Residual stress variation due to piping processes of austenitic stainless steel

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Abstract. In nuclear power plants, stress corrosion cracking (SCC) has been observed near the heat affected zone (HAZ) of the primary loop recirculation pipes made of austenitic stainless steel type 316L. Residual stress is a major cause of SCC. In the joining process of pipes, butt-welding is conducted after machining. Machining is performed to match the inside pipe diameter. Residual stress is generated by both machining and welding. In the case of welding after machining in manufacturing processes of pipes, it appears that residual stress due to machining is varied by the welding thermal cycle. In this study, residual stress variation caused by manufacturing processes was investigated. Residual stress variation was examined by the X-ray diffraction method. The residual stress distribution generated by welding after machining has a local maximum point in the HAZ. The Vickers hardness distribution also has a local maximum point. By the EBSD method, it is clarified that recovery and recrystallization due to welding heat do not occurred in the local maximum point. Residual stress distribution results from the superposition effect of hardening due to machining and welding. The location and value of the local maximum stress are varied by welding conditions. The region of the local maximum stress corresponds to the region where SCC has been observed. Therefore, in addition to a part of the manufacturing processes such as welding or machining, evaluation of all parts of the processes is important to investigate the effect of residual stress distribution on SCC.

1. Introduction

Recently, electric generation in nuclear power plants plays important roles in electrical power supplies and ecology. However, nuclear power plants have safety problems. An important problem is stress corrosion cracking (SCC). SCC has been observed near the heat affected zone (HAZ) of the primary loop recirculation pipes made of low-carbon austenitic stainless steel type 316L [1-3]. SCC is caused by three factors: material, environment and mechanical. The effect of residual stress on SCC is more important for a non-sensitization material such as stainless steel type 316L. In the joining process of pipes, butt-welding and machining are conducted. Machining is performed to match the inside pipe diameter, and provide a smooth surface finishing. Residual stress is generated by both machining and welding. SCC initiates as a transgranular SCC in the machined layer, and SCC propagates through the pipe thickness as an intergranular SCC. In the machined layer, hardness is increased. Moreover, high tensile residual stress is generated [4-5]. It has been proposed that machining has a large influence on SCC initiation [6-9]. However, in a manufacturing process of pipes, welding is often conducted after machining. It would appear that residual stress distribution generated by machining is varied by the welding thermal cycle.

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In order to further understand SCC, accurate evaluation of the residual stress is required. To achieve this, not only residual stress generated by only machining or welding but also residual stress variation induced by welding after machining which is conventional in the manufacturing process of pipes is important. In this study, residual stress variation caused by manufacturing processes was investigated.

2. Experimental Procedures

2.1. Manufacturing processes

Machining and bead on plate welding using a Tungsten Inert Gas (TIG) arc were conducted for thin plate specimens made of stainless steel type 316L. Yield stress, tensile strength and elongation are 278 MPa, 540 MPa and 61 %, respectively. The dimensions of the specimens are 150(l) × 100(w) × 8(t) mm. The schematic illustration of specimen preparation is shown in Figure 1. Welding was conducted after machining. This process was assumed as the manufacturing processes of a welded pipe joint in nuclear power plants. Machining and welding conditions are shown in Table 1. In order to confirm the effect of welding heat input on residual stress variation, two welding currents were used. During welding, argon was used as the shielding gas with a flow rate of 15 l/min. Three types of processed specimens were prepared. They are machined specimen, welding specimen and welding specimen after machining. They are named specimen M, specimen W(Q) and specimen M+W(Q), respectively, as shown in Figure 1. The Q provided in parentheses after W is the welding heat input. For example, specimen W(SQ) means a small heat input (I = 120 A), and specimen W(LQ) means a large heat input (I = 200 A).

![Figure 1. Preparation of each processed specimen.](image)

| Table 1. Machining and welding conditions. |
|-------------------------------------------|
| **Machining** | **Welding** |
| | Heat input | SQ | LQ |
| Cutting speed (m/min) | 100 | Current, I (A) | 120 | 200 |
| Feed rate (mm/rev) | 0.1 | Welding speed (mm/s) | 2 |
| Cutting depth (mm) | 0.1 | Arc length (mm) | 3 |

2.2. Measurements and observation

Residual stress distributions were measured by X-ray diffraction using the 2D method for the machined or welded surface of each specimen. The measurement device used was a D8 discover.
instrument with GADDS (Bruker AXS products). Residual stress was calculated from the whole strain of the Debye cone in the 2D method [10]. This method can measure residual stress with good accuracy. The measurement condition is presented in Table 2, and a schematic illustration of the measurement system using a two-dimensional detector is shown in Figure 2. Typically, residual stress measurement of the weld metal is difficult due to the large grains and orientation of the weld metal. For measurement of the weld metal, measurement with multi-axial rocking is efficient [11]. Multi-axial rocking can increase the number of grains contributing to diffraction. The rocking was conducted for the \( \omega \) axial and \( Y \) axial, as shown in Figure 2. To evaluate residual stress distributions, Vickers hardness measurement was performed. The measurement device used was an HMV-FA instrument with an automatic measurement system (Shimadzu Corp.). The indentation load is 490 mN, and the loading time is 15 s. Microstructure observation was performed using a FE-SEM instrument with an EBSD detector (JEOL products) in order to confirm the effect of the welding thermal cycle on the machined layer. The accelerating voltage is 25 kV. In the grain orientation analysis, the measurement step was 0.25 \( \mu \text{m} \).

![Figure 2. Geometry of the diffraction system for stress measurement.](image)

**Table 2.** X-ray diffraction conditions for residual stress measurement.

| Parameter                  | Value                        |
|----------------------------|------------------------------|
| Wave length (nm)           | 0.2291 (CrK\(\alpha\))      |
| Power (kV, mA)             | 36, 88                       |
| Beam size (mm)             | \(\phi 1\)                   |
| Diffraction peak (deg)     | 128 (220 plane)              |
| Young’s modulus (GPa)      | 209.78                       |
| Poisson’s ratio             | 0.278                        |
| Measuring time (s)         | WM: 80, BM: 30 \(\times\) 21 frame |
| Rocking (deg)              | \(\omega\): \(\pm 4\), \(Y\): \(\pm 0\) |

WM: weld metal, BM: Base metal

3. Results and discussion

3.1. Residual stress measurement
Firstly, residual stress measurement was performed for specimens W(SQ), M and M+W(SQ). Figure 3 shows the comparison of residual stress distributions of each specimen. The \( x \) direction is the welding
and cutting directions, and the $y$ direction is the welding transverse and feeding directions. The dimensions of the weld metal were measured using an optical microscope. The weld metal width is 6.21 mm. Residual stress of specimen W(SQ) have a tensile stress level in the HAZ region. Its stress level around the fusion line in the $x$ direction is nearly the average value of yield stress there. The residual stress decreases with distance from the welding centerline, and changes to the compressive stress. Residual stress in the $y$ direction shows lower tensile stress than the average yield stress in the whole region. These are typical tendency of residual stress distribution due to welding. Residual stress of specimen M was measured for 10 arbitrary points, and the average is shown. The average of $\sigma_x$ is 618.5 ± 12.4 MPa, and that of $\sigma_y$ is 381.57 ± 15.3 MPa. Residual stress of specimen M in both directions shows high tensile stress. Residual stress due to machining is caused by large plastic deformation and heat generation during machining. Residual stress distribution of specimen M + W(SQ) in the $x$ direction has a local maximum stress 7 mm from the welded center. The local maximum stress shows over 800 MPa, which far exceeds the value of the yield stress, and shows a higher value than specimen M. Residual stress decreases with distance from the welding centerline. This tendency is the same as specimen W(SQ). Residual stress in the $y$ direction also has a local maximum stress. However, the peak value is lower than that in the $x$ direction, and the location of the stress peak appears outside.

![Residual stress distribution](image)

**Figure 3.** Residual stress distribution generated by each process.

### 3.2. Hardness measurement

Vickers hardness measurement was performed to discuss residual stress variation generated by manufacturing processes. Measurement was conducted in the range of 0 to 15 mm from the welding centerline at 0.5 mm intervals. For comparison, measurement of a base metal was conducted for 15 arbitrary points, and this average is used.

Comparison of Vickers hardness distributions is shown in Figure 4. The average of the base metal is 167.2 ± 6.3 HV. Result of Vickers hardness of specimen W(SQ) has a small hardened region near 7.5 mm from the welding center. The other points show almost the same hardness as the average of the base metal. Result of specimen M shows high hardness in the whole region. For this reason, the average of the measured hardness is used, and this average is 328.1 ± 10.5 HV. This results from work hardening induced by machining. Result of specimen M+W(SQ) shows the average of the base metal near the weld metal. However, the hardness has a local maximum value of 370 HV at 8 mm from the welding center. At more than 9 mm, it decreases slightly and becomes the average hardness level of
specimen M. Therefore, the local maximum hardness in specimen M+W(SQ) is caused by the superposition effect of hardening due to machining and welding.

![Figure 4. Comparison of Vickers hardness distributions of each processed specimen.](image)

3.3. Microstructure observation

Microstructure observation with the EBSD method was performed for specimen M+W(SQ). Observation was conducted for regions A, B and C near the surface in the y-z cross-section, as shown in Figure 5. They are located 3.5, 5.5 and 7.5 mm from the welding centreline. The 3.5 mm location is near the fusion boundary, and the 7.5 mm location is the local maximum point of residual stress and Vickers hardness. The 5.5 mm location corresponds to the intermediate region.

![Figure 5. Cross sectional micrograph near the welding centerline.](image)

Results of microstructure observation are shown in Table 3. Table 3 shows the inverse pole figure (IPF) map and image quality (IQ) map superimposed kernel average misorientation (KAM). The IQ map shows reliability. KAM shows misorientation in adjacent pixels excluding grain boundaries. The misorientation parameter like KAM has been used as a barometer of plastic strain distribution [12-13]. The IPF map in region A shows no effect of plastic deformation due to machining, and KAM shows a low value. The IPF map of region B indicates grain rotations and slip lines near the surface. KAM shows a higher value than that of region A. The IPF map in region C shows many grain rotations and slip lines which are deep in comparison with those of other regions. Moreover, random pattern points exist near the surface. These patterns show the difficult points of measurement. KAM in region C shows the highest value. The high value of KAM means that region C has the largest plastic deformation.
From these results, it can be considered that recovery and recrystallization due to the welding thermal cycle occur in the machined layer. A machined layer like region C exists in the whole surface after machining. However, in region A, plastic deformation due to machining disappears completely because of recrystallization. As a result, the IPF map shows smaller grains in comparison with those of other regions. In region A, residual stress of specimen M+W(SQ) shows a similar value to residual stress of specimen W. Moreover, Vickers hardness shows the same value as the base metal. In region B, recovery occurs, and plastic deformation partly disappears. Residual stress and Vickers hardness show higher values than those of only welding. In region C, recrystallization and recovery do not occur, and plastic deformation does not disappear. Although residual stress is calculated by only elastic strain, there is a correlation between plastic strain and elastic strain. Plastic strain indicates the potential of elastic strain, and is related to hardness. The high tensile stress caused by machining mainly contributes to plastic strain. In other words, the effect of machining on residual stress remains only in the hardening region. Moreover, hardening due to welding is generated. This is smaller than that of plastic deformation generated by machining, resulting in a local maximum hardness. Therefore, residual stress distribution has a local maximum point at the region of the local maximum hardness.

Table 3. Comparison of the IPF map and IQ map superimposed KAM at 3.5, 5.5 and 7.5 mm from the welding centerline.

| Region | IPF | IQ+KAM |
|--------|-----|--------|
| Region A (3.5 mm from welding center) | ![Image of IPF map] | ![Image of IQ+KAM map] |
| Region B (5.5 mm from welding center) | ![Image of IPF map] | ![Image of IQ+KAM map] |
| Region C (7.5 mm from welding center) | ![Image of IPF map] | ![Image of IQ+KAM map] |

3.4. Effect of welding condition on residual stress
Residual stress measurements of specimens W(LQ) and M+W(LQ) were performed in order to clarify the effect of welding heat input. Figure 6 shows residual stress distributions of specimens W(LQ) and
M+W(LQ). The weld metal width with a large heat input is 12.17 mm. The weld metal of specimen W(LQ) has too many coarse and oriented grains. Residual stress measurement of this weld metal using the X-ray diffraction method is very difficult due to insufficient diffraction peaks for analyzing the stress. In this study, residual stress in the weld metal is not important. Thus, the measurement was performed outside the weld metal. Residual stress distributions of specimen M+W(LQ) also have a local maximum point. However, in both directions, locations of the local maximum stress are different from specimen M+W(SQ). In the $x$ direction, the local maximum of the stress is located at 12 mm from the welded centreline. Moreover, the local maximum stress is higher than specimen M+W(SQ). These variations are assumed to be due to difference of temperature distribution during welding. As mentioned above, the local maximum stress is caused by the superposition effect of hardening and microstructure variation such as recovery and recrystallization due to the welding thermal cycle. The hardened region due to welding and microstructure variations is affected by the temperature history. Therefore, relationship between the temperature history and microstructure variation is important in order to evaluate the local maximum stress due to manufacturing processes.

![Figure 6](image-url). Effect of welding heat input on residual stress variation generated by each process.

### 4. Conclusions

Residual stress variation due to manufacturing processes assuming piping of nuclear power plants was investigated using the X-ray diffraction method. In order to make clear residual stress variation, Vickers hardness measurement and microstructure observation with EBSD were performed. The following conclusions are obtained.

(a) Residual stress distribution generated by welding after machining has a local maximum stress in the HAZ.

(b) Vickers hardness distribution also has a local maximum point in the same region, showing the local maximum stress.

(c) In the local maximum region of stress and hardness, recovery and recrystallization due to the welding heat cycle are not observed.

(d) Residual stress has a local maximum point, which results from the superposition effect of hardening caused by machining and welding, in the region where recovery and recrystallization are not observed.
(e) The location and value of the local maximum stress are varied by welding conditions. This is caused by the difference of temperature history.

The location of the local maximum stress corresponds to the region where SCC has been observed. Therefore, in order to evaluate the initiation and propagation of SCC, not only one process but all processes are important.

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