8 mm A V based on the numerical data.\(^{21}\) Finally, the radius of bead surface calculation area, \( R_{\text{bead}} \) was expressed as:

\[
 R_{\text{bead}} = 0.00278\eta IV_{\text{wire}}^{0.5} + 1.41 
\]

based on the experimental data.\(^{14}\) These relations between heat source parameters and welding process conditions are all estimated based on the experimental and numerical data.
3. Results and Discussion

3.1. Comparison between Calculation and Measurement Results

Using the developed analysis, the effect of welding process conditions on the weldability of the MAG bead-on-plate welded structural steel plates was systematically investigated. To investigate the effect of welding current and welding speed individually, five welding conditions are examined. The base conditions are a 200-A welding current and a welding speed of 3.33 mm s\(^{-1}\). Two approaches for reducing weld heat input \(Q = IV/v\) (J mm\(^{-1}\)) are implemented. One is reducing the welding current (\(I\)-changed), and the other is increasing the welding speed (\(v\)-changed). These welding conditions are applied in the 12-mm plate thickness. Table 1 shows the welding process conditions implemented in the examination.

Figure 3 shows comparison results of the weld bead morphology and temperature distribution obtained via either calculations or observations. The observation results shown in the figure were obtained by the previous welding experiments.\(^{14}\) The bead surface profile, which was calculated based on the equation of molten pool balance, is depicted as a smooth curve, filled with black. Within that area, the grids used for thermal conduction analysis were added. The melting temperature of the material was set to 1 500°C in the calculations. Small differences can be seen in the weld penetration shape because conductive heat transfer in weld pool was considered in the present model, but on the whole there is good agreement between the calculated and the observed results of the weld bead morphology. In the steel used, the heat-affected zone (HAZ) of the tarnished area around the weld penetration, wherein the highest temperature is over about 800°C, approximately corresponds to the mechanical melting region. The mechanical melting region has recently been proposed to be a dominant factor influencing weld angular distortion.\(^{22}\) As can be seen in the figure, the mechanical melting region also provides good agreement between calculations and observations. It can be considered that temperature distribution at HAZ around the melted zone was strongly influenced by conductive heat transfer.

Figure 4 shows comparisons of temperature profiles on the welds between the calculations and the measurements. In the experiments,\(^{14}\) the temperature profiles during welding were measured by thermocouples located around the I : welding current (A), \(v\) : welding speed (cm/min)

| Table 1. Welding conditions implemented in this examination. |
|-------------------------------------------------------------|
|                | base | \(I\)-changed | \(v\)-changed |
| Welding current, \(I\) (A) | 200  | 160          | 100  | 200  | 200  |
| Arc voltage, \(V\) (V)     | 19.6 | 16.6         | 15.8 | 19.6 | 19.6 |
| Welding speed, \(v\) (cm/min) | 20   | 20           | 20   | 28   | 40   |

Fig. 3. Comparison of weld bead morphology and temperature distribution between calculations and observations.

Fig. 4. Comparison of temperature histories between calculations and measurements. (a) Effect of welding current (b) Effect of welding speed.
weld line at the longitudinal center of the welded specimen. Figures 4(a) and 4(b) show the effects of welding current and speed on temperature profiles on the welds, respectively. There is good agreement between the calculations and the measurements in both figures. Dimensions of the weld penetration and HAZ were also measured from the observation of macroscopic cross-section of the welded specimens. Figure 5 shows comparisons of depths of weld penetration and HAZ between the calculations and the measurements. The results showed that the calculated values are in good agreement with those measured. Thus, on the basis of a combined bead formation and thermal conduction analysis using the engineering heat source model developed, the weld bead morphology and temperature distribution caused by MAG welding were successfully simulated without preliminarily observation of weld bead morphology and measured temperature profiles obtained by welding experiments.

Based on the weld bead morphology and temperature distribution obtained, thermal elastic–plastic analysis with finite element methods was performed to simulate the weld angular distortion. The weld angular distortion was estimated using the vertical deflections at three different positions along the transverse axis in the longitudinal center of the welded steel plates and the equation shown in Fig. 6(a). The deflections were evaluated at room temperature after cooling. Figure 6(b) shows the comparison of weld angular distortion between the calculations and the measurements. The measurements were obtained in previous study. The deflections of the specimen were measured by displacement gauges on the weld line and both sides of the weld line at the longitudinal center of the welded specimen. The measurement locations are the same as those in the calculations. The results showed that calculated and measured angular distortions are in good agreement in each welding process condition.

From these comparisons, we concluded that coupled process-mechanics modeling and analysis of MAG welding and heat source parameter estimation based on welding process conditions were beneficial to accurately simulate the weld bead morphology, temperature distribution, and angular distortion.

3.2. Discussion about a Dominant Factor Influencing Weld Angular Distortion

Based on the calculation results, a dominant factor influencing the weld angular distortion of MAG welded structural steel plates was further discussed to obtain a more detailed understanding of the welding process condition-dependence of angular distortion.

Classical welding mechanics has presented the theoretical framework for quantifying weld shrinkage and distortion based on simplified models and empirical formulae. Consequently, the quantity of heat input per unit welding length provided to the material has traditionally been recognized as the dominant factor influencing the weld shrinkage and distortion. This was derived from welding thermal conduction theory with the assumption that an instantaneous heat source was available for approximately calculating the temperature distribution during welding with a moving heat source. In particular, weld angular distortion has traditionally been controlled by the heat input parameter, $Q/h^2$, where $h$ is...

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Fig. 5. Comparison of weld penetration and heat affected zone between calculations and measurements.

Fig. 6. Comparison of weld angular distortion between calculations and measurements. (a) Definition of and procedure for evaluating angular distortion (b) Angular distortions evaluated.
the thickness of the material to be welded.\textsuperscript{24}) However, the limitations to the application of the traditional heat input parameter are supported by a recent study and a parameter of mechanical melting region was newly proposed to more coordinately arrange the weld angular distortion.\textsuperscript{22})

Then, calculated angular distortions were arranged by the traditional heat input parameter and the newly developed parameter of mechanical melting region, respectively, as shown in Figs. 7(a) and 7(b). From the results of the traditional heat input parameter, different variation curves can be seen between the effects of welding current and speed, respectively. Meanwhile, the effect of welding process conditions on angular distortion was quantified by a unified curve to newly developed parameter of mechanical melting region. Thus, the usefulness of mechanical melting region for a dominant factor influencing weld angular distortion was also supported by the analysis developed in this study.

\section{Conclusions}

In this study, coupled process-mechanics modeling of MAG welding and heat source parameter estimation based on welding process conditions were developed for an efficient distortion analysis. The developed analysis was applied to investigate the effect of welding process conditions on the weldability of MAG welded structural steel plates; consequently, the following conclusions have been obtained.

(1) The calculated results of weld bead morphology, temperature profiles, and angular distortion provided good agreements with those measured under the same welding process conditions.

(2) The calculated results showed that weld angular distortion was more coordinately quantified by the parameter of mechanical melting region rather than by the traditional heat input parameter.

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