Comparison of residual stress distributions of similar and dissimilar thick butt-weld plates*

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Abstract

Residual stress distributions of 35 mm thick dissimilar butt-weld between A533B ferritic steel and Type 304 austenitic stainless steel (304SS) with Ni alloy welds and similar metal butt-weld of 304SS were measured using neutron diffraction. Effects of differences in thermal expansion coefficients and material strengths on the weld residual stress distributions are discussed by comparison of the residual stress distributions between the similar and dissimilar metal butt-welds. Residual stresses in the similar metal butt-weld exhibited typical distributions of a thick butt-weld and they were distributed symmetrically on either side of the weld line. Meanwhile, asymmetric residual stress distributions were observed near the root region of the dissimilar metal butt-weld, which was caused by differences in thermal expansion coefficients (CTEs) and yield strengths between parent and weld metals. Transverse residual stress distribution of the dissimilar metal butt-weld was similar to that of the similar butt-weld, since effects of differences in CTEs are negligible. Magnitude of the transverse residual stress near the root region depended on the yield strengths of each metal. The normal and longitudinal residual stresses in the dissimilar metal butt-weld distributed asymmetrically on either side of weld line due to the effects of differences in CTEs.

Key words: Welding, Residual stress, Neutron diffraction, Dissimilar metal butt weld, Similar metal butt weld

1. Introduction

Welding techniques have been utilized for joining components, and widely used in many engineering structures including safety desired components such as nuclear power plants. Although this is superior joining technique with high versatility, residual stresses induced by welding affects fracture mechanisms such as crack propagation as well as mechanical properties such as material strength. In particular, residual stresses in dissimilar metal welds should be more complicated than those in similar metal welds due to differences in thermal expansion coefficients and mechanical properties between parent and weld metals. For instance, dissimilar metal welds between ferritic and austenitic steels have been widely used in nuclear power plants, and stress corrosion cracking (SCC) has also been identified near the weldment in such dissimilar metal welds. Furthermore, cracking would be generated by decarburizing due to carbon diffusion in the heat affected zone, and then it propagates along the weld interface on the ferritic steel side. In those cases, residual stresses induced by
welding affect on these crack propagations, and hence it is very important to evaluate the weld residual stress distribution with high accuracy to estimate the crack propagations. There are some previous studies showing residual stresses in dissimilar metal butt-welds evaluated using experimental methods such as X-ray diffraction and strain gauge as well as numerical simulations to discuss residual stress distributions and also improve finite element methods for prediction of residual stresses in dissimilar metal butt-welds\(^{(1)-(5)}\).

In this study, residual stress distributions of a 35 mm thick dissimilar butt-weld between ferritic and austenitic steels with Ni alloy welds and a similar metal butt-weld of austenitic steels were measured using neutron diffraction. Effects of differences in thermal expansion coefficients and material strengths on the weld residual stress distributions are discussed by comparing the residual stress distributions of the dissimilar metal butt-weld with those of the similar metal butt-weld.

2. Principle of neutron stress measurement

Diffraction makes use of Bragg’s law

\[
\lambda = 2d_{hkl} \sin \theta_{hkl} \tag{1}
\]

to relate the measured diffraction angle, \(2\theta_{hkl}\), to the lattice spacing, \(d_{hkl}\), for a known wavelength, \(\lambda\), of neutrons determined by calibration with a standard powder. In angular dispersive neutron diffraction, monochromatic neutron beam with wavelength, \(\lambda\), is irradiated to sample and the diffraction angle of \(hkl\) reflection, \(2\theta_{hkl}\), is measured and then lattice spacing, \(d_{hkl}\), can be calculated using Eq. (1). The elastic strain is obtained from the measured lattice spacing, \(d_{hkl}\), in the sample and an appropriate reference lattice spacing, \(d^0_{hkl}\), according to Eq. (2).

\[
\varepsilon_{hkl} = \frac{d_{hkl} - d^0_{hkl}}{d^0_{hkl}} \tag{2}
\]

It is very important to know stress-free reference lattice spacing, \(d^0_{hkl}\), in order to evaluate residual stresses accurately\(^{(6)}\). The macroscopic stresses, \(\sigma_{11,hkl}\), \(\sigma_{22,hkl}\), \(\sigma_{33,hkl}\), may be derived from the macroscopic strains, \(\varepsilon_{11,hkl}\), \(\varepsilon_{22,hkl}\), \(\varepsilon_{33,hkl}\), with the use of the diffraction elastic constants, \(E_{hkl}\) and \(v_{hkl}\) in the accepted way,

\[
\sigma_{11,hkl} = \frac{E_{hkl}}{(1+v_{hkl})(1-2v_{hkl})}\left(1-v_{hkl}\right)\varepsilon_{11,hkl} + v_{hkl}\varepsilon_{22,hkl} + v_{hkl}\varepsilon_{33,hkl} \quad (i=1, 2, 3) \tag{3}
\]

with similar expressions for the \(\sigma_{22,hkl}\) and \(\sigma_{33,hkl}\) stresses.

3. Preparation of butt-welded specimen

Two kinds of butt-welded specimens were prepared: one is a dissimilar metal butt-weld between A533B low alloy ferritic steel and Type-304 austenitic stainless steel (304SS) welded by Ni alloy weld metal (YNiCr-3), and the other is a similar metal butt-weld of 304SS welded by Type-308 austenitic weld metal. The fabrication processes and the welding conditions of both specimens are described below. Two plates with dimensions of 100 mm width, 260 mm length and 35 mm thickness with X-grooved edges were joined together with tungsten inert gas welding along the longitudinal direction without pre-heating the plates. Then, both edges with 30 mm length were cut from the welded plates to eliminate unsteady regions of the start-finish welding points, and to obtain dimensions of 200mm×200mm×35 mm as shown in Fig. 1 (a). Total number of weld passes was 18 in 9 layers on each side as shown in welding sequence in Fig. 1 (b). The “butterfly” distortion was minimized by alternating welding between one side and the other side. Yield strengths...
of 304SS and A533B are 278 MPa and around 480 MPa, respectively. It was assumed in the present experiment that the principal axes were the longitudinal direction (LD) in the weld, the transverse direction (TD) and the plate normal direction (ND).

4. Experimental procedure

The strain measurements were carried out using the RESA-1 engineering diffractometer in the JRR-3 (Japan Research Reactor No.3) at the Japan Atomic Energy Agency in Tokai, Japan. Figure 2(a) shows the schematic optical layout of the RESA-1 diffractometer. The monochromatic beam of neutrons was obtained by reflection from the Si(311) asymmetric bent crystal monochromater. The wavelength of the incident beam determined by calibration using a standard nickel powder was approximately 0.16 nm. The incident neutron beam was 15 mm high and 5 mm wide in the transverse and normal strain measurements, and 5 mm high and 5 mm wide in the longitudinal strain measurement. The radial collimator was installed in front of the position sensitive detector (PSD) to observe diffraction from a gauge volume with 5 mm width. The schematic sizes of the gauge volume defined in each measurement are shown in Fig. 2(b).

Strain distributions of the austenite {311} reflection, which occurred at diffraction angle of approximately 95°, and the ferrite {211} reflection, which occurred at approximately 86°, were measured along Line-1, Line-2 and Line-3 shown in Fig. 1. The diffraction elastic constants were derived from the single crystal elastic constants\(^{(7),(8)}\) and the Kröner model\(^{(9)}\). The calculated diffraction elastic constant of the austenite {311} reflection was \(E_{311}=187\) GPa and \(\nu_{311}=0.303\), and that of the ferrite {211} reflection was \(E_{211}=224\) GPa and \(\nu_{211}=0.276\).

![Fig. 2](image-url)

Fig. 2 (a) Optical layout of the RESA-1 engineering diffractometer, (b) the gauge volume defined in each measurement.
5. Results and discussions

5.1. Stress-free lattice parameter

Three thin plates with dimensions of 35mm×48mm×3mm were taken from the weld center of a companion dissimilar metal butt-weld perpendicular to the weld line by the electro discharge method (EDM), and then multiple EDM slits with 2.5 mm depth were introduced at 3 mm intervals on both sides of all the thin plates to release the macroscopic residual stresses. Finally, a reference specimen was obtained by assembling three thin plates with multiple EDM slits into the original shape. Lattice parameters in the reference specimen were measured in a gauge volume of approximately 4×4×4mm³ at the equivalent positions of stress measurements along Line-1, Line-2 and Line-3 using the RESA-2 engineering diffractometer in the JRR-3, a small diffractometer similar to the RESA-1. Four austenitic reflections of {111}, {200}, {220} and {311} and three ferritic reflections of {110}, {200} and {211} were measured.

Average lattice parameters of four reflections on the 304SS side along Line-1 exhibited similar variations among the longitudinal, transverse and normal directions, and these variations were almost constant at average lattice parameter of 0.35922±0.00001 nm calculated in assumption of plane stress condition. It indicated that macroscopic residual stress was almost released in the reference specimen. Changes in chemicals and microstructures could not be observed along Line-1. Average lattice parameters at D=4 mm and D=31 mm from surface-A of Line-2 were 0.35917±0.00002 nm, which was relatively smaller than the average lattice parameter of Line-1, since a gauge volume involved Ni alloy weld metal of which lattice parameter is slightly smaller than that of 304SS. However, lattice parameters at other positions of Line-2 agreed well with the average lattice parameter of Line-1.

Average lattice parameters of three reflections on the A533B side in three orthogonal directions were almost constant at 0.28678±0.00001 nm along Line-1 and Line-3, which means that no influence of phase transformation has been appeared in the heat affected zone.

Table 1 shows stress-free reference lattice parameters used in calculation of residual stresses in the similar and dissimilar metal butt-welds. Stress-free reference lattice parameter in the similar metal butt-weld was determined at 0.35922±0.00001 nm which was the same value as average lattice parameter along Line-1 in the dissimilar metal butt-weld.

Table 1 Stress-free lattice parameters used in calculation of residual stresses.

<table>
<thead>
<tr>
<th>Dissimilar metal butt-weld</th>
<th>304SS</th>
<th>Line-1</th>
<th>0.35922±0.00001 nm</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Line-2</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>D=4, 31mm</td>
<td>0.35917±0.00002 nm</td>
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<tr>
<td></td>
<td></td>
<td>D=10, 17.5, 25mm</td>
<td>0.35922±0.00001 nm</td>
</tr>
<tr>
<td>A533B</td>
<td>Line-1, Line-3</td>
<td>0.28678±0.00001 nm</td>
<td></td>
</tr>
<tr>
<td>Similar metal butt-weld</td>
<td>304SS</td>
<td>Line-1, Line-2</td>
<td>0.35922±0.00001 nm</td>
</tr>
</tbody>
</table>

5.3. Residual stress distributions in similar metal butt-weld

Figure 3(a) shows residual strain distributions along Line-1 in the similar metal butt-weld. The longitudinal residual strains at X=±80 mm could not be measured due to specification limit of the RESA diffractometer. All residual strain components were distributed symmetrically on either side of the weld line. Large compressive residual strain with maximum value of about 0.002 was observed in transverse direction near the weld center. Both longitudinal and normal strains tended to increase gradually from compression to...
tension towards the weld center. Figure 3(b) shows through-thickness distributions of residual strains along Line-2 in the similar metal butt-weld. All residual strain components were distributed symmetrically on either side of the through-thickness center at $D=17.5$ mm.

Figure 4(a) shows residual stress distributions from $X=-50$ mm to $+50$ mm along Line-1 derived from the residual strain distributions in Fig. 3(a) according to Eq. (3). All residual stress components were distributed symmetrically on either side of the weld line. The transverse residual stress was about 400 MPa in compression at the weld center with a trend to small tension towards outside. The normal and longitudinal stress es were generally low with the exception of small compression near the weld center. Figure 4(b) shows through-thickness residual stress distributions along Line-2 derived from the residual strain distributions in Fig. 3(b). The transverse residual stresses exhibited typical V-shape distribution that was tension about 300 MPa towards both surfaces and dropping into compression about 300 MPa in the central region, which means that the transverse residual stresses were almost balanced in the through-thickness direction. The longitudinal residual stresses near both surfaces were about 400 MPa in tension and dropping into zero in the central region. The normal residual stress was again generally low, which was evidence that the stress-free reference lattice parameter in Table 1 is reasonable for determining residual stresses.

5.3. Residual stress distributions in dissimilar metal butt-weld

Figure 5(a) shows residual strain distributions along Line-1 in the dissimilar metal butt-weld. The residual strain at $X=0$ mm was omitted since sufficient diffractions were not observed from both $\{311\}$ and $\{211\}$ reflections. Furthermore, the longitudinal residual strains at $X=\pm80$ mm could not be measured as well as the strain measurement in the similar metal butt-weld. The transverse residual strain distributions exhibited similar trends on
either side of the dissimilar metal butt-weld. Transverse residual strains near the weld center on both 304SS and A533B sides were about 0.002 in compression. The longitudinal and normal residual strains showed different variation between the 304SS and A533B sides. Through-thickness residual strain distributions along Line-2 and Line-3 in the dissimilar metal butt-weld are shown in Figs 5(b) and (c), respectively. All residual strain components on both 304SS and A533B sides were distributed symmetrically on either side of the through-thickness center.

Figure 6(a) shows residual stress distributions along Line-1 derived from the residual strain distributions in Fig. 5(a) according to Eq. (3). All residual stress components were distributed asymmetrically on either side of the weld line. Large compressive residual stresses exceeding yield strengths were developed in transverse direction in the heat affected zone on both A533B and 304SS sides. The maximum compressive residual stresses near the weld center were about 400 MPa on the 304SS side and about 600 MPa on the A533B side. Normal and longitudinal residual stress distributions on the 304SS side were different from those of the A533B side. On the 304SS side, the normal residual stresses scattered around zero (<50 MPa), and the longitudinal residual stress was changed from small tension to compression towards weld center with a trend to zero towards outside. In contrast, both normal and longitudinal residual stresses near the weld center on the A533B
side were compression with maximum value of about 250 MPa, which was similar trend to the transverse residual stresses.

Figures 6(b) and (c) show through-thickness residual stress distributions along Line-2 and Line-3, respectively, derived from the residual strain distributions in Figs. 5(b) and (c). The transverse residual stresses on both 304SS and A533B sides exhibited typical V-shape variation that is tension towards both surfaces and balancing compressive residual stresses in the central region. The longitudinal residual stresses exhibited similar V-shape variation to the transverse residual stress distribution, although no compressive residual stresses were observed on the 304SS side. The normal residual stresses on the 304SS side were scattered around zero, whereas compressive residual stress with maximum value of about 250 MPa appeared on the A533B side.

5.3. Discussions

Figure 7 shows comparisons of residual stress distributions between the similar and dissimilar metal butt-welds. In Fig. 7(a), the transverse residual stress distribution in both butt-welds was similar along Line-1 that is compression near the weld center and small tension towards outside. The normal and longitudinal residual stresses in the similar metal butt-weld were distributed symmetrically on either side of the weld line, whereas asymmetric distributions were observed in the dissimilar metal butt-weld. As was shown in Fig. 7(b), through-thickness residual stress distributions on the 304SS side of the dissimilar metal butt-weld was similar to those of the similar metal butt-weld. In the A533B side in Fig. 7(c), transverse residual stress distribution exhibited similar trend between the similar and dissimilar metal butt-welds. Figure 8 shows distributions of diffraction peak width (Full width half maximum) associated with plastic deformation along Line-1. The peak width is averaged in three orthogonal directions. The peak width was increased near the weld center in both similar and dissimilar metal butt-welds due to plastic deformation induced by multiple pass welding. It can be shown in Fig. 8 that the plastic region was distributed symmetrically on either side of the weld line in both butt-welds.

In general, longitudinal residual stresses are generated by longitudinal shrinkage induced by overlaying welds, and hence it should be affected by differences in thermal expansion coefficients (CTEs) between parent and weld metals. The CTEs of 304SS, Ni alloy and low alloy steel are approximately $18 \times 10^{-6}$, $10.4 \times 10^{-6}$ and $12 \times 10^{-6}$, respectively (1). Therefore, longitudinal residual stresses in first several welding processes in the dissimilar metal butt-weld can be simply predicted to be asymmetric residual stress distribution that is higher tension in the 304SS side and lower tension in the A533B side. Overlaying welds more, longitudinal residual stresses near the root region are decreased due to longitudinal shrinkage, and then asymmetric residual stress distributions as shown in Fig. 6(a) were developed along Line-1 based on the asymmetric residual stress distributions after initial welding processes. On the other hand, transverse residual stresses are mainly caused by the welding distortion due to transverse shrinkage of weld metal, and hence an effect of differences in CTEs is negligible. Actually, transverse residual stress distributions on both 304SS and A533B sides of the dissimilar metal butt-weld exhibited similar trend that is compression near the root region even though the CTEs of 304SS and A533B are obviously different. According to peak width distribution in Fig. 8, plastic region induced by welding was symmetrically distributed near the weld center. Therefore, maximum compressive residual stress in transverse direction depended on yield strength of each material. In fact, the compressive transverse residual stresses near the root region were about 100 MPa higher than 0.2% yield strength of each material due to strain hardening. Furthermore, the compressive residual stress on the A533B sides was higher than that on the 304SS side since yield strength of A533B is higher than that of 304SS. Normal residual stresses would
be developed by restriction of normal deformation according to Poisson ratio associated with longitudinal and transverse residual strains. Therefore, normal residual stress in the dissimilar metal butt-weld was indirectly influenced by the effect of differences in CTEs associated with the longitudinal residual stresses distribution. On the other hand, differences in CTEs did not affect the residual stress distributions in the similar metal butt-weld since CTEs of 304SS and 308SS weld metal are almost same: $18\times10^{-6}$ and $18.7\times10^{-6}$, respectively \(^{(1)}\). Therefore, symmetric residual stress distributions in all three directions were observed along Line-1 and Line-2 as shown in Fig. 4.

Comparing residual stress distributions in Fig. 7, the transverse residual stresses exhibited similar distribution between the similar and dissimilar metal butt-welds since an effect of differences in CTEs is negligible in the transverse direction as described above. In particular, transverse residual stress distribution on the 304SS side of the dissimilar metal butt-weld had a good agreement in that of the similar metal butt-weld. According to Figs 7(b) and (c), residual stresses near the surface region exhibited similar trend between the similar and dissimilar metal butt-welds that is tension in the transverse and longitudinal directions and small in the normal direction. Therefore, kind of asymmetric residual stress distribution observed near the root region might be disappeared near the surface region of the dissimilar metal butt-weld.

As described above, residual stresses near root region were affected by differences in CTEs between parent and weld metals, which provided asymmetric residual stress distribution in the dissimilar metal butt-weld. However, transverse residual stress distribution induced by welding distortion exhibited similar trend between the dissimilar and similar metal butt-welds since effects of differences in CTEs are negligible in transverse direction. The magnitude of residual stress in plastic region near the root region depended on yield strength of each material.

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Fig. 7 Comparison of residual stress distributions between the similar and dissimilar metal butt-welds along (a) Line-1, (b) Line-2, and (c) comparison between residual stress distributions along Line-2 in the similar metal butt-weld and Line-3 in the dissimilar metal butt-weld.

Fig. 8 Distributions of diffraction peak width (full wide half maximum) along Line-1 of the similar and dissimilar metal butt-weld.
6. Conclusion

In this study, residual stress distributions of 35 mm thick dissimilar and similar butt-welds were measured using neutron diffraction to discuss an effect of differences in thermal expansion coefficients and material strengths on the weld residual stress distributions in the dissimilar metal butt-weld.

Residual stresses in the similar metal butt-weld exhibited typical distributions of a thick butt-weld and they were distributed symmetrically on either side of the weld line. Meanwhile, asymmetric residual stress distributions were observed near the root region of the dissimilar metal butt-weld, which was caused by differences in thermal expansion coefficients (CTEs) and yield strengths between parent and weld metals. The transverse residual stress induced by welding distortion exhibited similar variation between the similar and dissimilar metal butt-welds since effects of differences in CTEs on transverse residual stress are negligible. Magnitude of the transverse residual stress near the root region depended on the yield strengths of each metal. The normal and longitudinal residual stresses in the dissimilar metal butt-weld were distributed asymmetrically on either side of weld line, which was caused by effect of differences in CTEs.

Acknowledgements

The authors would also like to acknowledge the experimental assistance of Dr. T. Saito at Kobe Material Testing Laboratory, Co, Ltd. and Dr. T. Tobita at the Japan Atomic Energy Agency. A part of this research project has been conducted under the research contract with the Japan Nuclear Energy Safety Organization (JNES).

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