Thermal Stability of residual stress induced by heavy deformation on SUS316L Stainless Steel

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ABSTRACT

Residual stress induced by shot peening in specimens of SUS316L, an austenitic stainless steel, have been measured by means of synchrotron radiation diffraction. The materials are those used for shrouds in atomic reactors, which are surrounded with hot water at a temperature of 561 K. It is important to clarify effects of aging at such a relatively low temperatures on the residual stress. Thus, changes in residual stress on the shot peened specimens caused by prolonged aging were measured. Compression stress induced by shot peening was gradually decreased with aging at 523, 573 and 623 K for up to 8000 h.

Residual stress, shot peening, synchrotron radiation, prolonged aging

INTRODUCTION

It was reported that cracks were formed in shrouds in atomic reactors in service in 2002. Surface grinding for finishing welded areas was supposed to be a cause of cracking. The materials used for the shrouds were a low carbon austenitic stainless steel, SUS316L. Stress corrosion cracking (SCC) was believed to be suppressed in SUS316L, because chromium carbides were hardly formed in the steel. Although deformation promotes precipitation, low carbon content in SUS316L makes the formation of carbides difficult. The authors, however, showed that M_7C_3 and $M_{23}C_6$ types of carbides were formed in the specimen of SUS316L when the specimen was suffered from cold-rolling and prolonged aging at 573 K (Y. Ohnishi, 2007).

Shot peening is generally recognized to induce compression residual stress on the surface of the specimen and to prevent cracking. Dislocation substructures induced by shot peening is essentially same as those formed by cold-rolling. Therefore, changes in residual stress and precipitation of carbides are also expected to occur in prolonged aging in the case of shot peened specimens.

The purpose of the present study is to clarify the stability of residual stress and microstructures induced by shot peening.

METHODS

Chemical composition of the SUS316L steel listed in Table 1. Specimens were solution heat treated at 1323 K for 0.9 ks. Conditions for shot peening are listed in Table 2.

After shot peening, specimens were aged at 523, 573 and 623 K for up to 8000 h. Temperature of water arround the shroud in operating is 561 K.

Table 1 Chemical composition of the SUS316L (mass%).

C	Si	Mn	P	S	Ni	Cr	Mo	N	Fe
0.01	0.89	1.05	0.024	0.006	12.09	17.6	2.03	0.026	bal.

Table 2 Conditions of shot peeing.

Air pressure (MPa)	0.6
Processing temperature	R. T.
Shot	Cast steel with 1.0 mm diameter
Peening time (s)	20

Residual stress and diffraction measurements were carried out in synchrotron radiation (SR) facility, SPring-8, at BL01B2 and BL24XU, under beam energies of 70 and 10 keV, respectively.

Scanning electron microscopy (SEM) and electron backscattered diffraction pattern (EBSP) analysis were carried out on a cross section of the shot peened specimen.

RESULTS

Cross sectional view of the shot peened specimen is shown in Fig. 1, in which the left side is the shot peened surface. Distribution of crystal orientation is shown in (a) as an inverse pole figure (IPF) map, while crystal lattice imperfection is shown in (b) as an image quality (IQ) map. Dark contrast in IQ map corresponds to strained region, so the straight sharp lines and diffused line would be slip bands and sub-boundaries, respectively. Such crystal defects cause gradations in color in the IPF map (a). The surface region are highly strained, while slip bands are observed up to about 80 μm in depth from the surface.

In order to evaluate the residual stress at different depth from the shot peened surface, SR diffraction analyses were carried out with changing the incident bema angle to the surface from 3 to 25 degrees. Calculation showed that the depth of the gauge volumes were about 0.3, 1.0 and 2.0 μm when the incident beam angles are 3, 10 and 25 degrees, respectively. Plots of 2θ-$\sin^2\psi$ obtained with each condition are shown in Fig. 2. The residual stresses near the surface with 0.3 and 1.0 μm are similar one another, while the value obtained at 2 μm depth was larger by a factor of two than those for surface regions. Stress would be relieved near the surface. Although strained image was observed by SEM-EBSP analysis (Fig. 1), it shows deeper areas than those measured by SR diffraction method.

The compression residual stress is due to metal flow induced by shot peening, and the metal flow is caused by dislocation motions and multiplications to form a dislocation substructure which would be recovered by heating. The temperature of the water around the shroud, 561 K, seems to be relatively low, however it is in the temperature range for tempering steels in practical processes. Changes in residual stress in the shot peened specimens during aging at 523, 573 and 623 K are shown in Fig. 3. The compression stress was decreased with increasing aging time at all the temperatures.

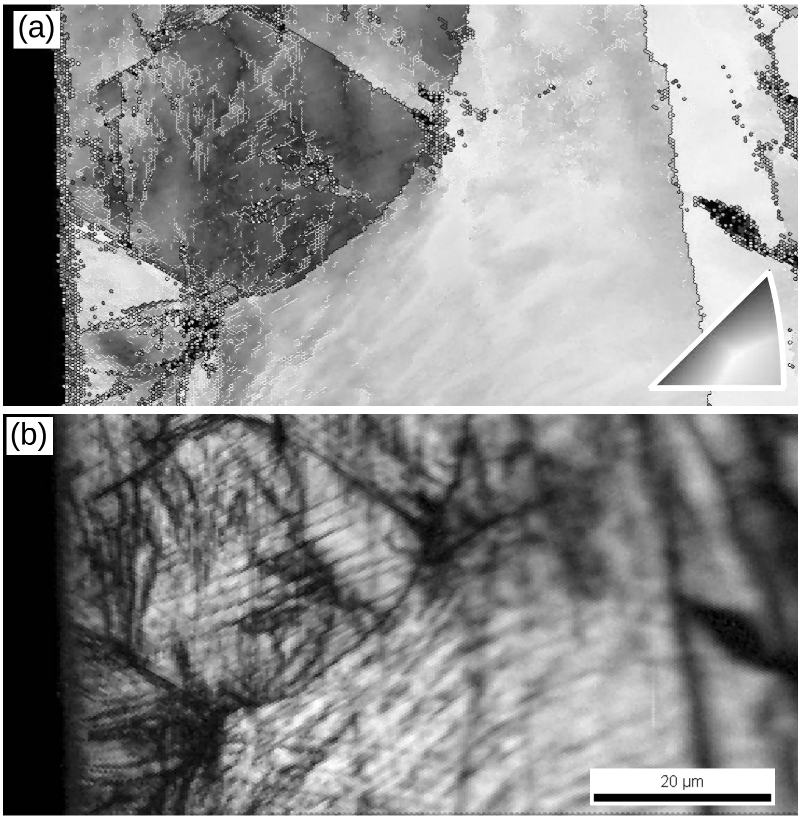

Fig. 1 SEM-EBSP analysis on the cross section of the shot peened specimen. (a) IPF map, and (b) IQ map.

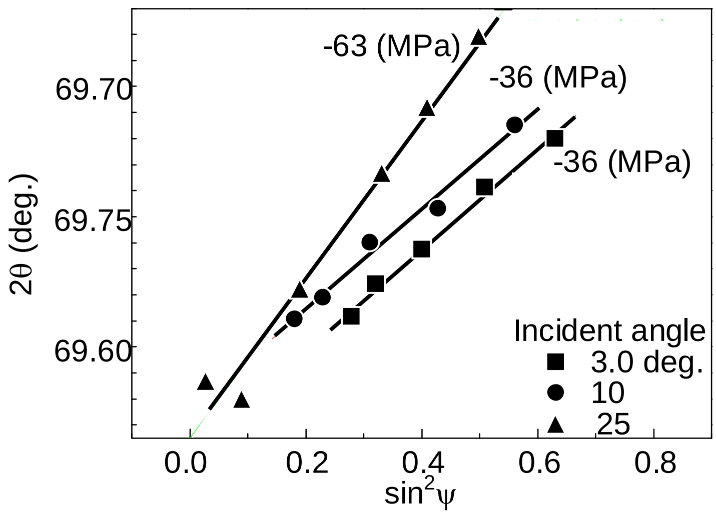

Fig. 2 2θ-$\sin^2\psi$ plots for the areas near the shot peened surface. Incident angle of 3, 10 and 25 correspond to 0.3, 1.0 and 2.0 mm depth, respectively.

The decrease in stress tends to be saturated except the highest value on the specimen aged at 537 K for 8000 h, because the dislocation substructures become stable at each temperature. Recovery of the dislocation substructures are caused by self diffusion of iron, volume diffusion of nickel and chromium. However, diffusion coefficients at low temperatures, such as 523, 573 and 623 K, were not reported. The lowest one was 849 K (R. A. Perkins, 1973). Relationships between the volume diffusion coefficient and 1/T for Fe, Ni and Cr showed good linearity in their papers. Self diffusion coefficient of iron at 573 K is obtained as $8x10^{-26}$ cm^2/s by extrapolating their data to 573 K. This value is too small to cause the recovery. Interstitial atoms and vacancies formed by severe deformation due to shot peening would promote the diffusion of solute atoms. Diffusion coefficient of Ni in irradiated stainless steel was reported as about $1x10^{-16}$ cm^2/s (W. Schüle, 2001), which shows that the diffusion distance at 573 K for 8000 h is about 1 μm. Interstitials and vacancies induced by severe deformation of shot peening would assist the diffusion of elements.

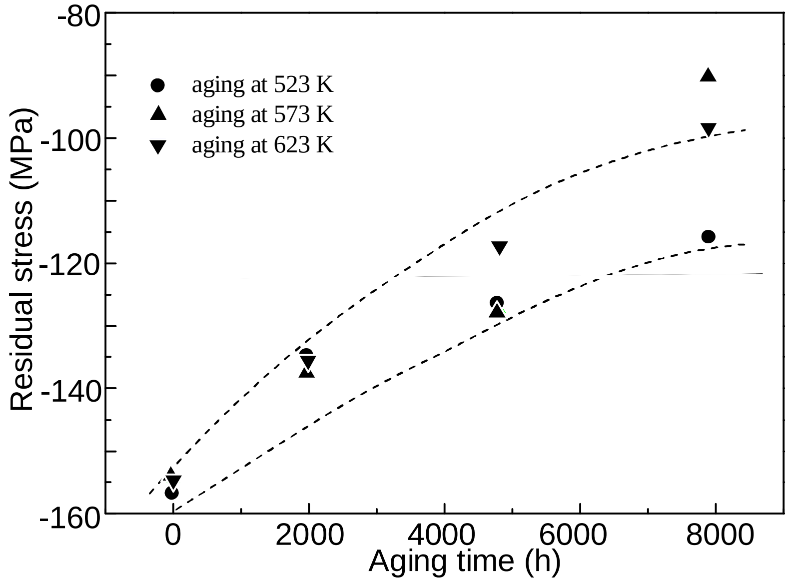

Fig. 3 Change in residual stress on the specimens aged at various temperatures.

SUMMARY

The present study shows that compression residual stress induced by shot peening is not stable but decreased by aging, even at lower temperatures around 561 K. The mechanism of decreasing is considered to be recovery of dislocation substructures, therefore the change is saturated by forming stable substructures at each temperature after prolonged aging. The residual stress at the stable condition depends on the conditions for shot peening. It is necessary to carry out prolonged aging at 561 K and measuring the residual stress when a shot peening is applied to practical shroud materials.

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