Computational simulation of weld microstructure and distortion by considering process mechanics

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Abstract. Highly precise fabrication of welded materials is in great demand, and so microstructure and distortion controls are essential. Furthermore, consideration of process mechanics is important for intelligent fabrication. In this study, the microstructure and hardness distribution in multi-pass weld metal are evaluated by computational simulations under the conditions of multiple heat cycles and phase transformation. Because conventional CCT diagrams of weld metal are not available even for single-pass weld metal, new diagrams for multi-pass weld metals are created. The weld microstructure and hardness distribution are precisely predicted when using the created CCT diagram for multi-pass weld metal and calculating the weld thermal cycle. Weld distortion is also investigated by using numerical simulation with a thermal elastic-plastic analysis. In conventional evaluations of weld distortion, the average heat input has been used as the dominant parameter; however, it is difficult to consider the effect of molten pool configurations on weld distortion based only on the heat input. Thus, the effect of welding process conditions on weld distortion is studied by considering molten pool configurations, determined by temperature distribution and history.

1. Introduction

Highly precise fabrication is being demanded, and so microstructure and distortion control are very important. It is important to determine welding process conditions by considering combinations of the various aspects of “process mechanics,” including the appearance of a bead, penetration shape through a cross-section, fabrication efficiency, microstructure, weld defects during and after welding, environment, thermal distortion, residual stress, and so on. In this study, computational simulations are performed to study the effects of welding process conditions and molten pool configurations on weld microstructures and distortion from the viewpoint of process mechanics.

For multi-pass weld metal, it is widely known that mechanical properties such as yield stress, tensile strength and fracture toughness are affected by the interpass temperature and heat input [1], [2]. Heterogeneity caused by multiple heat cycles makes it difficult to understand the results of mechanical testing. It is therefore very important to investigate weld thermal cycles and microstructure in relation to mechanical properties. Multiple welding heat cycles particularly affect joint performance. Many experimental and practical approaches have been applied to correlate welding conditions and joint performance [3]-[5], but the theoretical procedures of evaluation are very effective for complicated weld phenomena and the prediction of mechanical properties of welded joints [6]-[10]. Computational simulation is a convenient method of evaluation [11]-[15]. Numerical simulations using modified...
CCT diagrams can be used to evaluate the relationship between the hardness of multi-pass weld metal and welding conditions with respect to weld thermal cycles and microstructure.

A widely used equation for evaluating weld distortion is average heat input \( Q = \eta IE/v \), where \( \eta \): heat efficiency, \( I \): welding current, \( E \): arc voltage, \( v \): welding speed. For example, many prediction equations and analytical methods of weld distortion have been developed based on the empirical data of average heat input \( Q \) in conventional welding [4], [16]-[18]. In conventional welding, the recommended welding conditions are more or less fixed when the boundary conditions of the welding are given [19]-[21]. However, it is difficult to use only \( Q \) to consider the effect of multiple heat sources or waveforms, such as the pulse condition, on weld distortion [22]-[25]. The evaluation of weld distortion of complicated controlled welding processes should consider the molten pool configuration. Consequently, in this study, precise weld distortions depending on precise welding conditions are evaluated both by numerical analysis using the thermal elastic-plastic finite-element method and actual experiments with different molten pool configurations. The molten pool configuration is determined from the temperature distribution and history during the weld process, and weld distortion is determined from the temperature field. The effect of the energy density distribution on weld circularity distortion is also investigated. An appropriate molten pool configuration to reduce weld distortion is discussed by using process mechanics.

2. Prediction of weld microstructure and hardness under different interpass temperatures

Welded joints with root gap 8 mm and bevel angle 35° were fabricated. The materials used were JIS G 3106 SN490B for the base metal and JIS Z 3312 YGW11 for the welding wire. The temperature during welding was measured at a location on the surface of the base metal, as shown in Fig. 1. Interpass temperature is defined as the temperature measured at this location just before the start of each welding pass. Joints were welded under two conditions of interpass temperatures: “continuous welding” and “interpass temperature-controlled welding.” In the continuous welding condition, the interpass temperature is not controlled. In the interpass temperature-controlled welding condition, the interpass temperature is maintained at a temperature lower than 350°C during the entire welding process.

The fraction of each type of microstructure was calculated from weld thermal cycles based on CCT diagrams. In this study, the hardness of each microstructure was estimated from the cooling rate of the weld metal [14], [25]. However, CCT diagrams of the weld metal are not available, even for single-pass weld metal, due to the maximum temperature distribution; therefore, modified CCT diagrams for multi-pass weld metals were created. To create CCT diagrams of the weld metal in multiple heat cycles, a simulated weld thermal cycle test was conducted to observe the microstructural changes. The microstructures formed in multi-pass weld metal can differ depending on the maximum temperature, and the differences are found by comparing the microstructures of the heat-affected zone in multi-pass welds. The maximum temperature of the simulated weld thermal cycle for creating CCT diagrams was selected as follows: 1350°C for the coarse-grained region and 900°C for the fine-

![Figure 1. Configuration of a multi-pass welded joint.](image-url)
grained region. Observations of the microstructure and the results of the simulated weld thermal cycle test show that the microstructure of multi-pass weld metals is more dependent on the maximum temperature in reheating than in welding conditions such as the interpass temperature. Therefore, CCT diagrams for two maximum temperatures were created. In the CCT diagrams, ferrite + pearlite, bainite and austenite are considered to be the microstructural fractions [4], [6]-[10], [22]. The hardness distribution of the multi-pass weld metals is estimated with the linear rule of mixture. The fraction of the microstructure corresponding to weld thermal cycles is calculated from the newly created CCT diagrams.

The calculated distribution of the fraction of the ferrite + pearlite microstructure is shown in Fig. 2 together with macro cross sections of the welds. The distribution of ferrite + pearlite approximately corresponds to the reheated zone in the macro cross sections. The effect of the last weld pass by continuous welding is larger than that by the interpass temperature-controlled welding. The microstructural distribution by interpass temperature-controlled welding thus becomes more complicated than that by continuous welding.

The hardness distribution in the weld metal across the thickness direction is shown in Fig. 3. Hardness curves are estimated from the measured hardness values. As seen in these figures, the distribution of the microstructure corresponds to the distribution of hardness in both depositing sequences. Vickers hardness distributions are predicted precisely by using numerical analysis that considers the difference of welding conditions. The microstructure and hardness distribution are predicted when the appropriate CCT diagram for the multi-pass weld is used and when a detailed calculation of the weld thermal cycle is carried out.

3. Effect of molten pool configuration and energy density distribution on weld distortion

The energy density distribution of the heat input affects weld distortion, because the temperature distribution and history change when a heat source with a different energy density is used, even for the same total heat input. A profiler for laser beams is used to measure the energy density distribution, and the effect of the different distributions on weld distortion are studied.

The profiler for measuring energy density distributions scans the surface of a small-diameter opening drilled in the chip of the laser beam-receiving unit by moving in a circular and axial direction. The laser beam is introduced via the chip to a photodiode to sense the intensity of penetrating energy passing through the opening. The distribution of energy on the measuring plane is sent to a computer to process the position of the opening and the intensity of the energy. The three-dimensional energy density distribution is plotted by feeding the chip in the height direction to measure and compute the energy distribution at each level.
Two types of laser beams are measured: Gaussian-like and flattop. Figure 4 shows the results of the distribution of the laser energy density. The light-focusing diameter of the Gaussian-like distribution laser with a laser output of 300 W is approximately 450 µm, and the light-condensing diameter of the flat-top distribution laser is approximately 230 µm for the same laser output. The Gaussian-like distribution laser is designed so that an area with peripheral output lower than the center has a relatively wide range. In the flattop distribution laser, the area with output lower than the center steeply attenuates, in contrast. Thus, two different kinds of profiles were identified.

| Laser spatial distribution | Light-focusing properties |
|---------------------------|---------------------------|
| Broad base                | Focal position (a.u.)     |
|                           | Spot size (µm)            |
|                           | flatten                   |
| No broad base             |                           |

Figure 4. Results of monitoring laser beam profile.

The penetration geometry using these two laser profiles was evaluated by measuring the cross-sectional shape in bead-on-pipe irradiation. The bead width and penetration depth were measured as functions of the laser output and processing rate in an experiment to verify the melting conditions resulting from the beam profile. The laser beam is irradiated in a bead-on manner onto the test piece, which is a pipe made of type 304 stainless steel, as shown in Fig. 5. A comparison of the cross-section at the same bead penetration depth is shown in Fig. 6, and the cross-sectional geometry under the same laser welding conditions is shown in Fig. 7. The penetration depth tends to increase as the output increases, and the flattop distribution tends to have a larger penetration depth.

Figure 5. Configuration of bead-on-pipe component specimen.

Figure 6. Comparison of cross-section at the same penetration depth.

Figure 7. Comparison of cross-section with the same laser welding condition.
A comparison between the cross-sectional shapes in Figs. 6 and 7 indicates that the Gaussian-like distribution beam allows the bead to expand because the upper portion, which does not contribute to the welding depth, absorbs much of the heat and spreads. The Gaussian-like distribution facilitates the melting of the low-energy portion that then expands the bead width, and the keyhole geometry caused by the energy density efficiently guides energy in the thickness direction due to multiplex reflection. In contrast, the flattop laser allows deeper penetration with the same bead width. The beam profiles for these two types of lasers are very different in light focus, as is confirmed by the cross-sectional geometry.

The difference in effects between the flattop distribution beam and the Gaussian-like distribution beam also is due to the variation in circularity. Circularity measurements are taken by the minimum area center method. In this method, the difference between the radii of two circles representing the minimum difference between the inscribed circle and the circumscribed circle is defined as the circularity value. Circularity is measured before and after welding to identify the difference between the pre-welding and post-welding circularities.

Figure 8 shows the results of the circularity measurement after bead-on irradiation of the pipes with the flattop distribution laser and the Gaussian-like distribution laser. The processing conditions fulfilling a penetration depth of 0.4 mm are determined from the results of the experiment in the previous section, and the actual circularity variation is measure.

To achieve penetration at the same level as that with the flattop distribution beam, the Gaussian-like distribution beam requires larger welding deformation due to the irradiation of energy that does not contribute to penetration. The Gaussian-like distribution beam, which traditionally is used, is effective in improving circularity as the processing rate increases, even when compared with the flattop distribution beam at the same rate. However, processing rate limitations such as insufficient penetration remain higher than those of the flattop.

It is thus understood that the energy density distribution greatly affects weld distortion. This means not only the total heat input but also the heat input distribution, even for the same total heat input, is important for weld distortion reduction and control.

4. Summary
Highly precise fabrication is in demand, and therefore microstructure and distortion controls are essential. Thus, the process mechanics are important for intelligent fabrication. The microstructure and hardness distribution of multipass weld metals resulting from metallurgical and mechanical heterogeneity are estimated by a numerical simulation with weld thermal cycles and microstructural phase transformation. Modified CCT diagrams for the multi-pass weld metal are created to consider the effect of complicated welding heat cycles and to calculate phase transformation. The estimated hardness distribution shows good agreement with the experimental values by using an appropriate CCT diagram for the multi-pass weld and precise numerical simulation. The effect of energy density distributions at the same total heat input on weld distortion is also investigated in this paper. By
understanding the relation between weld distortion and molten pool configuration and determining the appropriate welding conditions, more precise fabrication can be obtained.

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