Effect of phase transformation strain on residual stress analysis results of multi pass bead on plate specimen

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Abstract

The weld pass sequence generally affects residual stress profiles. In this study, the residual stress profiles of bead on plate specimens were analytically and experimentally examined. The material used in this study was the low alloy steel SQV2A (JIS G 3120), which is equivalent to ASTM A533. Phase transformation usually occurs around the welded area in SQV2A and also affects the residual stress profiles. To estimate residual stress, three specimens were fabricated. One was single pass bead welded and the others were five pass and nine pass bead welded. To predict the residual stress profiles numerically, temperature history analyses and residual stress analyses were conducted. Phase transformation strain was taken into consideration as a component of thermal strain. Analysis results show that the amount of longitudinal tensile stress at the center of the last pass area is lower than that at the edges. The longitudinal residual stress profiles around the last pass area of the five pass and nine pass specimens are similar to that around the weld pass area of the single pass specimen. The longitudinal tensile stress in the previous passes area is higher than that at the center of the last pass in the five pass and nine pass specimens. These analysis results suggest that the phase transformation strain affects the residual stress profiles around the last pass area in each specimen. To validate the analysis results, residual stress of these specimens were measured by using the strain relief method. The analysis results with the phase transformation strain consideration are in agreement with the experiment results. Accordingly, these analysis results can be considered valid.

Key words: Weld, Residual stress, Finite element method, Stress-strain measurement, Structural analysis

1. Introduction

Low alloy steel SQV2A (JIS G 3120), which is equivalent to ASTM A533, is used to fabricate reactor pressure vessels. Welding is normally used to join the steels. The welding induces a certain level of residual stress in the resulting structure. The weld induced residual stress is released by post weld heat treatment (PWHT); however, accurately simulating the weld induced residual stress is important to predict the residual stress profiles in real components (Ogawa et al., 2008).

Phase transformation during the welding process affects residual stress. A lot of research on phase transformation and residual stress has been conducted (Satoh and Terasaki, 1976; Murata et al., 1993; Mochizuki et al., 2005; Shiga et al., 2011; Murakawa and Tsutsumi, 2014). Phase transformation is observed in the low alloy steel weld. Therefore, it is important to consider the phase transformation to simulate the residual stress profiles of the low alloy steel weld.

The low alloy steel used in a reactor pressure vessel is generally subjected to clad weld. Many studies on residual stress profiles in heat affected zone (HAZ) of clad welded plates have been conducted. To determine the residual stress field due to the cladding process, residual stress analysis was conducted (Siegele and Brand, 2007). Phase transformation strain in HAZ was considered in the analysis. The analysis result shows that tensile stresses in the cladding and compressive stresses below the cladding followed by tensile stresses in the plate.
Experimental measurement of residual stress at HAZ was conducted to confirm analytically simulated results (Katsuyama et al., 2013). Sectioning and DHD technique were applied and residual stresses were measured. The results showed that simulation results with consideration of phase transformation agreed with the experiment results.

To clarify the phase transformation behavior in HAZ of the low alloy steel, the temperature history 1 mm below the welded surface was measured in a nickel-based alloy clad-welding. A low alloy steel bar specimen was then subjected to the measured temperature history and the thermal strain behavior in the specimen was measured (Nishikawa et al., 2010). The results clarified what effect the phase transformation during the cladding process had on the thermal strain history. The thermal strain history was then used to predict residual stress profiles (Mizuno et al., 2010). Analysis results showed that tensile residual stress occurred in the nickel-based alloy clad and compressive residual stress caused by the phase transformation occurred in the heat-affected zone of the low alloy thick plate.

The residual stress profiles in the HAZ of the low alloy steel are affected not only the phase transformation strain but also dissimilarity between the low alloy steel and the clad weld metal. To focus on the effect of phase transformation strain on residual stress profiles in the low alloy steel weld, removing effects of material dissimilarity between the low alloy steel and clad weld metal is preferred. In our previous study (Yanagida and Saito, 2011, 2013), residual stress analysis of a single bead on plate specimen by considering the phase transformation strain was conducted. A bead weld was applied on the one-side surface of a plate. Residual stress profiles were both analyzed and measured. The specimen did not include dissimilar metals, so residual stress occurred in accordance with the material property of the particular steel. Thermal elastic plastic analysis with the phase transformation strain was performed to determine the effect of the strain on the residual stress profiles. A mock up specimen was fabricated and residual stress profiles were measured. The analysis and experiment results suggest that phase transformation strain should be taken into consideration to predict the residual stress profiles.

In real components, multi-pass welds are usually applied; however, how subsequent welds affect residual stress profiles has not been discussed. In this study, bead on plate specimens, which are plates that have a single pass, five passes and nine passes, are examined. Effects of the phase transformation strain and subsequent weld pass on residual stress profiles are discussed.

2. Experiment
2.1 Geometry of specimen

Figure 1 shows the geometry of a specimen. The welded plate has a width of 167 mm, a length of 180 mm, and a thickness of 10 mm. Three specimens were fabricated: one a single pass and the others a five pass and a nine pass. Figure 1 also shows thermocouple attached positions and the weld pass sequence of the nine pass specimen. Temperature histories in the bead weld process were measured at the thermocouple attached positions. The center line of a subsequent pass was adjusted to be a fusion line of the previous pass in the five pass and nine pass specimens.

Fig. 1 Geometry of low alloy bead on plate specimen
2.2 Welding conditions

Gas tungsten arc weld (GTAW) was used to fabricate all of the specimens. Filler wire was not supplied in the welding process. The surface of the plate was melted. The effect of the dissimilarity between the base metal and filler metal on residual stress profiles can be removed under this condition. The welding conditions are shown below.

- Preheating temperature: 155°C
- Inter pass temperature: 155°C
- Current: 140 A
- Voltage: 10.8 V
- Torch travel speed: 60 mm/min
- Heat input quantity: 15 kJ/cm

Figure 2 schematically shows the temperature history of preheating and bead weld. First, the entire specimen was uniformly heated to 180°C in an electric furnace and then the plate was set at the GTAW equipment. The 1st pass weld started when the temperature of the plate surface was decreased to 155°C. Only single pass weld was applied to the single pass specimen, while subsequent bead weld was applied to the five pass specimen and nine pass specimen, respectively. Temperature of the specimen reached 155°C and then the subsequent pass weld was started. The subsequent bead weld was repeated until the number of weld passes reached five or nine.

![Fig. 2 Thermal process sequence](image)

2.3 Measurement conditions

Temperature histories in the bead weld process were measured. Residual stress profiles of the specimens were also measured. Measurement conditions are described in this section.

Temperature histories in the welding process were measured by using thermocouples. The temperature measurement positions were 5 mm and 10 mm away from the fusion line of the bead on the welded surface and the opposite surface, respectively (Fig. 1). Data sampling was 2 Hz. Measurement results are discussed and compared with analysis results in section 4.1.

Residual stress profiles on both the welded surface and the opposite surface were measured by using a strain relief method. The residual stress measurement line is shown in Fig. 1. Strain gauges were attached to the specimen, which was then cut up into small pieces. The amount of release strain was measured through the strain gauges and the amount of residual stress was calculated through the stress and strain relation under the plane stress condition. Measurement results are discussed and compared with analysis results in section 4.2.

3. Numerical analysis

Temperature histories and stress profiles are analyzed to determine the mechanism of residual stress generation. Analysis conditions are described in this chapter.
3.1 Analysis model

Figure 3 shows a finite element mesh subdivision of the specimen. A three dimensional model was used to analyze the temperature histories of the bead weld and residual stress profiles of the specimens. An eight node cubic element was used in the analysis. There were 15,400 elements and 18,315 nodes. The moving heat source condition was used to simulate torch travel. The heat source travels from the weld start position to the weld terminate position on the welded area in Fig. 3. Drawing area of residual stress contour lines in Figs. 8 and 9 is also shown in Fig. 3

3.2 Material properties

Material properties from room temperature to melting temperature are required for temperature histories and residual stress analysis. The material properties necessary for the temperature history analysis are heat conductivity and specific heat and those for the residual stress analysis are stress-strain relation and thermal strain data. Material properties for these analyses are shown in Figures 4(a) and (b).

Phase transformation occurs around the weld area in the bead weld process and affects the residual stress profiles. To measure the phase transformation strain properties, specimen elongation during both the heating and cooling processes was measured. Figure 5 shows the thermal strain histories of the bar specimen. Phase transformation in the heating process occurs from 775°C to 850°C and in the cooling process from 500°C to 380°C. The thermal strain of expansion of $4 \times 10^{-3}$ was measured in the cooling process. This expansion affects the residual stress profiles. The
The relation between thermal strain path and temperature was specified using a subroutine program in a finite element analysis code.

![Fig. 5 Relation between temperature and thermal strain](image)

### 3.3 Temperature history analysis

Transient heat transfer analysis was conducted to determine the temperature history in the bead weld process. First, the initial temperature of the model was set to 30°C. The model was then uniformly heated to 155°C. The temperature for all of the nodes was specified as prescribed in the boundary conditions. After that, the temperature histories from the start of welding to termination were calculated by transient heat transfer analysis. The heat input from the torch to the plate was modeled using the moving heat-surface-flux conditions. The heat-surface-flux area moved along the weld line at the travel speed of the torch. A subroutine program in a finite element code was used to specify the heat-input area that moves along the welding path at the torch-traveling speed.

### 3.4 Residual stress analysis

Thermal elastic plastic (TEP) analyses were conducted to predict residual stress profiles of the bead on plate specimens. Thermal strain path shown in Fig. 5 was used to simulate the relation between temperature and the thermal strain. Two different conditions of thermal strain path were applied to the analyses. One was "with phase transformation strain condition," which was abbreviated to "with P.T. condition" in this paper. In the analysis with P.T. condition, thermal strain path of the cooling process is different from that of the heating process if the temperature is higher than 775 °C in the heating process. The other was "without phase transformation strain condition," which was abbreviated to "w/o P.T. condition" in this paper. In the analysis w/o P.T. condition, the thermal strain path of the heating process in Fig. 5 was only used for both the heating and cooling process. The thermal strain path in the cooling process is identical with that in the heating process.

Linear isotropic hardening law was used in the analysis. The temperature profiles calculated in the temperature history analysis were used in the TEP analyses. The thermal loads were calculated from the temperature profiles derived from the transient heat transfer analysis. The stress profiles in the specimen subjected to the thermal loads were calculated in the TEP analyses. The stresses after the temperature reached the initial condition were defined as the residual stress of the specimen.

### 4. Results and discussion

Analysis results and experimental results of the temperature history and residual stress profiles are shown and discussed in this chapter.

#### 4.1 Temperature history

Figure 6 compares temperature histories at the measurement positions in Fig. 1. These analysis results are in
agreement with the measurement results. Accordingly, the temperature analysis result can be considered valid. The measurement results in Fig. 6 show that the temperatures of these measurement positions are lower than 775°C, which is the phase transformation start temperature of the heating process. Accordingly, phase transformation does not occur in the area 5 mm from the edge of the weld pass. Figure 7 shows contour lines of temperature when the torch reached the center of a weld path and the terminate position of a weld path.

Fig. 6 Comparison between measurement and analysis data of temperature history

(a) Heat source location is at the half of the weld pass    (b) Heat source location is at the end of the 1st weld pass

Fig. 7 Contour lines of temperature of the 1st pass weld

4.2 Residual stress

Contour lines of residual stresses are shown in Figs. 8 and 9. Comparisons of experiment results and analysis results are shown in Figs. 10 and 11.

Figures 8(a-1), (b-1) and (c-1) show the contour lines of the longitudinal stress of the single pass, five pass and nine pass specimens. The analysis with P.T. condition was applied. Half of the analysis model is shown in these figures. High tensile stress occurs around the edges of the last pass in each specimen. The amounts of tensile stress at the center of the last pass in these specimens are lower than those at the edges of the last pass. These stress profiles are clearly affected by the phase transformation strain in the welding process. Temperature at the center of the welding area is higher than 775°C, and the phase transformation occurs in this area. The expansion phase transformation strain in the cooling process, the amount is $4 \times 10^{-3}$ as shown in Fig. 5, affects the longitudinal stress profiles.

The amount of longitudinal tensile stress from the 1st to the 4th pass area in the five pass specimen is higher than that at the center of the 5th pass area. The amount of tensile stress from the 1st to the 8th pass area in the nine pass specimen is also higher than that at the center of the 9th pass area. The temperature in the previously welded area increases as the subsequent pass is welded. However, the temperature in the previously welded area does not reach 775°C. Phase transformation does not occur in the previously welded area when the subsequent pass is being welded.
Accordingly, the amount of tensile stress in the previously welded area is higher than that at the center of the last pass.

Figures 8(a-2), (b-2) and (c-2) show the contour lines of the longitudinal stress of the analysis w/o P.T. condition. High tensile stress occurs in the whole area of the last pass in each specimen. The amount of tensile stress in the last pass area is higher than that in the previous pass area.

Figures 9(a-1), (b-1) and (c-1) show the contour lines of the transverse stress of the single pass, five pass and nine pass specimen. The analysis with P.T. condition was applied. The amount of tensile stress in the last pass area in each specimen is slightly higher than its surrounding area. Figures 9(a-2), (b-2) and (c-2) show the contour lines of the transverse stress of the analysis w/o P.T. condition. The amount of tensile stress in the last pass area on each specimen of the analysis w/o P.T. condition is lower than that of the analysis with P.T. condition.

Analysis results are validated by comparing experiment results. Residual stress profiles on both welded and opposite surfaces of the specimens are shown in Figs. 10 and 11. Figures 10(a-1), (b-1) and (c-1) show a comparison of experiment results and analysis results of longitudinal stress on the welded surface. Results of the analysis with P.T. condition show that the amounts of tensile stress at the center of the last pass in each specimen are lower than those at the edges of the last pass welded area. The amount of experimentally measured tensile stress at the center of each welded area is in agreement with that of the results of the analysis with P.T. condition. The amounts of tensile stress at the center of last pass area in each specimen of the analysis w/o P.T. condition are higher than those of measurement results. These results suggest that phase transformation strain should be taken into consideration in the residual stress analysis to accurately predict the longitudinal stress profiles around the last pass area. In contrast, residual stress profiles in the previous weld pass area of the analysis w/o P.T. condition are similar to those of the analysis with P.T. condition. These results show that the effect of the phase transformation strain on residual stress profiles is observed in the area where temperature is higher than 775 °C in the welding process.

Figures 10 (a-2), (b-2) and (c-2) show longitudinal stress profiles on the opposite surface. The amount of longitudinal stress at the last pass area in each specimen is higher than that of its surroundings. Stress profiles of the experiment results are in agreement with the analysis results. As discussed in section 4.1, the experiment and analysis results of the temperature history show that the temperature at the measurement positions is lower than 775°C, which is the phase transformation start temperature in the heating process, and that phase transformation does not occur on the opposite surface.

Figures 11(a-1), (b-1) and (c-1) show transverse stress profiles on the welded surface. The amount of measured tensile stress at the center of the last pass in each specimen is slightly higher than that in their surroundings. Results of the analysis with P.T. condition on the welded area are in agreement with the experiment results. In contrast, results of the analysis w/o P.T. condition on the welded area of five pass and nine pass specimens are higher than measurement results.

Figures 11(a-2), (b-2) and (c-2) show transverse stress profiles on the opposite surface. In this case, results of the analysis w/o P.T. condition of the five pass and nine pass specimens are in agreement with the measurement results. Temperature on the opposite surface does not reach 775 °C, which is phase transformation start temperature in the heating process, and effect of phase transformation strain on residual stress profiles is smaller than welded surface.

4.3 Effects of phase transformation strain and number of weld pass on residual stress analysis results

Phase transformation strain dominantly affects the residual stress profiles at the center of the last pass welded area and should be taken into consideration to accurately predict longitudinal tensile stress at the location. In contrast, the residual stress profiles in the previous pass area is less affected by the phase transformation strain of the subsequent pass welding, as the temperature does not reach phase transformation start temperature in the heating process.

Residual stress profiles around the last pass welded area in three specimens are mutually similar each other. This result suggests that residual stress profiles around the last pass area are mainly determined by the last pass weld itself. Effect of number of weld pass on residual stress profiles at the last pass area is little. On the other hand, residual stress profiles in the previous pass area are different in each specimen. Accordingly, subsequent pass weld affects the residual stress profiles in the previous welded area.
Fig. 8 Contour lines of longitudinal stress
(a-1) With considering phase transformation strain        (a-2) Without considering phase transformation strain

(a) Single pass specimen

(b-1) With considering phase transformation strain        (b-2) Without considering phase transformation strain

(b) Five pass specimen

(c-1) With considering phase transformation strain        (c-2) Without considering phase transformation strain

(c) Nine pass specimen

Fig. 9 Contour lines of Transverse stress
(a-1) Welded surface
(a) Single pass specimen

(a-2) Opposite surface

(b-1) Welded surface
(b) Five pass specimen

(b-2) Opposite surface

(c-1) Welded surface
(c) Nine pass specimen

(c-2) Opposite surface

Fig. 10 Longitudinal stress
Fig. 11 Transverse stress

Transverse stress (MPa) vs. Distance from the 1st pass (mm)

(a) Single pass specimen
- (a-1) Welded surface
- (a-2) Opposite surface

(b) Five pass specimen
- (b-1) Welded surface
- (b-2) Opposite surface

(c) Nine pass specimen
- (c-1) Welded surface
- (c-2) Opposite surface

Experiment
Analysis (with P.T.)
Analysis (w/o P.T.)

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5. Conclusions

The residual stress profiles of bead welded low alloy steel plates were discussed. The residual stress profiles were investigated by thermal elastic plastic analysis. The subsequent pass weld affects the residual stress profiles in the previous welded area. The last pass weld mainly determines the residual stress profiles around the last pass welded area. Phase transformation strain especially affects the longitudinal tensile stress at the center of the last pass. Accordingly, the phase transformation strain should be taken into consideration in the analysis to predict the residual stress at the position.

References