Effect of Welding Process Conditions on Angular Distortion Induced by Bead-on-plate Welding

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In this study, the effect of welding process and heat input conditions on the angular distortion induced by bead-on-plate welding was investigated through a numerical approach. Numerical models of gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW), which were developed in a previous study, were utilized for accurate distortion analyses. The calculated relation between welding conditions and angular distortion was quantified by using the conventional heat input parameter derived from welding thermal conduction theory. The results clarified the limits of applying the heat input parameter to quantify angular distortion under the various welding process and heat input conditions. In addition, the effect of the weld reinforcement generated in GMAW on angular distortion was coordinately examined by using a parameter, defined as the ratio of the area of weld reinforcement to the square of plate thickness. The effect was generally negligible except for in the case of a thin plate. Then, a parameter of the mechanical melting region on the plate thickness section was applied to quantify the angular distortion induced by GMAW and GTAW. As the results, a unified evaluation of the effect of welding process and heat input conditions on angular distortion was successfully achieved. Thus, it can be concluded that the developed parameter of the mechanical melting region on the plate thickness is the dominant factor for accurately quantifying angular distortion.

KEY WORDS: angular distortion; welding process conditions; gas metal arc welding; gas tungsten arc welding; mechanical melting region; weld reinforcement.

1. Introduction

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

To predict various types of shrinkage and distortion, classical welding mechanics has provided a theoretical framework based on simplified models and empirical formulae. It is well known that various types of shrinkage and distortion induced by welding can be controlled by the net heat input per unit welding length, \( Q_{\text{net}} \). The formulation of \( Q_{\text{net}} \) was derived from welding thermal conduction theory on the assumption that an instantaneous heat source can be used to approximately calculate the temperature distribution during welding produced by a moving heat source. In a simplified model based on a both-ends-fixed bar analogy, the generation characteristics of inherent strain, which is a theoretical concept representing a cause of weld shrinkage and distortion, depends on the temperature distribution during welding. To quantify the angular distortion induced by welding, the heat input parameter, \( Q_{\text{net}}/h^2 \), where \( h \) is the thickness of the material to be welded, was proposed based theoretically on the similarity rule of the temperature distribution on the plate thickness section. The results showed that the angular distortion induced by welding is a convex curve when plotted against the heat input parameter. Then, a unified evaluation regardless of the welding process could be used to quantify the angular distortion, if the heat input parameter is smaller than the heat input parameter at the angular distortion peaks in the convex curve. In recent years, however, experimental results for different welding process and heat input conditions have indicated limits in applying the heat input parameter to accurately quantify angular distortion. Then, a more detailed understanding of the effect of welding process and heat input conditions on angular distortion is urgently required to accurately predict and control shrinkage and distortion.

After thermal elastic–plastic analysis techniques using finite element methods were first applied to thermo-mechanical...
welding problems in the 1970s,\textsuperscript{9} advanced modeling and simulation techniques have been developed for calculating weld residual stress and deformation.\textsuperscript{10–12} For example, the double-ellipsoidal moving heat source model\textsuperscript{13} enhanced the mathematical theory of heat distribution during welding\textsuperscript{14} and the resulting residual stress and deformation.\textsuperscript{14–17} Recently, coupled process-mechanics modeling and simulation techniques for arc welding, such as gas tungsten arc welding (GTAW)\textsuperscript{19} and gas metal arc welding (GMAW),\textsuperscript{19} have been proposed to accurately calculate the angular distortion induced by bead-on-plate welding.

This study examines the effect of welding process and heat input conditions on the angular distortion induced by bead-on-plate welding through a coupled process-mechanics modeling and simulation technique, which was developed based on the experimental results in previous studies.\textsuperscript{18,19} The calculated relations between welding conditions and angular distortion induced by GTAW and GMAW are plotted against the conventional heat input parameter. To understand the effect of the welding process on angular distortion, the variation in angular distortion due to the existence of the weld reinforcement generated in GMAW was also investigated. Moreover, based on the results, the effect of the welding process and heat input conditions on angular distortion is examined by using a parameter of the mechanical melting region on the plate thickness section. This parameter was newly proposed based on inherent strain theory\textsuperscript{19} to discuss the dominant factor influencing angular distortion. Through the investigation, the usefulness of the developed parameter of the mechanical melting region is validated for a unified evaluation of the effect of welding process and heat input conditions on the angular distortion induced by bead-on-plate welding.

2. Numerical Analysis of Angular Distortion Induced by Bead-on-plate Welding

2.1. Numerical Modeling and Simulation Techniques

A coupled process-mechanics modeling and simulation technique, which was developed in previous studies,\textsuperscript{18,19} was utilized for systematically investigating the effect of welding conditions on the angular distortion induced by GMAW and GTAW. The bead surface and temperature profiles during welding, which are the input data for the thermal elastic-plastic analysis, were calculated through a combined bead formation and thermal conduction analysis with finite difference methods. The general-purpose finite element (FE) analysis code ABAQUS ver. 6.9.1 was adopted for the thermal elastic-plastic analysis of the weld angular distortion. In the finite element analysis, the welded plate and weld-deposited metal were considered as solid deformable bodies. The elements of weld reinforcement were added successively according to the forward movement of the welding torch.

Figure 1 shows the configuration of a bead-on-plate welding joint. The dimensions of the plate to be welded are as follows: length 200 mm, width 500 mm, and thickness from 8 to 28 mm. The weld length was 150 mm, which left unwelded sections of 25 mm at both ends of the plate. These dimensions are exactly the same as those of previous experiments.\textsuperscript{18,19} A fine FE 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. The initial temperature of the material to be welded and the atmospheric temperature were estimated to be 20°C. The heat transfer and thermal emission from the material surface to air were introduced as boundary conditions. The heat transfer coefficient and the thermal emissivity were set as $12.5 \times 10^{-6}$ W/mm$^2$K and 0.3, respectively. In the thermal elastic-plastic analysis, no restraints to prevent the thermal deformation due to welding were set. Other analytical conditions are given in previous papers.\textsuperscript{18,19}

The material properties determined for the 490 MPa class high-tensile-strength steel are shown in Figure 2. Figure 2(a) shows the density, specific heat, and thermal conductivity; these data were used in the welding thermal conduction analysis. Figure 2(b) shows the yield stress, thermal expansion coefficient, Young’s modulus, and Poisson’s ratio; these data were used in the welding thermo-mechanical
analysis. The temperature dependency of these properties was taken into account. In addition, work hardening of the material was taken into account in the thermal elastic-plastic analysis.20)

### 2.2. Welding Conditions
To investigate the effect of welding current and welding speed individually, five welding conditions were examined for GMAW. Table 1 shows the implemented welding conditions. As the base conditions, the welding current was 200 A for GMAW. Two approaches for reducing weld heat input and the welding speed was 3.33 mm/s. Two approaches for reducing weld heat input \(Q (= IV/v; J/mm)\) were used. One was reducing the welding current \((I\text{-changed condition})\), and the other was increasing the welding speed \((v\text{-changed condition})\). These conditions were applied in the 12-mm plate thickness. For base conditions that drastically change the value of the heat input parameter, the plate thickness was varied from 8 mm to 28 mm (\(h\text{-changed condition}\)). For the first GTAW conditions, the welding current was 200 A, the arc voltage was 11.4 V, and the welding speed was 1.67 mm/s. The first GTAW conditions were determined to investigate the effect of the welding process on the angular distortion under the same welding speed condition. The second GTAW conditions were determined to compare the angular distortion induced by GMAW and GTAW under the commonly used welding speed condition. Generally, the welding speed is higher in GMAW than in GTAW. The heat source model according to the welding heat input conditions was constructed by considering the physics of welding arc for GTAW18) and GMAW,19) respectively.

### 3. Results and Discussion

#### 3.1. Simulation Results
Figures 3(a) and 3(b) show the simulation results for an illustrative example of the base condition for a plate thickness of 12 mm. These figures show the two-dimensional (2D) distributions of the temperature fields and the residual vertical displacement of the welded plate, respectively. As shown in Fig. 3(a), the combined bead formation and temperature distribution calculations were successfully performed. As shown in Fig. 3(b), residual angular distortion was generated as the result of thermo-mechanical behavior due to the bead formation and the temperature fields during welding. Here, the value of the angular distortion induced by bead-on-plate welding was estimated from the vertical deflections at three different positions along the transverse axis in the longitudinal center of the welded steel plate and by the equation shown in Fig. 4. All deflections were evaluated at room temperature after cooling.

#### 3.2. Effect of Welding Process and Heat Input Conditions on Angular Distortion
From the simulation results, the effect of welding pro-

| Table 1. Welding conditions for GMAW process implemented in this examination. |
|-----------------|----------------|----------------|----------------|----------------|----------------|
| Welding current, \(I\) (A) | Base | \(I\text{-changed}\) | \(v\text{-changed}\) | \(h\text{-changed}\) |
| Arc voltage, \(V\) (V) | 200 | 160 | 100 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| Arc voltage, \(V\) (V) | 19.6 | 16.6 | 15.8 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 | 19.6 |
| Welding speed, \(v\) (cm/min) | 20 | 20 | 20 | 28 | 40 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Welding speed, \(v\) (mm/s) | 3.33 | 3.33 | 3.33 | 4.67 | 6.67 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 |
| Plate thickness, \(h\) (mm) | 12 | 12 | 12 | 12 | 12 | 28 | 20 | 18 | 16 | 14 | 10.5 | 9.5 | 9.0 | 8.5 |
| Heat input parameter, \(Q_{\text{net}}/h^2\) (J/mm³) | 7.0 | 4.7 | 2.8 | 5.0 | 3.5 | 1.3 | 2.5 | 3.1 | 3.9 | 5.1 | 9.1 | 11.1 | 12.4 | 13.9 | 15.7 |

| Table 2. Welding conditions for GTAW process implemented in this examination. (a) For higher welding speed condition, (b) For lower welding speed condition. |
|-----------------|----------------|----------------|----------------|----------------|----------------|
| Welding current, \(I\) (A) | Base | \(I\text{-changed}\) | \(v\text{-changed}\) | \(h\text{-changed}\) |
| Arc voltage, \(V\) (V) | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| Arc voltage, \(V\) (V) | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 |
| Arc voltage, \(V\) (V) | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 |
| Welding speed, \(v\) (cm/min) | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| Welding speed, \(v\) (mm/s) | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 | 3.33 |
| Plate thickness, \(h\) (mm) | 28 | 20 | 18 | 16 | 14 | 12 | 10.5 | 9.5 | 9.0 | 8.5 | 8.0 |
| Heat input parameter, \(Q_{\text{net}}/h^2\) (J/mm³) | 0.7 | 1.3 | 1.7 | 2.1 | 2.7 | 3.7 | 4.9 | 6.0 | 6.6 | 7.4 | 8.4 |

| (a) Welding current, \(I\) (A) | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| Arc voltage, \(V\) (V) | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 |
| Arc voltage, \(V\) (V) | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| Welding speed, \(v\) (cm/min) | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 |
| Plate thickness, \(h\) (mm) | 28 | 20 | 18 | 16 | 14 | 12 | 10.5 | 9.5 | 9.0 | 8.5 | 8.0 |
| Heat input parameter, \(Q_{\text{net}}/h^2\) (J/mm³) | 1.4 | 2.7 | 3.3 | 4.2 | 5.5 | 7.5 | 9.7 | 11.9 | 13.3 | 14.9 | 16.8 |

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cess and heat input conditions on the angular distortion induced by bead-on-plate welding against the conventional heat input parameter was quantified. Figure 5(a) shows the relation between the heat input parameter and the angular distortion under various welding heat input conditions for GMAW. The results show that a convex curve of the angular distortion against the heat input parameter was on the whole obtained, but the curve was slightly influenced by welding heat input conditions. Specifically, the angular distortion became larger as the welding speed became larger when the values of heat input parameter were almost the same. However, in comparison with the results for GTAW, the influence may be negligible. Figure 5(b) shows the relation between the heat input parameter and the angular distortion in both GMAW and GTAW. For GTAW, two different welding speeds, which were the same as and lower than that of GMAW, were implemented. The results show that the convex curve of the angular distortion against the heat input parameter was obviously different between GMAW and GTAW at the same welding speed. Meanwhile, a similar convex curve was obtained between GMAW and GTAW under different welding speeds, especially when the value of the heat input parameter was smaller than that at the peaks of the angular distortion in the curve. From the results, it was concluded that a unified evaluation of the effect of the welding process and heat input conditions on the angular distortion induced by bead-on-plate welding was not always obtained by using the conventional heat input parameter.

To clarify the effect of the welding process on angular distortion in more detail, the variation in angular distortion due to the existence of a weld reinforcement was quantified. Figure 6 shows the relation between the heat input parameter and the angular distortion with and without a weld reinforcement. For the FE model of GMAW without weld reinforcement, no elements of weld reinforcement
were added on the welded surface in the thermal elastic-plastic analysis; that is, the through-thickness temperature distribution in the welded plate was exactly the same with and without weld reinforcement. The results show that the existence of the weld reinforcement decreased the angular distortion and the variation in the angular distortion due to the existence of weld reinforcement increased as the heat input parameter increased. In other words, the effect of weld reinforcement on angular distortion becomes negligible when the plate thickness is large enough to have the value of the heat input parameter be smaller than that when the angular distortion peaks in the convex curve.

3.3. Discussion about Dominant Factor Influencing Weld Angular Distortion

From the investigation described in Section 3.2, the conventional heat input parameter did not always coordinately quantify the effect of welding process and heat input conditions on the angular distortion induced by bead-on-plate welding. Therefore, a more detailed understanding of the dominant factor influencing weld angular distortion was demanded for accurately quantifying the angular distortion.

Figure 7 shows a schematic illustration of the assumed distribution of inherent strain on a plate thickness section. In the semi-ellipsoid area within the welded plate and weld reinforcement, a uniform distribution of inherent strain was assumed as a control for angular distortion proposed in a previous study.\(^{21}\) On the basis of inherent bending distortion theory, the angular distortion, \(\delta\), was quantified in the following Eqs. (1) (for thick plate) and (2) (for thin plate).

\[
\delta = \frac{b}{h} \left(1 + \frac{c}{h}\right)^{-3} \\
\left[\frac{3\pi}{4}(d/h)(1-c/h) - 2(d/h)^2 + 3(c/h)\right] 
\]

\[
\delta = \frac{b}{h} \left(1 + \frac{c}{h}\right)^{-3} \\
\left[\frac{3\pi}{2} \left(1 - \frac{c}{h}\right) + \frac{(d/h)(1-c/h) + \frac{1}{d}(h/d)\sin^{-1}\left(\frac{h}{d}\right)}{1 - \left(\frac{d}{h}\right)^2} \right] \\
\left[1 - \left(\frac{d}{h}\right)^2\right]^{3/2} - 2(d/h)^2 \left[1 - \left(\frac{d}{h}\right)^2\right]^{3/2} \left(+ \frac{3(c/h)}{1}\right) 
\]

where \(b\) and \(d\) are the width and the depth of the generation area of inherent strain, \(c\) is the average bead height per width of the generation area of inherent strain, and \(h\) is the plate thickness. According to the equations, angular distortion can be quantified as a function of \(b/h\), \(d/h\) and \(c/h\). For thick plate, on the basis of omission of the high-level sections, angular distortion can be approximately quantified as a function of \((b/h)(d/h)\) and \((b/h)(c/h)\). The function of \((b/h)(d/h)\) is a representative parameter for the distribution of inherent strain on a plate thickness section, and the function of \((b/h)(c/h)\) is a representative parameter for the relative size of the weld reinforcement to the plate thickness. Then, \((b/h)(c/h)\) can be substituted by \((b_w/h)(c_w/h)\), where \(b_w\) is bead width and \(c_w\) is bead height.

Figure 8 shows the variation in angular distortion due to the existence of weld reinforcement arranged by the proposed parameter of \((b_w/h)(c_w/h)\). The results show that an almost linear relation between the proposed parameter and the variation in the angular distortion due to the existence of the weld reinforcement was successfully obtained regardless of welding heat input conditions, such as the base, \(I\)-changed, \(v\)-changed and \(h\)-changed conditions. Then, the variation in angular distortion was a maximum of only 0.003 rad within the scope of this study. From the results, it was concluded that nonuniformity of the curve between welding heat input conditions and the angular distortion induced by GMAW, as shown in Fig. 5(a), is not due to the weld reinforcement.

Then, the effect of the welding process and heat input conditions on angular distortion was quantified against the other parameter of the mechanical melting region on a plate thickness section, \((b_m/h)(d_m/h)\), as shown in Fig. 9. Here, \(b_m\) is the width of the mechanical melting region and \(d_m\) is the depth of the mechanical melting region on the...
plate thickness section. These were determined based on the assumption that the generation area of inherent strain controlling angular distortion approximately corresponds to the mechanical melting region.\(^\text{(2)}\) The temperature at which materials largely lose strength and stiffness before melting was defined as mechanical melting temperature. In the mechanical melting region, a material temperature is higher than the mechanical melting temperature. For the rolled steel for welded structure used, the mechanical melting temperature is approximately 800°C. In Fig. 9, angular distortion induced by not only GMAW but also GTAW are plotted. Moreover, two different welding speed conditions for GTAW are also shown in this figure. The results show that angular distortion induced by bead-on-plate welding under various welding process and heat input conditions was coordinately modeled by the developed parameter of the mechanical melting region on the plate thickness section. Especially, excellent uniformity is seen in the relation between the developed parameter and angular distortion when the value of the developed parameter is smaller than at the peaks of angular distortion in the convex curve. From the results, it was concluded that the developed parameter of the mechanical melting region on the plate thickness section is able to coordinate model the angular distortion induced by bead-on-plate welding under various welding process and heat input conditions. Thus, the developed parameter of the mechanical melting region on the plate thickness section is expected to be a useful as a dominant factor influencing weld angular distortion.

4. Conclusions

In this study, the effect of the welding process and heat input conditions on the angular distortion induced by bead-on-plate welding was investigated through the coupled process-mechanics modeling and simulation techniques for GMAW and GTAW. Through quantification of the relation between welding conditions and angular distortion by using the conventional heat input parameter and the developed parameter of the mechanical melting region on the plate thickness section, a dominant factor influencing angular distortion was determined. The following conclusions were obtained:

1) Under various welding process and heat input conditions, the limits in applying the conventional heat input parameter to coordinate model the angular distortion induced by bead-on-plate welding were clarified.

2) The variation in angular distortion due to the existence of weld reinforcement was coordinately modeled by a parameter of the ratio of the area of the weld reinforcement to the square of the plate thickness, but the influence was likely to be negligible, especially for a welded plate of large thickness.

3) The angular distortion induced by bead-on-plate welding under various welding process and heat input conditions was coordinately modeled by the developed parameter of the mechanical melting region on the plate thickness section.

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