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Improvement of Fatigue Strength of Nitrided High-Strength Valve Springs by Application of a New Super Fine Shot-Peening Technology

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ABSTRACT

The peening of fine steel beads with diameters less than 80μm (referred to as SS Treatment in this paper) on the surface of nitrided and then conventionally shot-peened (with 0.6mm diameter cut steel wires) high-strength helical springs made from developed high strength valve spring wire, was found to effectively improve spring fatigue strength. This improved fatigue strength is mainly the result of very high compressive residual stress caused by work hardening of the spring surface layer without inducing deleterious surface qualities such as harmful surface micro-fissuring or surface roughness.

INTRODUCTION

The effect of the SS Treatment on the fatigue strength of non-nitrided high-strength valve springs made of high-strength oil tempered wire for valve springs has already been reported by the present authors [1]. In that paper, bombarding steel beads with a nominal diameter of 50μm and an average hardness of HV 860 (SS Treatment) following conventional shot-peening using cut steel wires with a 0.6mm diameter and a hardness of HV 550 on the surface of non-nitrided high-strength valve springs made of the developed high-strength oil-tempered SOTHN valve spring wire [1], was reported to be very effective in improving valve spring fatigue strength.

The effect of two-stage shot-peening applied to high-strength nitrided coil springs has already been reported by other researchers. In a paper by O. Nakano et al [2], cut steel wires with a diameter of 0.25mm and a hardness of HV 800 was used as the media for second stage shot-peening after first-stage shot-peening with 0.8mm diameter steel shot particles. In another study by T. Itoh et al [3], cemented carbide particles with a diameter of 0.1mm or 0.2mm and a hardness of HV1400 and round cut steel wires with a diameter of 0.25mm and a hardness of HV800, were used as the media for second-stage shot-peening of nitrided high-strength coil springs. In that study, the highest fatigue strength was obtained when cemented carbide shot particles with a diameter of 0.1mm was used in the second-stage.

In this study, the effect of SS Treatment on the various properties of gas-nitrided (hereafter, referred to as nitrided) and conventionally shot-peened helical springs made of high strength SOTHN wire was investigated. This paper first describes the effects of second-stage shot-peening particle size including the effect of SS Treatment on the residual stress and hardness distributions of gas-nitrided and two-stage shot-peened high-strength SOTHN wire springs. Then, causes of the resultant improved compressive residual stress and surface layer hardness of the conventionally shot-peened (as first-stage) and SS-treated (as second-stage) high-strength nitrided springs are described based on the X-ray diffraction peak broadening (half value width), transmission electron microscopy etc. The improved fatigue strength of the nitrided, conventionally shot-peened and SS-treated high-strength SOTHN wire helical springs is further reported compared with the nitrided and conventionally shot-peened high-strength SOTHN wire helical springs. Moreover, using a newly developed high-strength oil-tempered SOTHS valve spring wire which has better nitriding characteristics than SOTHN wire, valve springs were made. Fatigue test result of the nitrided, conventionally shot-peened and SS-treated SOTHS valve springs is described briefly. Finally, an application of nitrided, conventionally shot-peened and SS-treated SOTHS helical springs, which are 57% lighter than non-nitrided chromium-silicon oil-tempered wire springs, used as car transmission accumulator springs, is reported in brief.

EFFECT OF SECOND-STAGE SHOT-PEENING PARTICLE SIZE ON RESIDUAL STRESS AND HARDNESS

WIRE AND SPRINGS USED FOR EXPERIMENTS – The 3.19mm diameter high-strength valve spring wire (SOTHN) used for this experiment is the same as that used in the previous paper [1]. The wire's chemical composition is shown in Table 1. The tensile strength of as-oil-tempered SOTHN wire specimens was 2091MPa and its tensile fracture area reduction was 51.5%. The helical springs used for the experiment were processed from the high-strength valve spring wire mentioned above as follows; cold coiling, stress-relief tempering at 708K for 20min, spring seat grinding, descaling, nitriding at 703K for 180min, first-stage shot-peening and low temperature annealing at 493K for 20min. As the first-stage shot-peening, an impellar type machine was used and cut steel wires with a diameter of 0.6mm and a hardness of HV550 were bombarded on spring surface at 73m/sec for 40min. This is referred to as conventional shot-peening in this paper. The spring dimensions are described in Table 2.

Table 1. Chemical composition of high-strength SOTHN wire.

Element	C	Si	Mn	Ni	Cr	V
Mass %	0.58	1.49	0.70	0.29	0.84	0.07

Table 2. Dimensions of helical springs tested

Wire diameter	3.2mm
Coil diameter	21.2mm
Total number of coils	6.5 turns
Active number of coils	4.5 turns
Free height	50mm

FINE STEEL BEADS AND APPARATUS FOR SECOND-STAGE SHOT-PEENING – The nitrided high-strength springs described above were shot-peened (second-stage) with steel beads with a nominal diameter of 50μm or 200 μm and a hardness of around HV850 for 20min. The apparatus used for second-stage peening experiments was an air-blast type machine that uses compressed air to propel the shot beads. The air pressure in the nozzle was controlled at 0.4MPa or 0.5 MPa. The apparatus was a SGK-L type machine manufactured by Fuji Seisakusho, Tokyo. Test springs placed into a rotary basket in the machine were rotated automatically while shot beads were bombarded on the spring surface.

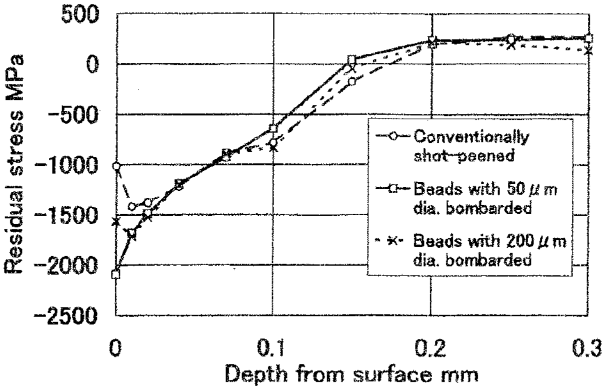

Fig. 1 Effect of second-stage shot-peening bead size on residual stress distribution

RESIDUAL STRESS AND HARDNESS DISTRIBUTIONS - Residual stress distributions of the prepared springs were measured by X-ray diffraction $(211)\alpha$ peaks using chromium $K\alpha$ X-rays. Hardness distributions of these springs below the surface were also measured. Figure 1 shows the effect of the steel bead size on the residual stress distribution near the surface. As the figure indicates, steel beads with a nominal diameter of 50μm yielded the highest compressive residual stress at the spring surface. The micro-hardness distributions measured are plotted in Fig. 2. The highest hardness nearest the spring surface was achieved when steel beads with a nominal diameter of 50μm were used for second-stage shot-peening.

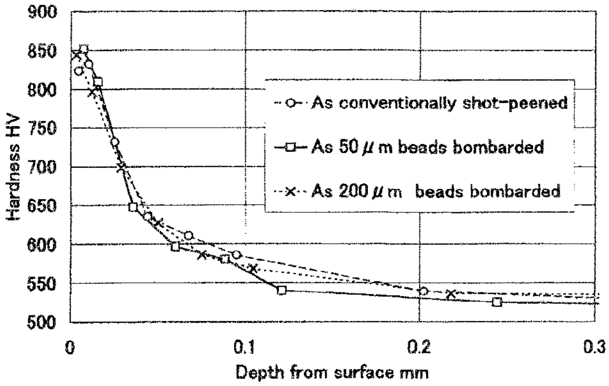

Fig. 2 Effect of second-stage shot-peening bead size on hardness distribution (HV, load: 2.94N)

SURFACE LAYER ANALYSES BY X-RAY DIFFRACTION

SPECIMEN PREPARATION AND METHOD OF X-RAY DIFFRACTION - To measure X-ray diffraction peak half value widths from the surface layer of as-nitrided wires and as-shot-peened wires, straight SOTHN wire specimens were prepared. The wire specimens cut into approximately 60cm length were each dipped in a hydrochloric acid solution to remove surface scales. As a result of this treatment, the wire diameter was reduced to around 3.17mm from 3.19mm. Descaled specimens were then nitrided at 708K for 180min. Some of the nitrided specimens were then dipped in a hydrochloric acid solution to remove compound layers (surface layers composed of iron nitride) on the surface, reducing the wire diameter to 3.16mm from the initial 3.17mm. Consequently, the wire was completely stripped of surface compound layers, leaving only the nitrogen enriched layer (nitrogen diffusion layer). As-nitrided specimens and the compound layer removed nitrided specimens were then conventionally shot-peened as described previously. Some of the conventionally shot-peened wire specimens were further SS-treated using 50μm nominal diameter steel beads for 20min. The air pressure in the nozzle was controlled at 0.4MPa. Copper Kα X-ray was used at this stage to determine the characteristics and properties of the thinnest wire surface layers (less than 10μm thickness).

EFFECT OF NITRIDING AND SHOT-PEENING ON THE MICROSTRUCTURE OF THE WIRE SURFACE LAYER - The X-ray diffraction spectra from the surface of the as-nitrided wire specimens (A), as-conventionally-shot-peened (nitrided and then conventionally shot-peened) wire specimens (B) and as-SS-treated (nitrided, conventionally shot-peened and SS-treated) wire specimens (C), are shown in Fig. 3. All diffraction spectra indicate the presence of ε iron nitride and α iron in their surface layers. Since ε iron nitride is reported to have solubility with carbon [4], there is a possibility that ε iron nitride is actually ε iron carbo-nitride. Hereafter, it is referred to just as ε iron nitride. According to optical microscopic observations of the cross sections of these specimens, the thickness of the compound layer formed during nitriding was found to be less than a few microns. Moreover, it was also found that a compound layer remained on the wire surface after the conventional shot-peening and even after the second-stage fine bead-bombardment (Fig. 4). It was also found that the generation of deleterious micro-cracks due to fine steel bead bombardment could be avoided and that a smoother surface could be obtained after conventional shot-peening and after SS-Treatment, compared to the as-nitrided specimen surface.

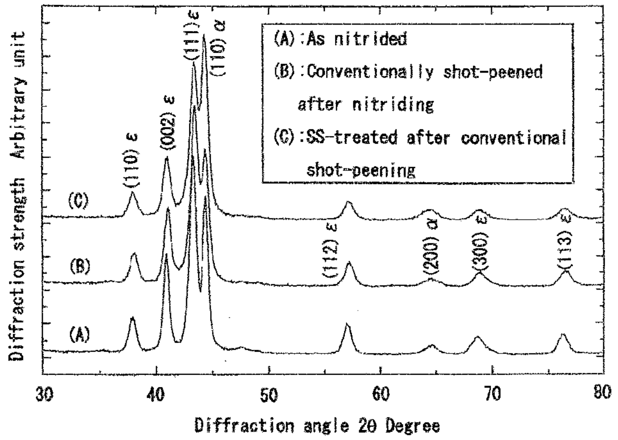

Fig. 3 X-ray (Cu Kα) diffraction spectra of as-nitrided wire (A) and nitrided and shot-peened high-strength wires (B) & (C).

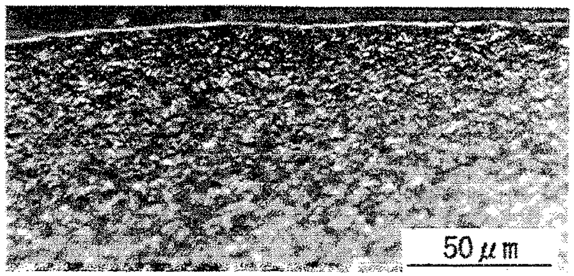

Fig. 4 Optical photo-micrograph of the nitrided, conventionally shot-peened and then SS-treated specimen surface layer (transverse cross section, nital etched).

EFFECT OF SHOT-PEENING ON HALF VALUE WIDTHS – For the three X-ray spectra shown in Fig. 3, each half value width for ε iron nitride was measured, not including the (111)ε peaks, which were difficult to measure because of overlapping with (110)α peaks. Figure 5 shows that most of the X-ray diffraction peaks from ε iron nitride in the SS-treated specimen have larger half value widths than as-conventionally-shot-peened specimens. This suggests larger non-uniform distortion, finer grain (cell) size or more frequent formation of stacking faults [5, 6] in the ε iron nitride in SS-treated specimen surface layers compared to conventionally shot-peened specimens. Theoretically, it is postulated that X-ray peak is broadened more as the diffraction angle 2θ increases when caused by grain refinement and/or by larger non-uniform distortion [6]. The X-ray spectra from a series of specimens in which the surface compound layers had been removed in acid solution (3.5 to 5μm per side) before the first shot-peening are shown in Fig. 6. The X-ray half value widths of α iron measured in these specimens are given in Fig. 7. It was also found that SS-treated specimens had larger X-ray half value widths than conventionally shot-peened ones. Moreover, the results shown in Figure 3

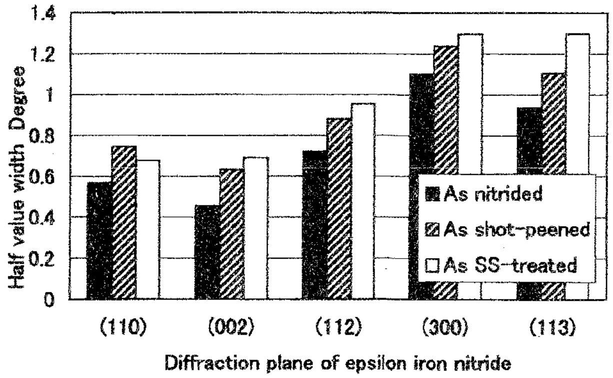

Fig. 5 Comparison of half value widths of X-ray diffraction peaks from ε iron nitride in samples as-nitrided and as-shot-peened differently.

and Figsures 5 - 7 indicate that the SS Treatment distorted the thin surface layers of the nitrided specimens more strongly than conventional shot-peening using 0.6mm diameter cut steel wires.

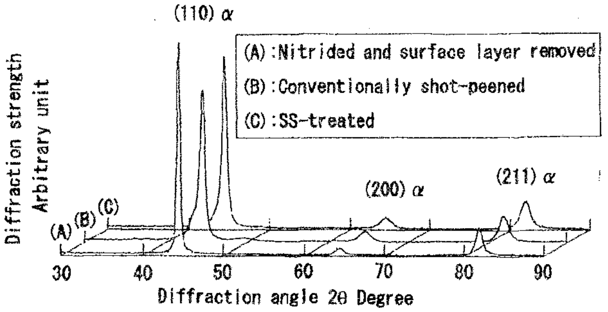

Fig. 6 X-ray diffraction spectra of specimen (A) with the surface compound layer removed after nitriding and the shot-peened specimens (B) & (C) after compound layer removal.

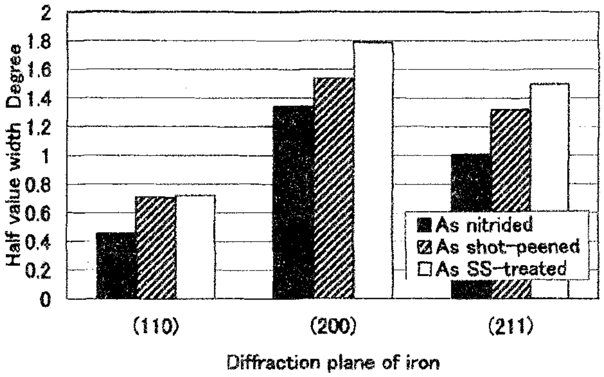

Fig. 7 Comparison of half value widths of α iron X-ray diffraction peaks from nitrided diffusion layers.

TEM SURFACE LAYER OBSERVATIONS

Transmission electron microscopic observations were made on the surface layer of three kinds of wire specimens prepared for the X-ray diffraction measurements described above:(i) as-nitrided (nitrided but not shot-peened), (ii) as-conventionally-shot-peened (nitrided and then conventionally shot-peened) and (iii) as-SS-treated (nitrided, conventionally shot-peened and finally SS-treated with 50μm nominal diameter steel beads). Thin foil specimens were prepared parallel to the transverse cross section of the wires. Selected area electron diffraction patterns were also obtained and were attached on the TEM micrographs. The depth from the surface where each electron diffraction pattern was obtained coincides with the pattern depth on each TEM image. The selected area electron diffractions were taken from within a 0.4μm diameter circle.

Fig. 8 TEM micrograph and electron diffraction patterns in the as-nitrided high-strength SOTHN wire surface layer

AS-NITRIDED SPECIMEN - Figure 8 shows a TEMmicrograph of the surface layer of the as-nitrided specimen. As indicated in the dark field image (Fig. 9), the compound layer with a thickness of approximately 1 - 1.5μm at the outermost surface region, is composed of polycrystalline solids with a grain size of approximately 20 - 100nm. Also, its main chemical composition was found to be iron and nitrogen according

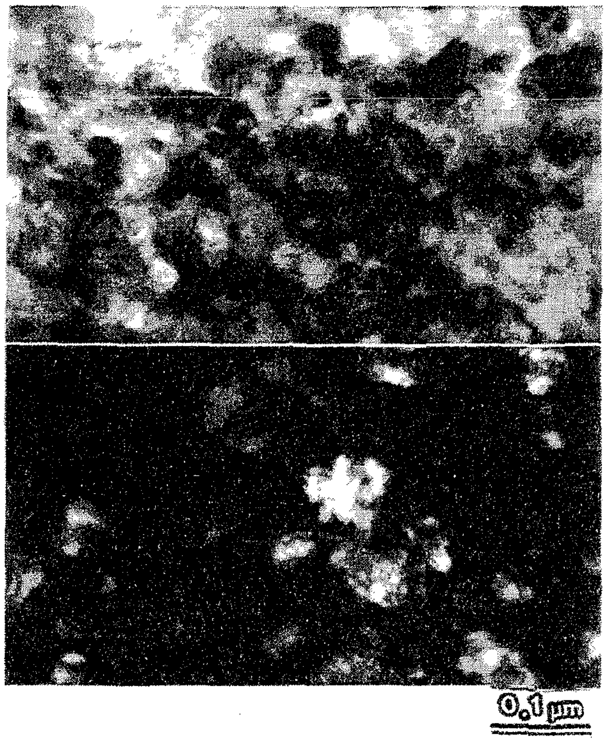

Fig. 9 Bright field image (upper photo) and the corresponding dark field image (lower photo) of the as-nitrided compound layer

to an EDX analysis. The selected area electron diffraction pattern obtained in the vicinity just below the surface (upper diffraction pattern in Fig. 8) indicates that the surface layer is composed mainly of hexagonal close packed ε iron nitride grains. Adding this to the X-ray diffraction analyses shown in Figure 3, the compound layer was concluded to be ε iron nitride. The TEM microstructure of the as nitrided specimen at a depth of approximately 7.5μm below the surface, as shown in Figure 8, indicates that the grain size was around 0.5μm when measured across a tempered martensite lath. The electron diffraction pattern from this area shown in Figure 8 (lower pattern) shows the α iron pattern.

AS-CONVENTIONALLY-SHOT-PEENED SPECIMENS - After conventional shot-peening, TEM micrograhps were taken. Figure 10, which shows one of these micrographs, reveals an approximately 1 - 2μm thick surface layer that was also determined to be polycrystalline ε iron nitride layer, based on the corresponding electron diffraction pattern (upper pattern in the figure) and the X-ray diffraction analysis in Fig. 3. In the nitrogen enriched steel matrix shown in the TEM micrograph below the ε iron nitride layer, strong plastic deformation by shearing, elongation, compression or kinking was not observed apparently. The selected area electron diffraction patterns obtained at a depth of 0.1 - 0.5μm and 7.5μm in Fig. 10 suggest the same conclusion that the distortion by conventional shot-peening is not large enough in the specimen surface layer (the layer up to 10μm below the outer spring surface) when compared with the as-nitrided specimens. This conclusion was obtained because the development of continuous Debye rings especially in the matrix steel was not enough in the electron diffraction patterns in Fig. 10, compared to those in Fig. 8. Comparatively low hardness level of conventional shot-particles (HV550) compared with the

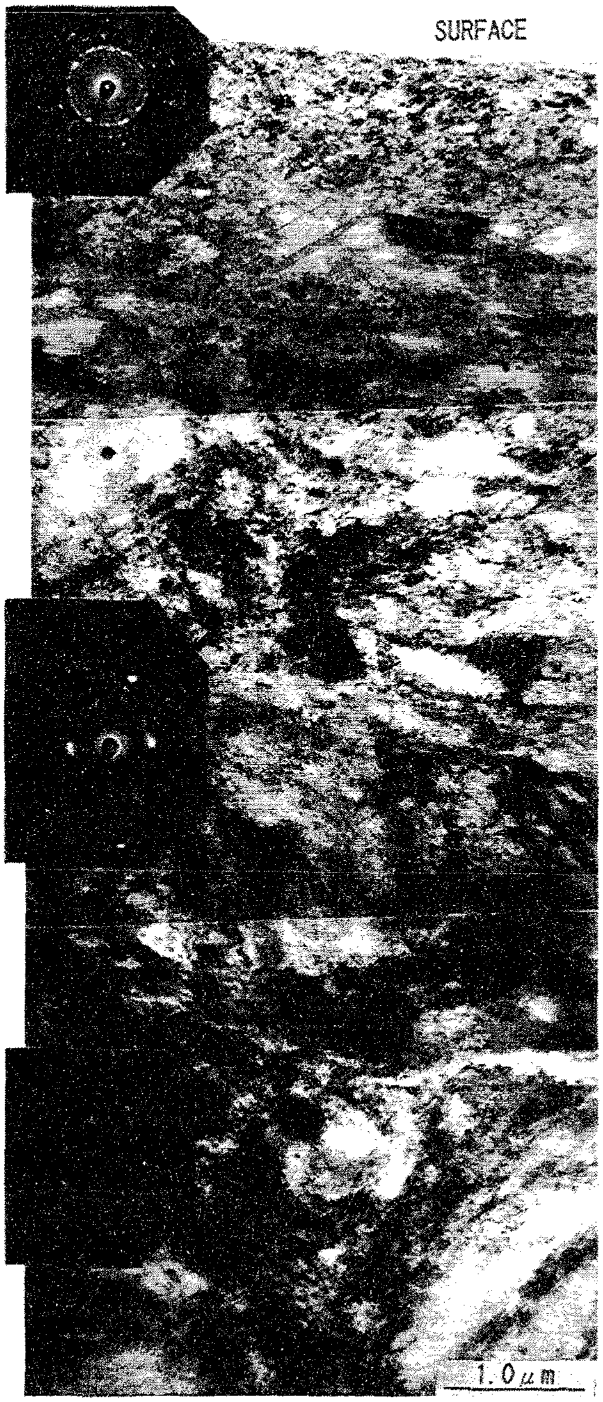

Fig. 10 TEM micrograph and electron diffraction patterns in the surface layer of nitrided and then conventionally shot-peened high-strength SOTHN wire.

Fig. 11 TEM micrograph and electron diffraction patterns in the surface layer of nitrided, conventionally shot-peened and SS-treated high-strength SOTHN wire.

hardness of the nitrided wire surface is considered to be one reason why surface layer large plastic deformation did not occur. However, as shown in the Figures 3 and 5, larger half value widths for most of the diffraction peaks obtained from as-conventionally-shot-peened specimens, as compared with the as-nitrided specimens, indicate the occurrence of larger distortion, finer grain size and/or more frequent stacking fault formation [5, 6]. At the subsurface layer below the nitrogen enriched layer, where the hardness is below around HV550 - HV600, significant plastic deformation is considered to have taken place by the conventional shot-peening and contributed to the compressive residual stress forming to about 0.15mm below the surface.

AS-SS-TREATED SPECIMEN – In the as-SS-treated specimen, comparatively large plastic deformation was observed in the steel below the compound layer to depth of approximately 10μm below the surface (see TEM image in Figure 11). The diffraction spots obtained by selected area electron beam diffraction from this thin foil specimen at depths of 0.1 - 0.5 μm and approximately 8μm formed Debye rings composed of more continuous lines than those found in other specimens. These results indicate that SS Treatment generates a larger number of diffraction spots and/or more diffused and elongated diffraction spots along Debye rings, compared with non-SS-treated processes. It can be concluded from these observations that the larger deformation caused by SS Treatment also caused larger non-uniform distortion, finer grain (cell) size or more frequent formation of stacking faults [5, 6] in the compound layer and in the steel than similar deformations caused by conventional shot-peening. In fact, the grain (cell) size of the SS-treated specimen approximately 7 to 8μm below the surface, as shown in Fig. 11, was determined to be approximately 0.2μm - 30nm across. These grain sizes are far smaller than those found in the TEM micrograph of as-nitrided specimen shown in Fig. 8. Moreover, in the TEM micrograph of the as-SS-treated ε iron nitride compound layer, many fringe patterns were observed as shown in Figure 12. These fringe patterns seem to be either contour lines caused by inclined grain boundaries or stacking faults. It might be possible that some of these are stacking faults generated by deformation by the SS Treatment.

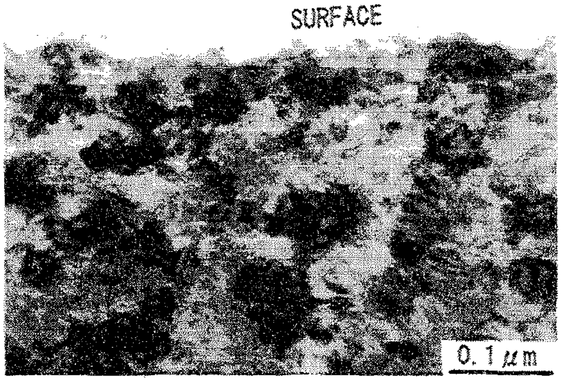

Fig. 12 TEM micrograph of as-SS-treated compound layer.

The temperature rise caused by the collision of each shot particle at and near the shot collided spring surface area is considered to be increasingly significant as the shot particle size is decreased, since the contact time between the two bodies is shortened as the particle size is decreased, resulting in more adiabatic deformation, according to F.P. Bowden and D. Tabor [7].

Consequently, as a result of fine shot particle collision, the spring surface layer temperature rises to warm temperature and the yield point decreases, resulting in the promotion of plastic deformation.

IMPROVED FATIGUE STRENGTH OF SS-TREATED NITRIDED SPRINGS

TEST SPRINGS – The test springs prepared for fatigue tests with the same dimensions as the springs detailed in Table 2 were made from high strength SOTHN wire. With the exception of timing differences, the test spring preparation processes were basically the same as those described in the section entitled EFFECT OF SECOND-STAGE SHOT-PEENING PARTICLE SIZE ON RESIDUAL STRESS AND HARDNESS on page 2. The air pressure in the nozzle of an air-blast type machine used for the second-stage shot-peening was controlled at 0.4MPa. Prior to fatigue tests, second-stage-shot-peened test springs were further cold pre-set. Since the SS-treated springs had the highest compressive residual stress in the spring surface layer as shown in Figure 1, fatigue tests were undertaken on SS-treated springs only (as a result of preliminary fatigue test conducted on 200 μm steel bead bombarded springs as second-stage, a fatigue fracture took place under a repeated stress τ_a of 588MPa and a mean stress τ_m of 686MPa at 2.21 X 10^7 cycles, starting from the surface). Fatigue tests were conducted at 20 cycles per second at room temperature. Six springs were fatigue tested under a same stress condition for each fatigue testing machine.

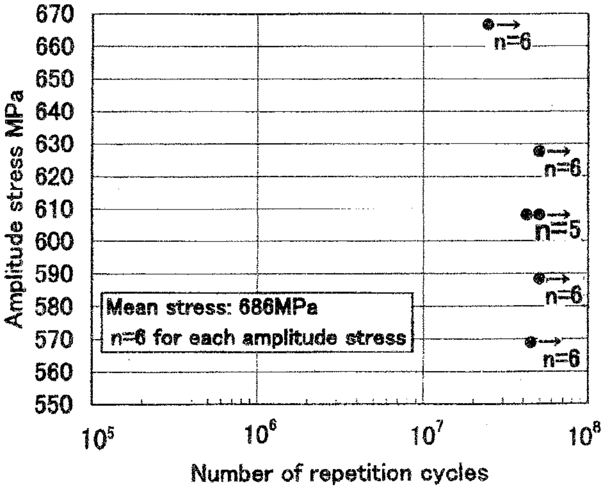

Fig. 13 Fatigue test results for nitrided, conventionally shot-peened and then SS-treated SOTHN springs.

FATIGUE TEST RESULTS – Fatigue tests of the aforementioned prepared springs were made at different amplitude stresses ± τ_a under a constant mean stress τ_m of 686MPa. This τ_m value was used because in similar fatigue tests conducted for nitrided and two or three-stage shot-peened helical springs, 686MPa [2] or 700MPa [3] had been selected as the mean stress. The fatigue test results are shown in Fig. 13. Since there was a fatigue fracture which occurred at N = 4.20 X 10^7 cycles under a stress repetition of 686 ± 608MPa, the fatigue strength of these tested springs at the stress repetition of 5 X 10^7 cycles was determined to be 686 ± 588MPa. The fatigue strength of nitrided, conventionally shot-peened but non-SS-treated high-strength valve springs made of SOTHN wire was reported to be τ_m 588 ± τ_a 529MPa at a stress repetition of 5x10^7 cycles by the Probit method[8]. When determined from the S-N diagram (Fig. 8 in [8]), the fatigue strength is found to be τ_m 588 ± τ_a 549MPa. This fatigue strength is considered to be equivalent to 686 ± 529MPa since the rise of mean stress by $\Delta\tau_m$ is equivalent to a stress amplitude level drop of 1/5 $\Delta\tau_m$ when the fatigue strength of valve springs at a constant cycles of stress repetition is considered. Based on these results, the fatigue strength improvement resultant from the application of the SS Treatment to nitrided and conventionally shot-peened high strength springs was found to be significant. This improved fatigue strength is mainly attributable to the very large compressive residual stress caused by large deformations in the spring surface layer without inducing deleterious surface qualities such as harmful surface micro-fissuring or excessive surface roughness. According to the fractographic investigation of the only one fatigue fracture which occurred at N = 4.20 X 10^7 cycles under a stress repetition of 686 ± 608MPa, the fracture was found to have started from a non-metallic inclusion located at 0.25mm depth below the surface. The residual stress in the surface layer of this fatigue fractured spring was –2033MPa, indicating no significant drop of compressive residual stress during fatigue testing. In contrast, high strength SOTHN valve springs nitrided and conventionally shot-peened were always fatigue fractured from surface [10]. These facts suggest that the SS Treatment can quite effectively prevent fatigue fracture from surface. Moreover, very high compressive residual stress in SS-treated surface layer can stop or delay the propagation of a fatigue crack initiated at a subsurface inclusion [1, 11], resulting in reduced fracture susceptibility to inclusions.

APPLICATIONS

VALVE SPRINGS - When applying the SS Treatment to nitrided valve springs, fatigue strength is improved significantly and as the result, several advantages are obtained for internal combustion engines. First, since the required installation height can be decreased, lower engine height is possible. Second, since the spring weight is decreased as a result of its much smaller cross sectional diameter, the spring load can be reduced. Consequently, lower moving valve train friction is realized, leading to improved fuel economy. Maximum engine rotation speed is also enhanced by increased resonance frequency and lower inertial mass. One way of making use of SS Treatment is to shorten the nitriding time, resulting in a reduction in total cost, without changing the fatigue strength of the finished springs. Besides, nitrided, conventionally shot-peened and SS-treated high strength coil springs can be used as clutch springs and other applications where repeated compressive stress is applied and reduced mass and/or compactness are/is required.

DEVELOPMENT OF NEW HIGH STRENGTH STEEL SOTHS WIRE AND ITS APPLICATION TO ACCUMULATOR SPRINGS - In order to meet the demand for better fatigue strength, newly developed high strength valve spring steel SOTHS wire was applied to high strength valve springs. This steel wire has a chemical composition characterized by a higher silicon, manganese and vanadium content than conventional high strength valve spring SOTHN wire. One typical chemical composition in the steel is 0.60 C – 2.00Si – 0.88Mn – 0.24Ni – 1.00Cr – 0.10V (mass%). The higher silicon, manganese, chromium and vanadium in the SOTHS wire (see Table 1) allows for spring nitriding at higher temperature than the conventional high strength SOTHN wire springs [9]. As a result, higher compressive residual stress and higher hardness are obtained in the surface zone of nitrided SOTHS wire springs, resulting in a much higher fatigue strength. SOTHS wire with a diameter of 3.2mm was cold-wound to form helical springs with the same dimensions as given in Table 2. Then both ends of the cold wound springs were ground down to make seats. The resultant springs were then nitrided, shot-peened with cut steel wires with a diameter of 0.6mm, SS-treated, tempered and finally cold set. Fatigue test results for these springs are shown in Figure 14.

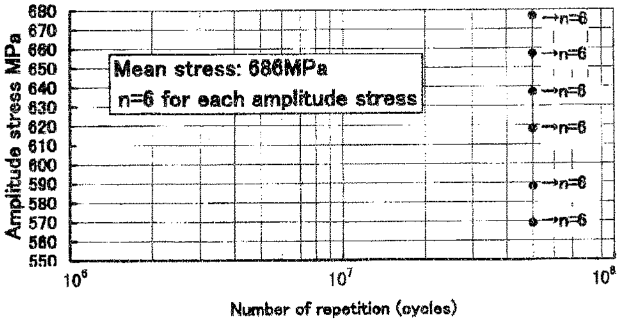

Fig. 14 Fatigue strength of newly developed nitrided, shot-peened and SS-treated SOTHS wire springs.

The results shown in Figure 14 indicate that the fatigue strength obtained was more than 686 ± 677MPa at a stress repetition of $5X10^7$ cycles, although the number of tested springs per each amplitude stress level was limited to 6 pieces (it was impossible to conduct fatigue tests at higher amplitude stress since the repeated contacts between neighboring wire turns in a spring during fatigue tests were unavoidable). This fatigue strength level seems to be superior to those reported in previous papers for nitrided high strength helical springs [2, 3]. The nitrided, conventionally shot-peened and SS-treated SOTHS springs used as an accumulator springs in automobile automatic transmissions instead of the conventional non-nitrided, conventionally shot-peened chromium silicon steel oil-tempered wire (JIS SWOSC-V, SAE 9254) springs could reduce the spring mass by 57%. Table 3 shows the material grades and dimensions of these two types of springs. Figure 15 shows photographs of both kinds of springs. A detailed quality analysis (residual stress distribution etc) for the newly developed SOTHS springs will be reported on in a later paper.

Table 3 Comparison of two accumulator spring types.

	Conventional (non-nitrided and non-SS-treated)	Newly developed (nitrided and SS-treated)
Material grade	JIS SWOSC-V (CrSi or SAE 9254)	SOTHS (newly developed)
Wire diameter	3.2mm	2.7mm
Free height	82.7mm	49.3mm
Total coil number	14.0 turns	8.75 turns
Mass	42.2gr	18.1gr

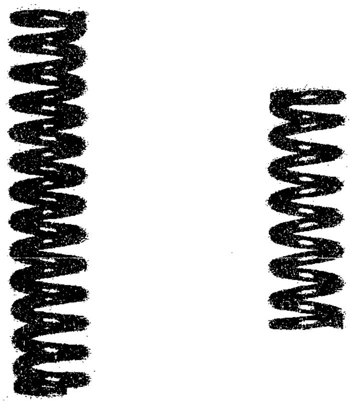
Conventional Newly Developed

Fig. 15 Automatic transmission accumulator springs.

CONCLUSIONS

Using gas-nitrided high strength valve springs made of high strength valve spring SOTHN wire, SS Treatment effects on spring properties were investigated and the following conclusions were obtained.

1. A compressive surface residual stress in the matrix steel as high as 2,000MPa could be obtained through the application of SS Treatment.
2. The hardness at the surface layer tended to increase as a result of SS Treatment.
3. Comparatively large plastic deformation in the surface layer matrix steel of a nitrided, conventionally shot-peened and SS-treated springs was confirmed

by both TEM observation and X-ray diffraction peak broadening.

4. The high compressive residual stress and the high hardness in the SS-treated surface layer were considered to be caused by large deformations in the layer.

5. The fatigue strength obtained for the nitrided, conventionally shot-peened and SS-treated high-strength SOTHN valve springs was 686 ± 588MPa at a stress repetition of $5X10^7$ cycles, as compared to 686 ± 529MPa for non-SS-treated springs [8].

6. The compound layer formed on the surface of the SOTHN wire by nitriding with a thickness less than a few microns, was found to be poly-crystalline ε iron nitride composed of individual crystal grains ranging from 20 to 100nm across.

A brief introduction of the new high strength oil-tempered SOTHS wire and the fatigue strength of the gas-nitrided, conventionally shot-peened and then SS-treated coil springs made from this new grade of wire was made and the following results were reported.

7. A fatigue strength of more than 686 ± 677MPa was obtained at a stress repetition of $5X10^7$ when fatigue testing nitrided, shot-peened and SS-treated SOTHS coil springs, although the number of tested springs was limited to 6 pieces for each test stress level.

8. As an application of the nitrided, shot-peened and SS-treated SOTHS springs, an accumulator spring application example was briefly introduced in which the mass of each individual spring was reduced by 57% as compared with conventionally shot-peened chromium silicon steel oil-tempered wire springs.

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