X-ray Investigation of the Effect of Machining Condition on Residual Stress Distribution due to Welding after Surface Machining*

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In nuclear power plants, the high tensile residual stress introduced by welding after surface machining may be an important factor in the occurrence of stress corrosion cracking in welds of low-carbon austenitic stainless steel type SUS316L. This study investigated the effect of machining conditions on variations in the distributions of residual stress introduced through surface machining and sequential welding. First, in experiments, test specimens were prepared by surface machining under different machining conditions. Then, bead-on-plate welding under the same welding conditions was conducted on the test specimens with different surface machined layers. The residual stress variations were evaluated by X-ray diffraction method. As a result, the residual stress introduced by surface machining showed nearly uniform distributions and varied drastically depending on the machining conditions. After welding, the welding longitudinal residual stress had a maximum tensile stress in the heat affected zone and the values of residual stress were independent of the residual stress due to surface machining. Based on the Vickers hardness testing results, we concluded that the magnitude of the maximum residual stress introduced by welding after surface machining is strongly dependent on the degree of work hardening due to surface machining.

Key Words: X-ray diffraction method, Residual stress, Surface machining, Welding, Vickers hardness test

1. Introduction

It is well known that residual stress is introduced through the various manufacturing processes such as surface machining and welding. The residual stress has significant influences on material properties such as fatigue strength and corrosion resistance. One example is the occurrence of stress corrosion cracking (SCC) in the core shroud and the recirculation pipe of boiling water reactor (BWR) plants. It is well known that SCC is generated by the interactions of material, environmental, and mechanical factors. Although each factor has been improved by past measures1,2, the occurrence of SCC has been recently observed in the welding heat affected zone (HAZ) of shroud and pipe made of low-carbon austenitic stainless steel3. Therefore, the residual stress, which is one of the mechanical factors contributing to SCC, has attracted attention.

In manufacturing core shroud and recirculation pipe, welding is performed after surface machining and surface finishing. As previously reported, in the welding after surface machining, the maximum tensile residual stress is generated in the welding HAZ because of the hardened layer generated by surface machining4,5. Moreover, the magnitude of the maximum tensile residual stress is higher than that individually introduced by either welding or machining. The maximum tensile residual stress may be an important factor in the occurrence of SCC in nuclear power plants; therefore, we need to thoroughly understand the residual stress distribution, with a focus on the coupling effect of surface machining and welding.

This study investigated the effect of machining conditions on the variations in the distributions of residual stress introduced through surface machining and sequential welding by the X-ray diffraction method.

2. Experimental conditions

2.1 Material

The testing material was low-carbon austenitic stainless steel type SUS316L. The chemical composition and mechanical properties of SUS316L are shown in Tables 1 and 2. As shown in Fig. 1, the specimen was a plate with dimensions 150 × 100 × 8 mm.

Table 1  Chemical composition of SUS316L (mass%).

| C   | Si  | Mn  | P  | S   | Ni  | Cr  | Mo |
|-----|-----|-----|----|-----|-----|-----|----|
| 0.019 | 0.66 | 1.19 | 0.033 | 0.001 | 12.11 | 17.41 | 2.05 |

Table 2  Mechanical properties of SUS316L.

| Yield stress (MPa) | Tensile strength (MPa) | Elongation (%) |
|-------------------|-----------------------|---------------|
| 278               | 540                   | 61            |

Fig. 1 Illustration of test specimen.
2.2 Surface machining conditions

The surface machining was carried out by large vertical lathe equipment. The conditions on the surface machining are shown in Table 3. As the parameters for the surface machining conditions, the cutting speed \( V \) (m/min) and the feed rate \( f \) (mm/rev) were given different values. Furthermore, to clarify the effect of the cutting oil, dry and wet processing were carried out. The cutting direction was in the x-direction in Fig. 1 and the feed direction was in the y-direction.

| No | Cutting speed, \( V \) (m/min) | Feed rate, \( f \) (mm/rev) | Dry / Wet |
|----|-------------------------------|-----------------------------|-----------|
| 1  | 15                            | 0.1                         | Dry       |
| 2  | 30                            | 0.1                         | Dry       |
| 3  | 45                            | 0.1                         | Dry       |
| 4  | 70                            | 0.1                         | Dry       |
| 5  | 100                           | 0.1                         | Dry       |
| 6  | 45                            | 0.05                        | Dry       |
| 7  | 45                            | 0.3                         | Dry       |
| 8  | 45                            | 0.1                         | Wet       |

2.3 Welding conditions

Bead-on-plate welding was performed on all the specimens under the same welding conditions, shown in Table 4. The welding was performed in the longitudinal direction at the center of the test piece. In addition, the welding direction was set to coincide with the cutting direction of the surface machining. The welding length was 130 mm, which left unwelded sections of 10 mm at both ends of the plate.

| Material | SUS316L |
|-----------|---------|
| Welding current (A) | 120 |
| Welding speed (mm/s) | 2 |
| Arc length (mm) | 3 |
| Shielding gas | 100% Ar |
| Shielding gas flow rate (L/min) | 15 |

2.4 X-ray stress measurement

The distributions of residual stress introduced through surface machining and sequential welding in each specimen were measured by X-ray diffraction using the \( 2\theta - \sin^2 \psi \) method. The micro-area X-ray residual stress measurement system (Rigaku, Cr-K\( \alpha \) radiation) was used for the stress measurement, and the diffraction plane was \{220\}. The measured residual stress was the component in the cutting direction (x-direction). The irradiated area of the specimen surface was limited by a collimator with a diameter of 2 mm. To improve the measurement accuracy and increase the grain contributing to diffraction, we added to incident X-ray oscillation by \( \pm 5^\circ \) in the y-direction during the X-ray irradiation. The residual stress in the weld longitudinal direction was in a constant region. Hence, in the weld metal (WM), x-direction oscillation parallel to the weld line was performed, and the measurement time and the number of the \( \psi \) angle were also increased. Moreover, the collimator diameter of the WM was larger than that of the base metal (BM). The elastic constants and Poisson’s ratio for the \( 2\theta - \sin^2 \psi \) method were estimated by using the Kröner model and the monocristalline stiffness. Further detailed conditions of the measurement by X-ray diffraction are shown in Table 5. The measurement positions of the residual stress after the surface machining were set at 0, 6, 20, 30, and 45 mm from the centerline. After welding, the positions were changed to 0, 4, 6, 7, 8, 9, 10, 20, 30, and 45 mm from the weld line center. These changes of positions enabled us to measure the residual stress distribution in the vicinity of the WM and HAZ in more detail.

| No | Wave length (nm) | Diffraction plane | Power (kV, mA) | Beam size (mm) | Measuring time (s) | \( \psi \) angle (point) | Oscillation | Young's modulus (GPa) | Poisson’s ratio |
|----|-----------------|------------------|----------------|---------------|------------------|------------------------|-------------|----------------------|----------------|
| 1  | 0.2291(CrK\( \alpha \)) | \{220\} | 40, 15 | \( \phi_4 \) | 150 | 15 | \( \psi \) axis: \( \pm 5^\circ \), x axis: \( \pm 5 \) mm | 209.76 | 0.2777 |
| 2  | 0.2291(CrK\( \alpha \)) | \{220\} | 40, 40 | \( \phi_2 \) | 150 | 15 | \( \psi \) axis: \( \pm 5^\circ \), x axis: \( \pm 5 \) mm | 209.76 | 0.2777 |
| 3  | 0.2291(CrK\( \alpha \)) | \{220\} | 40, 40 | \( \phi_2 \) | 100 | 10 | \( \psi \) axis: \( \pm 5^\circ \), x axis: \( \pm 5 \) mm | 209.76 | 0.2777 |
| WM : weld metal, HAZ : heat affected zone, BM : base metal |

2.5 Vickers hardness test

To consider the residual stress distribution in more detail, the Vickers hardness test was also carried out at the cross-section of the welded specimens. The apparatus for the Vickers hardness measurement was a micro hardness tester HMV-1 (Shimadzu). As shown in Fig. 2, the Vickers hardness test was performed in 0.5 mm intervals from the weld center to 15 mm on the test piece cross-section after welding. The upper end of the indentation was positioned at 10 \( \mu \)m from the surface of the test piece. At the measuring surface, we performed wet polishing with emery paper and then finished the surface by buffing. The indentation load was 245.2 mN and the indentor dwell time was 15 s. The hardness test was performed at each measurement point with two additional indentation points 50 \( \mu \)m at the left and right of the pre-defined
point. Then, the average value of these three points was regarded as the measured value.

![Fig. 2 Measurement points for Vickers hardness testing.](image)

### 3. Result and discussion

#### 3.1 Residual stress distributions introduced by surface machining

Figure 3 shows the measurement results of the transverse distributions of the residual stress in cutting direction caused by surface machining. The residual stress introduced by surface machining showed that the tensile stress exceeded the yield stress of the virgin material (278 MPa). Moreover, the stress distributions were nearly uniform in all the specimens. The magnitude of the residual stress became monotonously greater with increasing cutting speed and feed rate. This was probably because the surface residual stress was strongly affected more by the frictional heat effect than the mechanical effect\(^{10}\). In the wet process, rapid cooling occurred in comparison with the dry process and the lubricating effect of the cutting oil reduced the frictional heat effect during cutting. Therefore, the influence of the compressive residual stress by the mechanical effect is greater in the wet process. As a result, the dry process resulted in greater tensile residual stress than that in the wet process.

#### 3.2 Residual stress distributions after welding

The measurement results of the longitudinal residual stress after welding are shown in Fig. 4. First, from the welding center to the vicinity of the fusion boundary in all of the specimen, the tensile residual stress had a value of about 330 MPa, and the stress rapidly increased with increasing distance from the fusion boundary. Subsequently, the residual stress had a maximum tensile stress in almost the same position among all specimens, and the values of the residual stress were independent of the machining conditions. The maximum residual stress far exceeded the yield stress of the virgin material and the residual stress caused by the surface machining. In the area away from the region of the maximum stress, the tensile residual stress gradually decreased. However, the stress did not show a compressive value. Furthermore, in this area, the residual stress showed different distributions according to the machining conditions. The residual stress had the same tendency as the magnitude relation of the residual stress before welding. We concluded that in the base metal away from the weld center, the residual stress was assumed to be the sum of the residual stress introduced by surface machining and that introduced by welding.

![Fig. 3 Residual stress distributions introduced by surface machining.](image)

#### 3.3 Vickers hardness after welding

In consideration of the dependence of welding longitudinal residual stress on the yield stress of material\(^{11}\), the Vickers hardness test was carried out at the cross-section of each welded specimen. Figure 5 shows the measurement results of the hardness distributions. Although the hardness in the vicinity of the weld metal and fusion boundary was almost equal to that of the virgin material (approximately 170 HV), the hardness increased with
increasing distance from the welding center in the region near the fusion boundary \((y = 5-8 \text{ mm})\). In the area sufficiently apart from the welding center, the hardness showed an almost constant value. From the results, in the region from the welding center to the fusion boundary, the work hardened layer seemingly disappeared due to the melting and solidification during the welding. Moreover, in the region from the fusion boundary to approximately \(y = 8 \text{ mm}\), the work hardened layer was assumed lost to some extent, because of the recovery and recrystallization due to the welding thermal cycle. Then, in the region apart from the weld center, where the hardness was substantially a constant value, the work hardened layer by surface machining was considered to be almost the same before welding. In this region, the hardness was slightly different according to the machining conditions. However, the hardness deviation was approximately a maximum of 25 HV. Therefore, the effect of the machining conditions on the hardness due to surface machining was not obvious.

Fig. 4 Residual stress distributions after welding.

(a) Effect of cutting speed

(b) Effect of feed rate

(c) Effect of cutting oil

Fig. 5 Vickers hardness distributions after welding.

3.4 Discussion about hardness dependency of longitudinal tensile residual stress

Matsuoka revealed the correlation between the 0.2% proof stress and the Vickers hardness of SUS316L\(^{12}\). The correlation is represented by Eq. (1).

\[
\sigma_{0.2} = 3.44 \times HV - 239
\]  

(1)

By using Eq. (1), 0.2% proof stress distribution was estimated from the hardness distribution in each specimen. The estimated 0.2% proof stress was about 300 to 330 MPa in the weld metal. In the region where the work hardened layer by surface machining was almost the state before welding, the 0.2% proof stress was about 800 to 880 MPa. The value approximately corresponded to the maximum residual stress. The dimensionless residual stress distributions obtained by dividing the measured residual stress by...
the estimated 0.2% proof stress are shown in Fig. 6. From these results, the welding longitudinal residual stress in the HAZ was presumed to be dependent on the yield stress of the surface machining layer. The estimated 0.2% proof stress was slightly lower than the maximum residual stress. This was probably because the weld zone had a multi-axial stress field, so the maximum residual stress in the welding HAZ slightly exceeded the yield stress.

4. Conclusions

In this study, the effect of machining conditions on the variations in the distributions of residual stress introduced through surface machining and sequential welding was investigated by X-ray diffraction method. The conclusions obtained in this study are as follows.

The residual stress of the weld metal was almost the same as the yield stress of the virgin material, because the work hardened layer was completely lost through the melting process during welding. Subsequently, at the position indicating the maximum residual stress in the HAZ, the residual stress was strongly dependent on the resultant degree of work hardening due to surface machining and subsequent welding. In the base metal away from the weld center, the residual stress was assumed to be the sum of the residual stress introduced by surface machining and that introduced by welding. Thus, the detailed generation characteristics of residual stress introduced through surface machining and subsequent welding were clarified.

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