Research Article

The Effect of Welding-Pass Grouping on the Prediction Accuracy of Residual Stress in Multipass Butt Welding

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The residual stress analysis of a thick welded structure requires a lot of time and computer memory, which are different from those in thin welded structure analysis. This study investigated the effect of residual stress due to welding-pass grouping as a way to reduce the analysis time in multipass thick butt welding joint. For this purpose, the parametric analysis which changes the number of grouping passes was conducted in the multipass butt weld of a structure with a thickness of 25 mm and 70 mm. In addition, the residual stress by thermal elastoplastic FE analysis is compared with the results by the neutron diffraction method for verifying the reliability of the FE analysis. The welding sequence is considered in order to predict the residual stress more accurately when using welding-pass grouping method. The results of the welding-pass grouping model and half model occurred between the results of the left/right of the full model. If the total number of welding-pass grouping is less than half of that of welding pass, a large difference with real residual stress is found. Therefore, the total number of the welding-pass grouping should not be reduced to more than half.

1. Introduction

The safety of the steel structure poses an issue as the thickness of a component is increased following the large size of a structure which is intended to maximize productivity and efficiency. With the increases of ships and plant structures operating under a low-temperature environment, the brittle fracture safety of the structure becomes an important issue. An et al. [1, 2] performed a large-scale brittle fracture test for various thicknesses in order to find out the factors affecting unstable fracture by applying high-heat input welding process and low-heat input welding process. In addition, they investigated the effect of residual stress on the unstable fracture by measuring residual stress distribution [3, 4] according to each welding process. They found out that crack propagation path, which was generated during unstable fracture, was largely affected by the residual stress according to welding process. The residual stress distribution towards thickness particularly

affected the crack propagation path greatly. Therefore, the measurement and predication of the welding residual stress are highly important in order to evaluate structure safety. In order to evaluate the generation and propagation of a crack, it is important to measure not only surface residual stress but also internal residual stress. Surface residual stress can be measured by X-ray method [5], hole drilling method [6], and so forth while internal residual stress can be measured by neutrons [7, 8], deep-hole drilling [9, 10], inherent strain [3, 11], and contour method [12]. In this study, neutron method was used to measure internal residual stress in order to compare with the result of thermal elastoplastic FE analysis.

There are broadly two methods to predict welding residual stress in a large steel structure: thermal elastoplastic analysis and inherent strain method. Thermal elastoplastic analysis [13, 14] is a method of performing heat distribution and thermal elastoplastic stress analysis to predict welding deformation and residual stress that occur along with the

FIGURE 1: Cross-sectional macrostructure of (a) 25 mm and (b) 70 mm.

TABLE 1: Properties of base metal.

Thickness (mm)	Material	Remark	YP (MPa)	TS (MPa)	EL (%)
25 mm	EH47-grade	Steel	490	590	21
70	EH40-grade	Steel	390	530	21
Consumables			570	610	19

movement of the welding heat source. With this method, even for the case of a coupon-size specimen, a huge amount of time for modeling and analysis is consumed [15]. If the analysis subject is large, the analysis may not be possible due to the excessive time consumed and shortage of memory capacity of the computer. Recently, a study method to analyze welding residual stress has progressed by accelerated explicit method. Accelerated explicit method [16] and idealized explicit FEM [17] drastically reduced the memory usage so that large-scale models for residual stress and welding deformation can be analyzed. To reduce the analyzing time, the GPU parallel computing [17–19] was adopted and the welding distortions in large models of a construction structure and a suspension unit in automotive structures [19] were computed with a high efficiency. A welding residual stress prediction method by elasticity analysis was studied in order to resolve the issue of calculation time and the capacity of computer for thermal elastoplastic analysis. The representative method is the inherent strain method [3, 11]. This method predicts residual stress and deformation by using inherent strain, which is the source of residual stress and deformation. For that, the database of inherent strain distribution from thermal elastoplastic analysis or many experiment results are needed.

As previously described, measuring and predicting residual stress, according to the increase of thickness of steel structures, are important. Total welding pass in butt welding joint is about 60 passes in case of a thickness of 60 mm. The residual stress analysis of thick welded structure requires a lot of time and computer memory and should not be compared to those in thin welded structure analysis. Recently, weld pass grouping method [20, 21], which merges several welding passes during welding FE analysis, has been applied in order to compensate for these problems although it can induce some unsatisfying results in welding deformation. The results of FE analysis using welding-pass grouping agree well in thin

welding joint. However, in thick welded joint, which has an X-shaped groove with 23 layers and 108 welding passes, the thermal elastoplastic analysis needs a lot of analysis time even if the GPU parallel computing is employed. Thus, in order to reduce analysis time and memory, a total of 23 layers were reduced by 6 layers (26%). The welding residual stress of the full model and grouping model [22] has a lot of differences, however. There is a lack of research on welding-pass grouping because the existing research has been studied in thin welding joint and specific conditions.

This study investigated the effect of residual stress due to welding-pass grouping as one way to reduce the analysis time in multipass thick butt welding joint. For this purpose, the parametric analysis which changes the number of grouping passes was conducted in the multipass butt weld of a thickness of 25 mm and 70 mm. In addition, the residual stress by thermal elastoplastic FE analysis is compared with the results by the neutron diffraction method for verifying the reliability of the FE analysis.

2. Experiment and Measurement of Residual Stress Using the Neutron Diffraction Method

The specimens used in this research have a thickness of 25 mm and 70 mm and multipass butt welding joint. The specimen with a thickness of 25 mm had a width of 280 mm and length of 100 mm, while the specimen had a thickness of 70 mm, width of 400 mm, and length of 200 mm. The physical properties of two steel materials and welding wires are shown in Table 1. FCAW welding was applied for both materials having two types of thicknesses, and the detail of the welding condition is tabulated in Table 2. Figure 1 shows a micro cross-section of steel plates having a thickness of 25 and 70 mm.

TABLE 2: Welding condition.

Thickness (mm)	Welding process	Welding consumables	Shield gas	Current	Voltage	Speed	Heat input	Number of passes/layers
25	FCAW	SF-36E	100	255 A	32 V	30 CPM	15~17 kJ/cm	13/9
70		(NSSW)	CO ₂					60/21

FIGURE 2: Dimension of model of thickness 25 mm.

FIGURE 3: Welding sequences of thickness 25 mm.

FIGURE 4: Dimension of model of thickness 70 mm.

FIGURE 5: Welding sequences of thickness 70 mm.

FIGURE 6: Grouped weld passes model.

FIGURE 7: Welding residual stress of thickness 25 mm.

FIGURE 8: Welding residual stress of thickness 70 mm.

FIGURE 9: Measurement and comparison position.

FIGURE 10: Welding residual stress in welding direction, thickness = 25 mm at (a) $y = 5$ mm, (b) $y = 12.5$ mm, (c) $y = 20$ mm, and (d) $y = 35$ mm.

The material having a thickness of 25 mm has 9 layers and 13 passes, while the material having a thickness of 70 mm has 21 layers and 60 passes.

Welding residual stress was measured by neutron diffraction method using the same specimens of the experiment. The residual stress is measured by neutron diffraction method using the change of the interplanar distance of the lattice plane when elastic stress loads on each grain constituting the material. Neutron beam scatters in various directions due to atom but neutron beam can be expressed by Bragg's

law under atom regularly arranged in three dimensions as follows.

$$2d \sin \theta = n\lambda. \quad (1)$$

Here, d is the interplanar distance of the lattice plane, θ is the diffraction angle, and λ is the wave length of the neutron.

$$\varepsilon = \frac{\Delta d}{d_0} = \frac{d_0 - d}{d_0} = -\cot \theta_0 * \Delta \theta. \quad (2)$$

FIGURE 11: Welding residual stress in welding direction, thickness = 25 mm at line top (a), middle (b), and bottom (c).

Here, Δd is the difference of the interplanar distance of the lattice plane ($d_0 - d$), d_0 is the initial interplanar distance of the lattice plane without stress, $\Delta\theta$ is the difference of diffraction angle, and θ_0 is the initial diffraction angle without stress.

Diffraction angle is changed according to changing the interplanar distance of the lattice plane due to residual stress or load stress. Rewritten by differentiating (1), strain (ϵ) is equal to the following expression. Strain (ϵ) can be calculated by measuring the difference of the interplanar distance of the lattice plane or diffraction angle. Therefore, when we measure the residual stress using neutron diffraction method, we should measure the initial diffraction angle (θ_0) after stress relief heat treatment. Residual stresses ($\sigma_x, \sigma_y, \sigma_z$) can be obtained with three-direction strains ($\epsilon_x, \epsilon_y, \epsilon_z$) and Young's modulus (E) using (3). In this study the residual stress was measured by neutron diffraction method to verify the authenticity of the analysis result and was compared using comparative analysis.

$$\begin{aligned}\sigma_x &= \frac{E}{1+\nu} \left[\epsilon_x + \frac{\nu}{1-2\nu} (\epsilon_x + \epsilon_y + \epsilon_z) \right], \\ \sigma_y &= \frac{E}{1+\nu} \left[\epsilon_y + \frac{\nu}{1-2\nu} (\epsilon_x + \epsilon_y + \epsilon_z) \right], \\ \sigma_z &= \frac{E}{1+\nu} \left[\epsilon_z + \frac{\nu}{1-2\nu} (\epsilon_x + \epsilon_y + \epsilon_z) \right].\end{aligned}\quad (3)$$

3. Modeling and Grouping of Multipass Welding Sequence

Figure 2 shows the dimensions of the full model, full pass grouping model, and half model of the multipass butt joint specimens with a thickness of 25 mm used in this FE analysis and experiment. The three-dimensional solid element and moving heating source were used in the FE analysis. The temperature-dependent thermal physical properties and mechanical properties were considered to calculate the welding residual stress. The welding conditions and properties of steel were shown in Tables 1 and 2, respectively.

Welding-pass grouping sequence is shown in Figure 3. The full model has the same welding sequence of the real welding specimen. The full grouping model has a welding sequence of welding-pass grouping in the full model. The welding passes in the same layer merge into one pass in the full grouping model. The half model is the half portion of a full grouping model to reduce the analysis time. Through this analysis, the effect of welding-pass grouping and half model was investigated.

Figure 4 shows the two-dimensional model of 70 mm thickness. In order to investigate the effect of welding-pass grouping, welding-pass models were formed and organized into 4 categories as shown in Figure 5. Figure 5(a) is the same model of real welding passes (60 passes); (b) shows the model

FIGURE 12: Welding residual stress in width direction, thickness = 25 mm at (a) $y = 5$ mm, (b) $y = 12.5$ mm, (c) $y = 20$ mm, and (d) $y = 35$ mm.

of a half pass of real welding passes; (c) is model of grouping the real welding pass to 8 layers and 8 passes; (d) is the model of grouping the real welding pass to 4 layers and 4 passes.

As the weldment thickness increases, the number of weld passes also increases, which need a lot of computation time to analyze the welding residual stress. A lumped pass model [3] was developed to reduce the total computational time. It assumes that a couple of weld beads merge into one lumped pass. As shown in Figure 6(a), the actual welding time for the heat source to pass through the unit thickness of the model is $t_1 + t_2$. The term t_3 indicates the ramp-down time and is assumed to be the same as t_1 . The heat flux magnitudes and heating duration in an accumulative manner are determined as Figures 6(b) and 6(c). The specification of the computer employed in this analysis is as follows: the CPU is an Intel Core™ i7-5775C 3.30 GHz processor, the memory is 16 GB, and the GPU is an NVIDIA GeForce GTX 960 processor having 1024 computing units. The ratio of computing time of each model is shown in Table 3. The computational time dramatically decreases with the reduction of layer and passes. This study verifies the effect of the welding-pass grouping on the computing time and the analysis results.

The welding residual stresses of thermal elastoplastic FE analysis in the welding direction of 25 mm thickness are shown in Figure 7: (a) is the result of the full model, (b) is the result of the full grouping model; (c) is the result of the half model. The residual stresses of 3 models in welding direction seem to be agreeing well. The tensile residual stress was generated in the vicinity of the weld joint while away from the welding joint where the compressive residual stress occurred. There are asymmetry residual stresses near final welding pass due to the welding sequence in Figure 7(a). Maximum tensile residual stress occurred under final welding pass due to the restraint of previous welding metal.

Welding residual stresses of thermal elastoplastic FE analysis in the welding and width direction of 70 mm thickness are shown in Figure 8: (a) is the result of 60 welding passes, (b) is the result of 30 welding passes; (c) is the result of 8 layers-8 passes; (d) is the result of 4 layers-4 passes. The distributions of the approximate residual stress are highly similar to each other. Welding residual stress is all tensile in the welding direction but on the other hand, residual stress in the width direction of the compressive residual stress was generated in the internal portion and the tensile part in both surfaces.

FIGURE 13: Welding residual stress in width direction, thickness = 25 mm at line top (a), middle (b), and bottom (c).

TABLE 3: Computation time according to each model.

Thickness (mm)	Model	Layer	Pass	Ratio of computation time (%)
25	Full	9	13	100
	Ramped	9	9	73
	Half	7	7	9
70	2D_60	21	60	100
	2D_30	21	30	59
	2D_8	8	8	22
	2D_4	4	4	8

4. Results of Analysis and Experiment and Discussions

Figure 9 shows the coordinate and position for comparing the welding residual stresses of thermal elastoplastic FE analysis. Figure 10 shows the internal residual stress of welding direction according to positions $y = 5, 12.5, 20$, and 35 mm from the center of the welding joint in a specimen thickness of 25 mm. Figure 10 shows the residual stress according to top, middle, and bottom of thickness in the welding direction. The left/right stresses around the weld center were shown separately in order to examine the difference by the welding sequence. The results of neutron diffraction method were compared with those of thermal elastoplastic FE analysis. The results of the half and full grouping model

are between the left/right results of the full model. The results of neutron agree with the right result of thermal elastoplastic FE analysis at $y = 12.5$ mm. There are differences between the results of the experiment and analysis which are over 20 mm from the weld joint because the area is affected by the initial stress [3] and the residual stress (Figure 11) is fluctuating near $y = 20$ mm. Initial stress, which is generated during the manufacturing of steel structure, occurs due to a temperature difference on the surface and inner side of steel while it goes through the heating and cooling process during manufacturing. According to research results, the magnitude of initial stress during steel manufacturing occurred until almost 60% of yield stress [3]. Figure 11 shows the residual stress according to top, middle, and bottom of thickness in welding direction. There was no big difference of welding

FIGURE 14: Welding residual stress in welding direction, thickness = 70 mm at (a) $y = 5$ mm, (b) $y = 30$ mm, (c) $y = 60$ mm, and (d) $y = 100$ mm.

FIGURE 15: Welding residual stress in welding direction, thickness = 70 mm at line top (a), middle (b), and bottom (c).

FIGURE 16: Welding residual stress in width direction, thickness = 70 mm at (a) $y = 5$ mm, (b) $y = 30$ mm, (c) $y = 60$ mm, and (d) $y = 100$ mm.

residual stress according to the analytical model in width direction.

Figure 12 shows the internal residual stress of width direction according to positions $y = 5, 12.5, 20$, and 35 mm from the center of welding joint in 25 mm thick specimen. Figure 13 shows the residual stress according to top, middle, and bottom of thickness in width direction. The tensile residual stress occurred in both surface and compressive residual stress in the inner side at $y = 5$ mm. The maximum tensile residual stress was generated near the first welding pass. Such a large tensile stress can adversely affect the safety of the structure in combination with the stress increase due to the weld bead shape. Both the results of experiment and analysis agreed well and there were no differences according to the analysis model.

Figure 14 shows the internal residual stress of the welding direction according to positions $y = 5, 30, 60$, and 100 mm from the center of the welding joint in 70 mm thick specimen. Figure 15 shows the residual stress according to top, middle, and bottom of thickness in welding direction. There are big differences in residual stress according to the welding-pass grouping method at $y = 5$ mm from welding center in welding direction. A difference of about 300 MPa occurred in the analysis when less than half of the total number of

weld passes is grouped in the weld pass. However, if the total number of welding passes grouping not exceeds the half of the total number of the real welding passes, the residual stress of welding-pass grouping model is similar to that of the real welding-pass model.

Figure 16 shows the internal residual stress of width direction according to positions $y = 5, 30, 60$, and 100 mm from the center of welding joint in 70 mm thick specimen. Figure 17 shows the residual stress according to top, middle, and bottom of thickness in width direction. The residual stresses of width direction are affected by welding-pass grouping like in welding direction. In particular, there is a difference of 400 MPa to reduce the real welding pass to 4 welding passes and the range affected by grouping is near the weld metal. This result is very similar to that of Shibahara's research which simulated the pipe structure which has an X-shaped groove with 23 layers and 108 welding passes. In order to reduce analysis time and memory, a total number of 23 layers were reduced by 6 layers (26%). The welding residual stress of the full model and grouping model has a lot of differences in terms of distribution shape and magnitude of the residual stress [22].

From the results above, it can be drawn that the welding-pass grouping affects the residual stress on the left/right side

FIGURE 17: Welding residual stress in width direction, thickness = 70 mm at line top (a), middle (b), and bottom (c).

value and near the weld metal if welding pass is reduced for over half of the real welding passes number. Increasing the thickness of welding joint, the residual stress of width direction is affected by welding-pass grouping.

5. Conclusion

This study investigated the effect of residual stress due to welding-pass grouping as a way to reduce the analysis time in multipass thick butt welding joint. For this purpose, the parametric analysis which changes the number of grouping passes was conducted in a multipass butt weld with thicknesses of 25 mm and 70 mm. In addition, the residual stress by thermal elastoplastic FE analysis was compared with the results by the neutron diffraction method for verifying the reliability of the FE analysis. The summary is as follows.

- (1) The welding sequence is considered in order to predict more accuracy in the residual stress when using welding-pass grouping. The residual stress of the welding-pass grouping model and half model occurred between the results of the left/right welding pass of full model.
- (2) The residual stresses of the half model using 1/2 of full model agreed with one of the left/right of the full model.

- (3) The residual stress measurements by neutron method were in good agreement with the full model results. Therefore, the reliability of the thermal elastoplastic FE analysis result was confirmed.
- (4) Upon increasing the thickness of welding joint, the residual stress in width direction is affected by welding-pass grouping more than in welding direction and the area affected by welding-pass grouping is just near the welding joint.

Competing Interests

The authors declare that they have no conflict of interests regarding the publication of this paper.

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