General paper

FATIGUE PROPERTIES OF HARD SHOT-PEENED SUS316L Behaviors of Hardness Distribution, Residual Stress Distribution and Fatigue Cracks during the Fatigue Process

Kiyotaka MASAKI*, Yasuo OCHI** and Akira ISHII**

*Graduate School, Univ. of Electro-Communications

**Dept. of Mechanical and Control Engineering.,

Univ. of Electro-Communications

1-5-1, Chofugaoka, Chofu, Tokyo 182-8585, Japan

Abstract: The rotating bending fatigue properties of normal shot-peened (SP) and hard shot-peened (HSP) 316L austenitic stainless steels were investigated from the viewpoints of the changes of hardness distribution and compressive residual stress distribution during the high-cycle fatigue test. The investigation of the crack growth behavior was also carried out using a replication technique. It was found that the fatigue strength was improved by shot-peening treatments, and the fatigue crack propagation mechanisms were clarified in the SP and HSP specimens. The fatigue crack growth behavior in the SP and HSP specimens was completely different from that of the non-peened specimens. The differences were caused by the change of the hardness distributions and the residual stress distributions during the fatigue test.

Key words: 316L stainless steel, Hard shot-peening (HSP), Rotating bending fatigue, Residual stress distribution, Hardness distribution, Crack propagation

1. INTRODUCTION

Surface hardening treatments are very useful for the improvement of the fatigue strength of steel. The shot-peening treatment is one such method which has been studied by some researchers[1-7] with respect to the treatment of spring steels and gear steels. In recent years, the shot-peening treatments have been applied to aluminium alloys[7,8], titanium alloys[9,10] and ductile irons (DI)[11,12]. In addition, a study of shot-peening treatments for austenitic stainless steel which was taking notice for use as an atomic pile structure material has been reported[13-17]. In one of the reports, shot-peening treatments were shown to be very useful for the prevention of stress corrosion cracking (SCC) of austenitic stainless steel[15]. However, only a few studies have been reported regarding the fatigue properties of shot-peened austenitic stainless steel [16], and the fatigue properties with respect to the high-cycle fatigue tests were not clarified. Recently, hard shot-peening (HSP) treatments under the condition that the arc height was over 0.5 mmA, have been carried out for metals, but studies regarding the effects of the HSP treatments on the fatigue strength have not been reported until now.

In this study, the effects of two types of shot-peening treatments, i.e., the arc height is 0.2 mmA (normal shot-peening, the SP treatment) and in the other it is 0.6 mmA (hard shot-peening, the HSP treatment), on the rotating bending fatigue properties of SUS316L stainless steel were investigated. The fatigue properties of the materials subjected to the surface hardening treatments were studied in the following way. First, the hardness distribution, the residual

stress distribution, and the half-value breadth (HVB) distribution were measured before the test. Second, the changes of these distributions and the crack growth behavior were investigated during the test. Finally, the fracture surface was observed by a scanning electron microscope (SEM) after the test.

In this paper, the fatigue properties were investigated, taking into consideration of the variation of the hardness distribution, the residual stress distribution and the HVB distribution during the fatigue test, and taking to consideration of the crack growth behavior, on the SP and HSP treated SUS316L stainless steel. The surface crack growth behavior was observed using a replication method.

2. EXPERIMENTAL PROCEDURES

2.1. Materials

The material used in this study was SUS316L stainless steel, having the chemical composition of: 0.017 C, 0.39 Si, 0.80 Mn, 0.029 P, 0.014 S, 12.17 Ni, 16.31 Cr, 2.06 Mo. SUS316L stainless steel is a low carbon type of SUS316 stainless steel that is used for fast breeder reactors. The austenitic matrix of SUS316L stainless steel does not transform into martensitic matrix, and so, the effect of the martensitic transformation by shot peening treatments can be neglected. In the previous paper, the martensitic matrix was not confirmed by the X-ray diffraction method[18]. For other austenitic stainless steels, for example SUS304 stainless steel, the measurements of residual stress by X-ray diffraction is difficult because of the martensitic transformation[19].

The mechanical properties and microstructure of

FATIGUE PROPERTIES OF HARD SHOT-PEENED SUS316L

SUS316L stainless steel used in this study are given in Table 1 and Fig.1, respectively. The average grain size of the austenitic structure was about $87.5\ \mu\text{m}$. The shapes and dimensions of the specimens are shown in Fig.2. The specimens have a circumferential shallow notch at the center as shown in Fig.2. Fatigue cracks are initiated naturally in the shallow notch (the stress concentration factor K_t is about 1.06). After the machining, all the specimens were polished by abrasive paper of # 400-1500 and were annealed at $1100\ ^\circ\text{C}$ for 1 h in a vacuum furnace. Then, the center part of specimen was finished by polishing with alumina paste with $1\ \mu\text{m}$ diameter, and then the specimens were shot-peened.

2.2. Shot-peening Treatment

The specimens were pneumatically peened by steel shots of 60 HRC for 30 s at an air pressure of 0.196 MPa from a distance of 200 mm. Then, the uniform shot-peening quality was obtained by rotating the specimens at 20 rpm. Also, by changing the diameter of the shot grid as shown in Table 2, two types of shot-peened specimens (the SP specimen: arc height is 0.2 mmA, the HSP specimen: arc height is 0.6 mmA) were obtained.

Table 1. The mechanical properties.

Material	Tensile strength σ_B [MPa]	0.2 % proof strength $\sigma_{0.2}$ [MPa]	Reduction of area ϕ_n [%]	Hardness Hv
SUS316L	549	178.3	82.9	135

Fig.1. The microstructure of the specimen.

Fig.2. The shape of the specimen (mm).

Table 2. Conditions of shot-peening.

	SP	HSP
shot treatment	normal shot	hard shot
shot size	0.3 mm dia.	0.6 mm dia.
arc height	0.2mmA	0.6mmA

Fig.3. The microstructure of the HSP specimen.

The surface roughness of the SP and the HSP specimens were increased by the shot-peening treatments. An arithmetic mean deviation, R_a , was $0.3\ \mu\text{m}$, $2.2\ \mu\text{m}$ and $6.0\ \mu\text{m}$ for the non-peened (n.p.) specimens, the SP specimens and the HSP specimens, respectively. A maximum height of roughness profile, R_{max} , was $1.8\ \mu\text{m}$, $16.0\ \mu\text{m}$ and $40.0\ \mu\text{m}$ for the n.p. specimens, the SP specimens and the HSP specimens, respectively. For the HSP specimens, both R_a and R_{max} were about twenty times as those of the n.p. specimens. The surface layer had many slip bands as a result of plastic deformation in the HSP specimens as shown in Fig.3.

2.3. Fatigue Test

Rotating bending fatigue tests were conducted for about 10^8 cycles at 50 Hz under water cooling condition using deionized water (pH: 7.05 at $20\ ^\circ\text{C}$ was measured). The high-cycle fatigue tests for the n.p. specimens, the SP specimens and the HSP specimens were carried out.

3. RESULTS AND DISCUSSION

3.1. Results of the Fatigue Tests

The results of the fatigue tests are shown in Fig.4. Both fatigue strength and fatigue limit of the SP and HSP specimens were markedly improved in comparison with the n.p. specimens. The fatigue limits at about 10^8 cycles were about 200 MPa for the n.p. specimens, about 340 MPa for the SP specimens and about 370 MPa for the HSP specimens. The reasons for the improvement in the fatigue strength were assumed to be due to the mean stress effect of the compressive residual stress, and due to the shift in the crack origin from the surface to subsurface (surface effect) by surface hardening caused by the plastic deformation and the compressive residual stress[18]. The hardness measurement and the X-ray diffraction residual stress measurements were carried out by noting

Fig. 4. S-N curves under water cooling condition.

the condition of stress amplitude at which the fatigue lives of those specimens were equal to about 3×10^5 cycles at 250 MPa for the n.p. specimens, 350 MPa for the SP specimens and 420 MPa for the HSP specimens. In addition, these measurements were carried out at each time for all treatments before, after, and during the fatigue test.

3.2. Change of the Hardness and Residual Stress Distributions

3.2.1. The hardness distribution

The hardness distributions were measured from the surface to a depth of 1 mm, using the micro-Vickers hardness tester under the conditions of load $P=0.245$ N and time $t=15$ s. Considering the differences of hardness in each test piece, the value was divided by the minimum value of the hardness distribution, based on the consideration that the austenite matrix does not soften. Figure 5 shows the changes of the ratio of Vickers hardness distribution during the fatigue test. The hardness of the inside of the n.p. specimen was increased during the fatigue test. This can be considered to be due to cyclic strain hardening during the test because the specimens were annealed before the fatigue tests. However, the surface layer of the n.p. specimens did not harden. This may be caused by the following reasons: the fatigue cracks appeared on the surface at an early stage of fatigue life, and the stress amplitude was not completely carried at the surface, resulting in no cyclic hardening of the surface layer. Detailed discussions regarding the fatigue crack growth behavior are given later. For the SP specimens and the HSP specimens, the hardness of the surface layer decreased. This could be considered to be due to cyclic strain softening during the test because the hardness of the hardened layer was very high. For the SP specimens and the HSP specimens, the internal matrix hardness was increased by cyclic strain hardening. Therefore, in the SP specimens and the HSP specimens, the cyclic strain softening and the cyclic

Fig. 5. The change of the hardness distribution.

strain hardening occurred at the same time and on the same specimens.

However, the point worth noting in Fig. 5 is that the boundary layer between the surface layer (the hardened layer) and the internal matrix was unchanged. This was the weakest layer in the specimen during the fatigue test. As the fatigue crack initiated at the weakest point in the specimen, it could be considered that the fatigue crack was initiated in the boundary layer [18] and then propagated inwards as the surface layer of the specimen was hardened.

3.2.2. The residual stress distributions by the X-ray diffraction method

The residual stress distributions were measured by the X-ray diffraction method and their values estimated on the basis of the " $\sin^2\psi$ " method. All the residual stress measurements were performed using (220) austenite reflection with Cr $K\alpha$ radiation under the conditions of diffraction angle: 128.7° , tube voltage: 40 kV, tube current: 50 mA, irradiation time: 100 s, ψ_0 oscillation method: 3.0° at $12.0^\circ/\text{min}$.

To investigate the residual stress distributions of specimens, subsurface stress measurements were performed after successive layer removals by an electrochemical polishing technique. The measurements were carried out from the surface to a depth of 500 μm . The measurement point was about 5 mm away from the center of the fatigue test specimen. The results of the residual stress measurements are shown in Fig.6. In the n.p. specimen, the residual stress distribution was unchanged by the fatigue test. So, the residual stress is not produced by the cyclic load in the specimen during the fatigue test. In the SP specimens, the surface compressive residual stresses were reduced. In the HSP specimens, the maximum residual compressive stresses inside the specimens (distance from the surface is about 100 μm) were reduced. However, the residual compressive stresses were not fully released, so these stresses were the factors which caused the improvement in the fatigue strength, thus preventing fatigue crack propagation during the fatigue test.

Fig.6. The change of the residual stress distribution.

Fig.7. The change of HVB distribution.

The HVB distributions were also measured by the X-ray diffraction method. Figure 7 shows the change of the HVB distributions during the fatigue test. The HVB distributions were not markedly changed. These results may be due to the fact that the measurement of the HVB distributions were not carried out on the fracture surface itself and the HVB distributions were not sensitive to fatigue stress amplitude.

3.3. Crack Growth Pattern

The initiation and growth behavior of the surface cracks were investigated using the replication technique. The crack propagation behavior in the n.p. specimen is shown in Fig.8. An example of a surface crack is shown in Fig.9. Some fatigue cracks were initiated on the surface at an early stage of fatigue life, and these crack growth rates were comparatively low at the early stage of fatigue. Finally, these cracks combined with each other to form a long main crack. This trend was similar to those described in other reports of fatigue properties of austenitic stainless steel [20]. The crack propagation behavior in the SP specimen is shown in Fig.10. An example of a surface crack is shown in Fig.11. In the SP specimens, the growth

behavior of the surface crack was different from that in the n.p. specimens. A fatigue crack appeared at the surface during the final stage of fatigue life ($N/N_f=0.78$) and the crack grew rapidly at the surface.

Fig. 8. Crack length l as a function of the relative number of cycles N/N_f in the n.p. specimen.

Fig. 9. Successive observation of the surface fatigue crack in the n.p. specimen.

Fig. 10. Crack length l as a function of the relative number of cycles N/N_f in the SP specimen.

In the HSP specimen, the surface crack observations were carried out at a stress amplitude of 420 MPa. However, the surface cracks were not observed until the cycle ratio N/N_f reached a value over 0.95.

The relationships between the crack growth rate da/dN and the half crack length a in the n.p. and the SP specimens are shown in Fig. 12. In the SP and the HSP specimens, the fatigue crack was initiated in the boundary layer between the surface layer (the hardened layer) and the internal matrix. The crack propagated towards the inside of the specimen as the surface layer was hardened. The crack progress was prevented by the hardened layer and the high compressive residual stress near the surface. As a result, on reaching the surface, the crack has spent most of its fatigue life. When the fatigue crack appeared on the surface, it had already progressed considerably inside the specimen and so the surface crack grew fast. The crack origin and the internal crack propagation behavior will be discussed in a subsequent paper.

Fig. 11. Successive observation of the surface fatigue crack in the SP specimen.

Fig. 12. Relationship between crack propagation rate da/dN and half crack length a .

4. CONCLUSIONS

High cycle fatigue tests of the non-peened (n.p.), the normal shot-peened (SP) and the hard shot-peened (HSP) SUS316L stainless steels were carried out and the effects of the shot-peening treatments on the fatigue properties were investigated. The following points were concluded from the study.

1. The rotating bending fatigue strength was improved by the SP and HSP treatments and the improvement trend was more remarkable in the HSP specimens.
2. The internal matrix hardness of the n.p., SP and HSP specimens increased by cyclic strain hardening during the fatigue test. However the hardness of the surface hardened layer of the SP and HSP specimens decreased by cyclic strain softening.
3. The compressive residual stresses caused by the SP and HSP treatments were released partly by the fatigue loading, and the maximum residual stresses were reduced.
4. In the n.p. specimens, some fatigue cracks appeared at the surface during the early stage of fatigue life. These cracks propagated and combined with each other. However, in the SP and HSP specimens, only one fatigue crack was initiated in the boundary layer and propagated preferentially into the inside of specimen. The crack growth rate of the surface crack on the SP specimen was still faster than that on the n.p. specimen.

Acknowledgments —The authors are grateful to Mr. Toshihiko Iwano and Mr. Tatuyuki Senoh (Dowa Mining Co., Ltd, Thermo Technology Center) for their help during the shot-peening treatments and to Dr. Yasuo Inoue (Faculty of Engineering, Yamanashi Univ.) for his valuable advice regarding the X-ray diffraction stress measurements.

REFERENCES

1. T. Honma, J. Japan Inst. Metals, **6** (1967)770.
2. S. LYU, K. Inoue, M. Kato, M. Ohnishi and K. Shimoda, JSME International Journal, Ser. C, **39** (1996)108.
3. K. Ogawa, T. Asano, K. Suzuki, H. Aihara and K. Shimoda, Trans. Japan Soc. Mech. Eng., Ser. A, **61**(1995)233.
4. K. Inoue, S. LYU, G. Deng and M. Kato, Trans. Japan Soc. Mech. Eng., Ser. C, **62** (1996)306.
5. D. N. Kocanda, S. Kocanda and J. Miller, Fatigue Fract. Engng Mater. Struct., **19** (1996)911.
6. K. Iida and K. Taniguchi, Trans. Japan Soc. Shot Peening, **8** (1996)9.
7. D. W. Hammond and S. A. Meguid, Eng. Fract. Mech., **37** (1990)373.
8. K. Ito, H. Suzuki, S. Nishino and A. Teranishi, Trans. Japan Soc. Mech. Eng., Ser. A, **62** (1996)1316.
9. K. Asami and M. Hironaga, J. Soc. Mater. Sci., Japan, **43** (1994)12.
10. Y. Kato, S. Takafuji and M. Kiriya, J. Soc. Mater. Sci., Japan, **45** (1996)43.
11. M. Hashimoto, M. Shiratori, M. Ito and K. Hirai, Trans. Japan Soc. Mech. Eng., Ser. A, **61** (1995)889.
12. H. Suzuki, A. Magata, W. M. Gong and Y. Ito, Trans. Japan Soc. Mech. Eng., Ser. A, **61** (1995)2349.
13. M. Watanabe and H. Watanabe, Trans. Japan Soc. Mech. Eng., Ser. 3, **29** (1963)614.
14. K. Iida and K. Tosha, Trans. Japan Soc. Shot Peening, **5** (1993)4.
15. M. Kohata and R. Sudo, Resent Studies of Shot-Peening in Japan of 1994 (1994)16.
16. E. R. delos Rios, A. Walley, M. T. Milan and G. Hammersley, Int. J. Fatigue, **17** (1995)493.
17. H. Sueyoshi, K. Hamaishi, Y. Nakamura and J. Kiyofuji, Mater. Trans. JIM, **37** (1996)150.
18. K. Masaki, Y. Ochi and A. Ishii, J. Soc. Mater. Sci., Japan, **46** (1997)1130.
19. M. Hayashi, and K. Enomoto, J. Soc. Mater. Sci., Japan, **45** (1996)1107.
20. J. Polak, K. Obrtlík and M. Hajek, Fatigue Fract. Engng. Mater. Struct., **17** (1994)773.