EFFECTS OF SHOT PEENING ON TORSIONAL FATIGUE STRENGTH OF HIGH STRENGTH SPRING STEEL IN AIR AND CORROSIVE ENVIRONMENT

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ABSTRACT
Torsional fatigue tests were conducted for spring steels,SUP7 prepared in the heat treatment, whose Vickers hardness was 480. The effects of the shot peening on the fatigue strength in the corrosive environment and air were studied. The effect of shot peening for the smooth specimens on the fatigue strength in air were comparatively small. This was considered to be caused by the decrease of the residual stress during the fatigue strength test and the effect of the surface roughness by the shot peening was small. On the other hand, the effect of the shot peening for the smooth specimens with artificial pits on increasing the fatigue strength in air was large.
And the effect of the shot peening for the smooth specimens on the fatigue strength in the corrosive environment was remarkably large, except for the case of short fatigue life. This was considered to be caused by the residual stress from shot peening, preventing the crack initiation from corrosion pit or crack propagation.

KEY WORDS
Torsional fatigue, Spring steel, Shot peening, Corrosive environment, S-N curve

INTRODUCTION
One measure for improving the fuel economy of vehicles is reducing the weight of suspension coil springs used in automobiles, coupled with other efforts such as enhancing spring steel strength and improving fatigue strength by shot peening. To reduce the coil spring weight, the authors have developed high-strength springs with particular focus on improvements in corrosion fatigue strength, and conducted research on the use of high corrosion-resistant spring steel in cold-rolled coil springs.
On the other hand, shot peening is a well-known process of improving spring strength and much research has been conducted on the fatigue strength of shot-peened materials. However, past research mainly relates to plane or rotary bending fatigue, and there has not been a sufficient number of reports on the torsional fatigue strength of coil springs (K. Saruki, N. Hirose and K. Ohbayashi,2004). Moreover, research on the effect of shot peening on the torsional fatigue strength of notched specimens in a corrosive environment has rarely been conducted.
In this research, with respect to heat-treated and shot-peened specimens of spring steel (JIS SUP7) having Vickers hardness of 480 with a smooth surface and an artificial pit (hereinafter called “smooth SP specimen” and “notched SP specimen,” respectively), torsional fatigue tests were conducted in both an air environment and a corrosive environment of saltwater to obtain the fatigue strength of said specimens. Then, the effect of shot peening on torsional strength was studied by comparing the specimens with those not subject to shot peening as previously reported (M. Wakita, T. Kuno,A. Amano, et al., 2007). In addition, the mechanism by which shot peening

Table 1. Shot-peening conditions.

Peening machine	Impeller type	Velocity	70 m/s
Shot diameter	0.8 mm	Coverage	300%
Shot hardness	600 HV	Arc height	0.557 mmA

improves strength was studied based on microscopic observation results of fatigue crack shape and fracture surfaces and the distribution of residual stress measured by X-ray diffraction.

METHODS

Materials and Specimens

The material used in the tests was spring steel employed in hot rolling (JIS SUP7) that was melted in an actual mass production furnace. This hot-rolled spring steel is actually being used for vehicle coil springs. This material was also used in the previous report (M. Wakita, T. Kuno, A. Amano, et al., 2007). The composition of this material is: C 0.6, Si 2.0, Mn 0.9, P 0.014, and S 0.019 (mass%).

The specimens were roughly machined and quenched in oil after being heated at 1173 K for 20 minutes. Then the specimens were tempered at 723 K for 60 minutes, and cooled with water to adjust hardness to 480HV. This matches the hardness applied to general spring materials (JIS B 2704) in practical use. According to the hardness conversion table of SAE J417, this hardness is equivalent to a tensile strength of 1620 MPa.

After the above treatment, shot peening was applied to specimens using cut wire 0.8 mm in diameter as a peening media under the conditions listed in Table 1. This peening media is equivalent to that used in general shot peening prescribed by JIS B 2711 and applied to vehicle suspension springs. With respect to the smooth SP specimens, the surface layers of some specimens were left untreated, while those of others were electrolytically polished within the range of 0.1 mm from the surface in order to remove the effect of surface roughness due to shot peening. Hereinafter, shot-peened specimens are called the "SP specimens" and specimens in the previous report (M. Wakita, T. Kuno, A. Amano, et al., 2007), which were not subject to shot peening, are called the "non-SP specimens."

After shot peening, an artificial pit was created. A hemispheric depression 600 μm in diameter and 300 μm in depth was produced at the center of the parallel section of the specimens by using an electrolytic polishing device (manufactured by Rigaku Corporation), and with ammonium chloride solution used as an electrolyte. These artificial pit dimensions were determined by assuming said dimensions as the maximum values of measured pits on suspension springs being practically used. According to FEM analysis, the factor of vertical stress (principal stress) concentration α under a torsional load was 2.2.

Residual Stress Distribution

After the specimens were produced, the residual stresses in the axial direction, 45° direction, and circumferential direction were measured using an X-ray diffraction method. The measurements were taken in accordance with a $\sin^2\psi$ method defined by the JSMS-SD-5-02 standard using Cr-Kα radiation.

Torsional Fatigue Test

Torsional fatigue tests were conducted using a Schenk-type cyclic torsion/bending tester (model FTS-100 manufactured by JT TOHSI INC., with capacity of 100 N•m) under conditions where the stress waveform was a perfect alternating sine wave, with a stress ratio of -1 and frequency of 30 Hz. During tests in the corrosive environment, the parallel section of the smooth specimen were corroded for 16 hours using a salt spray tester (manufactured by Suga Test Instruments Co., Ltd.). As a corrosive solution, a 5% sodium chloride solution—defined by JASO C604 and used in many corrosion fatigue tests of vehicle suspension springs—was used. Then the specimens were removed from the salt spray tester, rinsed and dried, and then the salt-corroded areas were covered with cotton soaked in said 5% sodium chloride solution. After wrapping the specimens in ethylene film on the cotton to prevent drying, fatigue tests were conducted. Fatigue tests were terminated upon reaching 10^7 cycles.

RESULTS

S-N Curve

In Figure 1 (a) for the smooth specimen in the air environment, the S-N curve of the SP specimen is located almost parallel to and higher than that of the non-SP specimen, though the difference is relatively small.

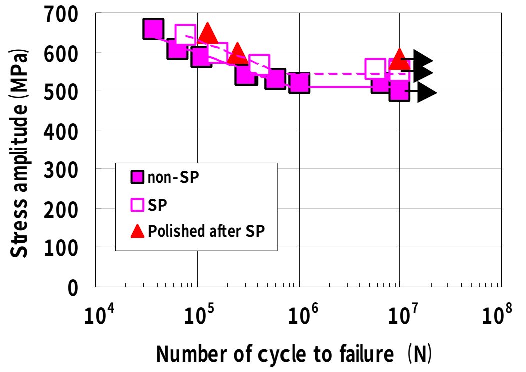
Generally, the improvement in fatigue strength by shot peening is attributed to the compressive residual stress on the surface and the increased hardness due to work hardening of the material. On the other hand, it is thought that the roughness on the surface will reduce fatigue strength. Though the increase in the hardness due to shot peening is not significant in the specimens used in this research, an improvement in fatigue strength due to compressive residual stress on the surface is expected. However, after the smooth specimen is shot-peened, the surface becomes rougher, raising the ten-point average surface roughness R_z to 16 μm from 2 μm of the smooth specimen, which may contribute to reduce fatigue strength. Therefore, the fatigue test was also conducted on the SP specimen that was electrolytically polished by about 0.1 mm. The figure also shows the result of this test, and there is little increase in the fatigue strength of this electrolytically polished specimen, suggesting that surface roughness has no effect on fatigue strength.

In Figure 1(b) obtained from the notched specimen in the air environment, the S-N curve of the SP specimen is located almost parallel to and significantly higher than that of the non-SP specimen. Here, notch factor β for each life N_f is defined by the following equation:

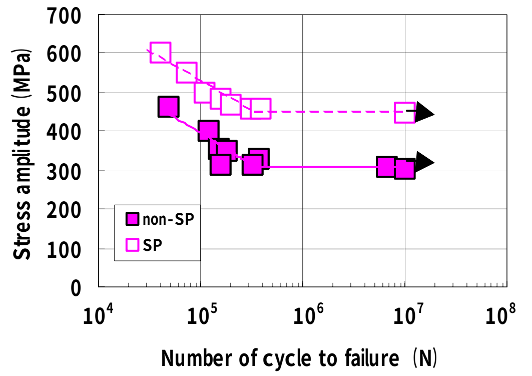
$$\beta = \tau_{wo}(N_f) \,/\, \tau_{w1}(N_f) \qquad (1)$$

where, $\tau_{wo}(N_f)$ denotes the stress amplitude for the life of smooth specimen N_f, and $\tau_{w1}(N_f)$ the stress amplitude for the life of notched specimen N_f. β of the non-SP specimen at the fatigue limit is about 1.7, while that of the SP specimen is about 1.2,suggesting that shot peening reduces the notch sensitivity.

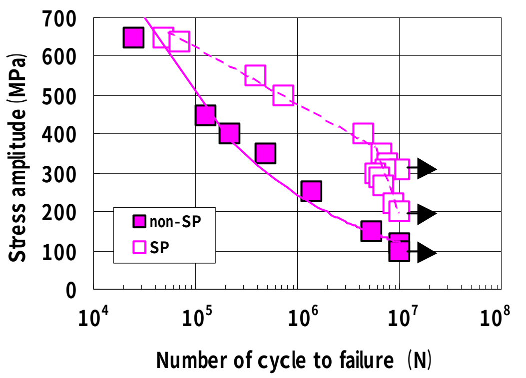
On the other hand, Figure 1 (c) shows the S-N curves obtained from the smooth specimens tested for fatigue in the corrosive environment. These curves show a small difference in fatigue strength between the SP and non-SP specimens in the short life range. This difference is similar to that in the short life range in the air environment as shown in (a), suggesting that the effect of corrosion is insignificant. However, shot peening increases fatigue strength in the life range around 10^6 cycles, and then the strength of the SP specimens is significantly reduced and becomes



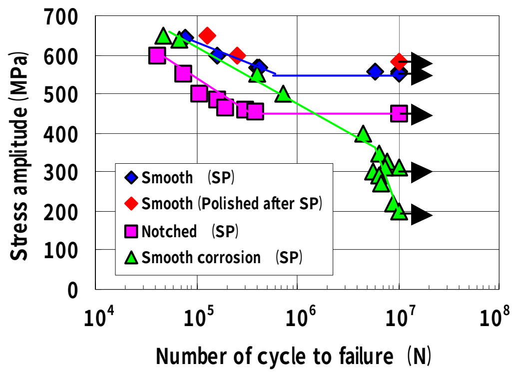
(a) Smooth specimen under fatigue in air



(b) Notched specimen under fatigue in air



(c) Smooth specimen under corrosion fatigue



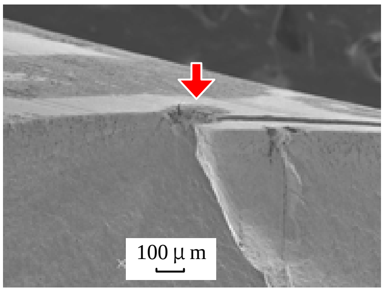
(d) Shot-peened specimens

Fig. 1 S-N diagrams.

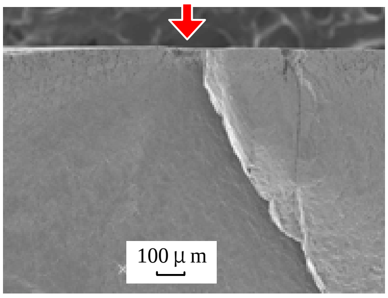
close to that of the non-SP specimens in the long life range around 10^7 cycles.Figure 1 (d) shows the S-N curves of the smooth and notched SP specimens tested for fatigue in the air and corrosive environments. There is little difference between these environments for both of the smooth and notched SP specimens until 3 x 10^5 cycles. However, though the fatigue limit appears at about 4 x 10^5 cycles in the air environment, fatigue strength in the corrosive environment continues to decrease and then drop at about 10^7 cycles. On the other hand, as previously reported (M. Wakita, T. Kuno, A. Amano, et al., 2007), in the non-SP specimens in the corrosive environment, a decrease in the fatigue strength is observed even in the short life range of 10^5 cycles or less. In other words, shot peening reduces the decrease in strength caused by the environment.

Crack and Fracture Surface Observation

Figure 2 shows the SEM images taken near the fracture origin in the non-SP specimen. In these images, the pit is observed at the fracture origin. Figure 3 shows enlarged SEM images taken near the fracture origin in the SP specimen to which shear stress amplitude τ_a = 325 MPa was applied. Many microcracks were formed on this the surface of this specimen, and in the region at the depth of about 0.3mm from the fracture surface, there are areas that include many secondary cracks.
Here, the average depth of the microcrack region was measured, and then the stress intensity factor calculated by using the following equation as suggested by Murakami

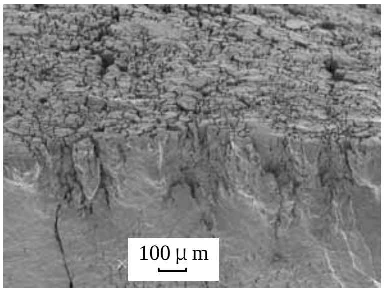


(a) Surface of fracture origin

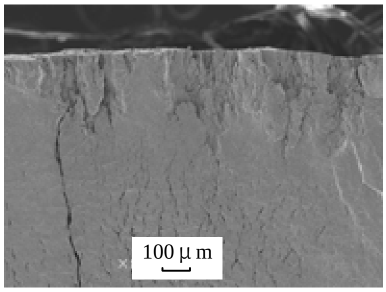


(b) Fracture origin

Fig. 2 Micrographs of fracture origin of non-SP specimen. (τ_a=350 MPa, N_f=4.9×10^5)



(a) Surface of fracture origin



(b) Fracture origin

Fig. 3 Micrographs of facture origin of SP specimen. (τ_a=325 MPa, Nf=7.7×10^6)

(Y. Murakami,1993) for narrow and long surface cracks:

$$\Delta K = 0.65\,\sigma_a\sqrt{\pi\sqrt{10c}} \qquad (2)$$

where, c denotes the depth of the microcrack region, and σ_a the principal stress amplitude equal to the shear stress amplitude. The stress intensity factors were calculated from about 13 to 15 $\mathrm{MPa}\sqrt{\mathrm{m}}$. On the other hand, as previously reported (M. Wakita, T. Kuno, A. Amano, et al., 2007), the stress intensity factors for the corrosion pits in the non-SP specimens were almost constant at about 2 to 3 $\mathrm{MPa}\sqrt{\mathrm{m}}$ regardless of stress amplitude. The crack is considered to propagate when this value is reached. Compared with this value, the stress intensity factors of the SP specimens are about fivefold larger. The reason for this is considered that, while microcracks cannot propagate inside the specimens due to the compressive residual stress on the surface, many cracks form on the surface and are combined to create a deeper crack, which then propagates as the primary crack.

Changes in Residual Stress due to Fatigue

Figure 4 shows the residual stress distribution measured by X-ray diffraction on the fatigue-tested surfaces of SP specimens. In this figure, the values measured on smooth specimens tested for fatigue until 10^7 cycles in both the air and corrosive environments, and those measured on the notched specimen tested for fatigue until 10^7 cycles in the air environment are shown as residual stresses at near the fatigue limit. The characteristics are summarized below. First, initial residual stress is relieved even at near the fatigue limit. The degree of relief of the initial equibiaxial residual stress is greatest with the axial direction and decreases in 45° and circumferential directions, though the differences are insignificant. In the case of corrosion fatigue, residual stress in the region within about 0.05 mm from the surface

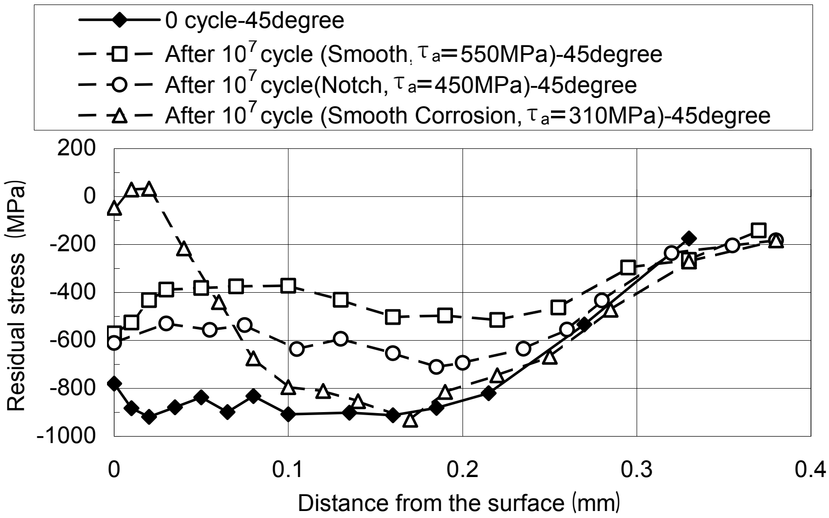


Fig. 4 Distribution of residual stress after fatigue testing of SP specimens.

is -100 MPa or less (nearly zero), whereas in the case of fatigue in the air, -400 to -600MPa of residual stress is left in the same region. The reason for this is considered that, in the case of corrosion fatigue, the surface residual stress is relieved due to a number of cracks forming on the surface as mentioned above. On the other hand, residual stress in the region within 0.1 to 0.2 mm from the surface does not depend on the test environment, and the degree of compressive residual stress relief becomes greater as the applied stress amplitude increases. For example, there is little relief at an amplitude of 310 MPa, and the residual stress is -200 MPa or less at an amplitude of 637 MPa.

CONCLUSION

Torsional fatigue tests were conducted in both air and corrosive environments on smooth and notched SP specimens created from spring steel (SUP7) having Vickers hardness of 480. The results were compared with those of non-SP specimens in examining the effect of shot peening. The following summarizes our conclusions:

(1) The degree of increase in the fatigue strength of the smooth specimens in the air environment due to shot peening was relatively small, and the fatigue strength did not change even after removing the surface layer by electrolytic polishing. Shot peening reduced the notch sensitivity of the notched specimens.

(2) Shot peening significantly increased the corrosion fatigue strength in the medium life range. However, strength of the SP specimens in the long life range (at near 10^7 cycles) became similar to that of the non-SP specimens.

(3) Shot peening causes compressive residual stress in the region within 0.2 to 0.3 mm from the surface. Said residual stress in the inner regions after the fatigue of the specimens decreases depending on the stress amplitude. In the case of corrosion fatigue, residual stress in the region near the surface decreases to nearly zero due to a number of microcracks.

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