Effects of Surface Grinding on Hardness Distribution and Residual Stress in Low Carbon Austenitic Stainless Steel SUS316L

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1. Introduction

It has been reported that stress corrosion cracking (SCC) occurs in core shrouds made with a low carbon austenitic stainless steel, SUS316L, in-service.1) The cracks were initiated at grain interiors in surface layer and propagated with trans-granular (TG) mode at a distance, and then the mode was changed into inter-granular (IG) type.2) It was also reported that hardness in surface region near cracks was higher than those in internal regions, which was attributed to surface grinding treatment.3) Sensitization due to formation of chromium carbides at grain boundaries was not observed.1) It seems to be difficult to interpret the TGSCC phenomenon on the basis of the conventional mechanism of SCC. Especially, effects of surface grinding on SCC phenomenon are not sufficiently clarified. Therefore, in the present study, residual stress and strain induced by grinding have been focused and measured by means of relatively new techniques.

2. Experimental Procedures

The chemical composition of the steel used is listed in Table 1. Specimens were cut with about 50×16×2 mm in sizes, then solution heat treated at 1 323 K for 0.9 ks. One of the surfaces was ground with 150 μm using a grinding disk with a grit size of #30.

Cross sections of the ground surfaces, parallel to the grinding direction (GD) and perpendicular to the grinding direction (TD) were examined by a scanning electron microscope (SEM) equipped with an electron backscattered pattern (EBSP) analyzer (MSC-2200, Tex SEM Labo. Inc.). Inverse pole figure (IPF) mapping and image quality (IQ) mapping on the surfaces were obtained. Hardness near the ground surface was also measured on the cross section parallel to GD by a micro-Vickers hardness tester with a load of 0.49 N.

Residual stress induced by surface grinding was measured in synchrotron radiation (SR) facility, SPring-8. Hyogo prefecture beam line, BL24XU, was used. In order to measure a distribution of residual stress in depth direction, the ground surface of the specimen was partly electropolished with about 10 and 30 μm in depth remaining a part of as-ground surface. Residual stresses were measured based on \(2\theta-\sin^2 \psi\) method in the as-ground and the electropolished surfaces by side inclination with the diffraction of (111) in SUS316L under a beam energy of 10 keV. The inclination angles, \(\psi\), were in a range of \(0 \leq \psi \leq 63.4\) degree, which corresponds to a range of \(0 \leq \sin^2 \psi \leq 0.8\). Residual stresses along GD and TD directions were evaluated.

3. Results and Discussion

Hardness distributions on the cross section parallel to GD in solution heat treated and surface ground specimens are shown in Fig. 1. Surface hardness in the solution heat treated specimen was about 160 in HV which is about the same as those in an interior region. On the other hand, hardness in the surface ground specimen was significantly high, 230, near the surface, which decreased to the same level as those in the solution heat treated specimen within about 50 μm in depth from the surface.

Two kinds of maps taken with EBSP on the cross section parallel to GD are shown in Fig. 2. IQ map and IPF maps, (a), (b) and (c), respectively. In the IQ map, difference in orientation between neighboring two points of sampling, 0.5 μm step in this case, are represented in brightness, darker the brightness larger the difference in orientation. On the other hand, orientations of grains are represented in IPF map (b) with colors shown in the inserted standard stereographic triangle. These maps are taken on the same view field. Comparing (a) with (b) shows that the dark contrasts indicated by the arrows A, B and C in (a) are due to grain boundary, twin boundary and scratch induced by mechanical polishing. In (b), large angle grain boundaries (\(\delta \geq 15\) degree, \(\delta\): angle between neighboring grains) are indicated by black lines. Near the surface region, mottled contrasts

Table 1. Chemical composition of the specimen (mass%).

| C  | Si  | Mn  | P  | S   | Ni  | Cr  | Mo | N  |
|----|-----|-----|----|-----|-----|-----|----|----|
| 0.011 | 0.89 | 1.05 | 0.024 | 0.006 | 12.99 | 17.60 | 2.03 | 0.026 |

Fig. 1. Hardness near the surfaces on the solution heat treated and surface ground specimens.
can be seen in (b). Small angle grain boundaries (d<15 degree) are indicated by white lines in (c). Comparing (b) with (c) shows that the mottled contrasts are due to small angle grain boundaries. The dark contrast beneath the surface shown in (a) corresponds to the region in (c) where a density of small angle grain boundary is higher than the internal region. In this case, the dark contrast in the IQ map represents strained region, therefore the dark lines indicated by the arrow D in (a) are slip lines or slip bands. Effects of surface grinding are localized in the region with about 25 μm in depth under the surface.

Image quality and inverse pole figure maps on a cross section parallel to TD are shown in Fig. 3. Many slip bands and small angle grain boundaries were observed near the surface, although the strained region seemed to be shallow compared with that in Fig. 2.

Hardened region shown in Fig. 1 is about 50 μm in depth, which is relatively larger than those shown in Figs. 2 and 3, which is due to difficulty in EBSP method for detecting a difference of orientation on dislocation substructures formed at the early stage of plastic deformation, while hardness testing is sensitive to such a condition.

Figure 4 shows 2θ–sin^2 ψ plots measured on the surface-ground specimen. Solid marks represent residual stresses in the direction parallel to GD on the as-ground surface, and electropolished surfaces with 10 and 30 μm from the surface, while open marks represent those in the direction parallel to TD. Residual stress on the as-ground surface in the direction of GD is calculated as tensile stress of about 430 MPa with using the values of Young’s modulus: E=197 GPa and Poisson’s ratio: ν=0.29. Electropolishing the surface region with about 10 and 30 μm from the original surface resulted in decreasing residual stresses into about 150 MPa in tensile stress. On
the other hand, residual stress in the direction parallel to TD was lower compared with those in the direction of GD, about 110 MPa in tensile stress on the ground surface. On the electropolished specimens, $\theta - \sin^2 \psi$ plots were not linear but curved with concave downward, so, residual stresses were not calculated. When the plots are roughly fitted as lines, inclinations of them seem to be positive, which means compression residual stress.

Compression stress is applied to a surface region in a specimen during grinding and the surface is deformed by a rotating grinding disk. It is considered as follows: a slip system having a high Schmid factor for the deformation is activated, low stacking fault energy in SUS316L leads to planar slips, cross slips of screw dislocations would occur to annihilate mutually even in such conditions because of heavy deformation, and edge dislocations are remained and piled-up to satisfy the compressive condition. Schematic illustration for this interpretation is shown in Fig. 5.

Difference in orientations of neighboring two un-slipped regions is larger in the side A than in the side B because of the nature of the edge dislocation. The sides A and B are represented in Figs. 2(a) and 3(a), respectively. After grinding, compressive strain stored in the dislocation substructures is relieved to exert tensile residual stress, anisotropy of which is also due to the nature of edge dislocations.

It has been shown by the present study that surface grinding increases hardness of the specimen and causes anisotropic residual stress depending on the grind direction. However, there are few papers reported on relationships between direction of cracks and direction of grinding and on effects of microscopic stress concentration at grounding traces in the actually troubled shrouds. Therefore, the results obtained in the present study may not directly interpret the SCC in shrouds but it is worth to notice that the sub-grain boundaries formed near the surface (Figs. 2(c) and 3(c)) would play a role of large angle grain boundaries to provide crack paths for TGSCC.

4. Summary

Effects of surface grinding on hardness distribution and residual stress have been measured on specimens of SUS316L. Hardness in the surface region is increased by surface grinding into about 230 in HV, which decreases into about 130 in HV within about 100 µm in depth from the surface. Many slip bands and small angle grain boundaries have been observed to be formed and localized in the surface region with about 25 µm in depth by EBSP method. Residual stresses at the ground surface measured parallel and perpendicular to the grinding direction are about 430 and 110 MPa in tensile, respectively.

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