An attempt to enhance numerical models of angular distortion by considering the physics of the welding arc

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ABSTRACT

Recently, it has become necessary to control or reduce weld distortion, which has a negative influence on structural integrity, without loss of manufacturing efficiency. Some studies on the fundamental characteristics of weld distortion and its control or reduction have been conducted. However, the results cannot be applied to all welding processes because such processes are becoming more diversified. For this reason, to understand the fundamental characteristics of weld distortion based on the welding conditions, the heat transport phenomenon in arc physics must be investigated. In this study, an experiment and numerical simulations are conducted to investigate the link between arc physics and weld distortion. As a result, the relation between weld distortion and the heat transport phenomenon is further clarified.

IIW-Thesaurus keywords: Arc physics; Distortion; Energy input; Simulating.

1 Introduction

It is well-known that weld distortion, which has a negative influence on material properties, on the ability to fabricate structures, and structural integrity, should be controlled. There are many methods for controlling or reducing weld distortion, but most of them involve costly processing in addition to the welding process. In-process control of weld distortion becomes preferable to post-weld control when manufacturing efficiency is considered.

Traditionally, weld distortion is controlled by weld heat input. Weld heat input is controlled by the following: welding current and arc voltage from the welding power source, welding speed from a welding robot; and arc efficiency of the welding method. However, it is also known that weld distortion is not totally controlled by weld heat input only. Therefore, it is important to clarify the factors affecting weld distortion.

In this study, two types of investigations are performed to consider the relationship between weld heat input and weld distortion. The first one is an experiment and the second one is numerical analysis. In the numerical analysis, an approach to linking arc physics and weld distortion is presented.

2 Knowledge about dominant factor affecting weld distortion

2.1 Similarity rule of temperature distribution in a plate thickness section

The cause of weld residual distortion is inherent strain, which is plastic strain generated due to an inhomogeneous temperature distribution during welding. To clarify the dominant factor affecting weld distortion, it is important to understand the actual generation behaviour of plastic strain in relation to the inhomogeneous temperature distribution. An example is the model of a bar clamped at both ends. In this case, the generation behaviour of plastic strain in the welding direction can be explained almost completely. However, the generation behaviour of plastic strain in the transverse direction is more complex, and it is difficult to ascertain the dominant factor affecting weld distortion, such as transverse shrinkage and angular distortion in the transverse direction. For this reason, one approach has been to clarify the dominant factor affecting weld distortion in the transverse direction in relation to the similarity rule of temperature distribution in the plate thickness section [1].

By considering a non-moving (instantaneous) line heat source, thermal conduction theory can be used to express the temperature distribution in a plate thickness section during welding [2], as stated below:

\[ T = \frac{1}{(2\sqrt{\pi}kt)^2} \cdot \frac{Q_{\text{net}}}{c \rho} \cdot \exp\left\{-\left(y^2 + z^2\right)/4kt\right\} \]  

(1)

where

- \( \rho \) is density,
- \( c \) is the specific heat,
- \( \lambda \) is the heat conductivity,
- \( t \) is time and
- \( h \) is the plate thickness,
- \( Q_{\text{net}} \) is the net heat input,
- \( T \) is temperature.
In Equation (1), by converting each variable number into plate thickness $h$, the temperature distribution is expressed as follows:

$$T = \left( \frac{Q_{\text{net}}}{h^2} \right) \cdot \left( \frac{2}{c \rho} \right) \cdot \exp\left[-\left(\frac{X^* + Y^*}{\tau^*}\right)^2\right] / \pi \tau^*$$  \hspace{1cm} (2)

that is, $Q_{\text{net}} = \eta/V/u$, $Y^* = y/h$, $Z^* = z/h$, $\tau^* = 2\sqrt{kt}/h$,

where

$\eta$ is the arc efficiency.

According to Equation (2), the dominant factor affecting temperature distribution in the plate thickness section is $Q_{\text{net}}/h^2$, which is called the heat input parameter. At this time, the welding heat input $Q_{\text{net}}$ means the heat intensity per welding length [$J/mm$], not per time [$J/s$]. The heat input parameter represents the temperature rise at one location at one time, and the generation behaviour of plastic strain at one location at one time. The deformed state in welded joints is shown in Figure 1. In this figure, transverse distortion conforms to the similarity rule of temperature distribution and distortion, which means that the transverse shrinkage per plate thickness is dependent on the heat input parameter, and angular distortion is dependent on the heat input parameter [1].

### 2.2 Characteristics of angular distortion

According to the similarity rule of temperature distribution in the plate thickness section, angular distortion is dependent on the heat input parameter. As shown in Figure 2, when the welding method is the same, angular distortion produced in any welding conditions can be evaluated by one curve which depends on the heat input parameter. When the heat input parameter is small, rigidity due to plate thickness prevents the welded plate from being distorted. In contrast, when the heat input parameter is large, the temperature gradient through the thickness direction becomes uniform. Then, angular distortion becomes smaller. As a result, the maximum angular distortion occurs in the intermediate condition of the heat input parameter.

### 3 Experimental examination

#### for relation between weld heat input and weld distortion

**3.1 Experimental procedure**

The steel used in the experiment is SM490. The chemical composition of this steel is shown in Table 1, and the configuration of the welded joint used in the experiment is shown in Figure 3. The dimensions of the plate are the following: length 200 mm, width 500 mm, and thickness 6 or 12 mm. The weld length is 150 mm, which leaves unwelded sections of 25 mm at both ends of the plate. The plate is placed on a sill plate due to the heat transfer from the bottom of the welded plate to the air.

The locations of the thermocouple and displacement gauge are shown in Figure 4. The temperature histories are measured by five thermocouples, and the deflection is

<table>
<thead>
<tr>
<th>Plate thickness [mm]</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.15</td>
<td>0.25</td>
<td>1.42</td>
<td>0.020</td>
<td>0.004</td>
</tr>
<tr>
<td>12</td>
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<td>0.28</td>
<td>1.45</td>
<td>0.015</td>
<td>0.003</td>
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</tbody>
</table>

Table 1 – Chemical compositions [mass %]