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Recent Progress with Nitrided Valve Springs for Automobile Internal Combustion Engines

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ABSTRACT

The gas-nitriding characteristics of valve springs made from three different grades of oil-tempered wires were investigated as a preliminary study, and the springs made from the most heat resistant grade of oil-tempered wire (SOTHS) were selected for further study. As a result, fatigue limit strength as high as 736MPa (mean stress) +/- 665MPa (amplitude stress) at a stress repetion of 5×10^7 cycles was obtained by applying gas-nitriding, followed by multi-stage shot-peening, the last stage of which was very fine steel bead peening with the average size less than 50 μm (SS-Treatment). The reasons for the high fatigue endurance obtained are also discussed.

INTRODUCTION

In the previous papers by the present authors, it was reported that considerable improvement in both fatigue strength and surface compressive residual stress can be obtained by peening with fine steel beads with the mean diameter less than ϕ 50 μm (This treatment is also referred to as "SS-Treatment" in this paper) to the normal shot-peened (with ϕ 0.6mm diameter cut steel wires) non-nitrided high strength SOTHN wire valve springs [1], to the normally shot-peened gas-nitrided high strength SOTHN wire valve springs or to the normally shot-peened gas-nitrided high strength SOTHS wire valve springs [2]. More precisely, the average diameter and the average hardness of the fine shot particles used in the SS-Treatment for the second shot-peening in these papers were reported as ϕ 43 μm and around HV 850, respectively. In the first part of the present paper, helical springs made from different valve spring steel wire grades, i.e., the conventional JIS SWOSC-V wire (Valve spring quality CrSi steel oil-tempered wire, where CrSi steel is identical to the steel grade SAE9254.) and two kinds of high strength valve spring quality steel wires, i.e., SOTHN [1, 2] wire and the newly developed SOTHS wire [2, 3], were gas-nitrided under the same conditions and the effects of these three kinds of different steel wire grades on the resultant nitriding characteristics were investigated. Since it was found that the new high strength grade SOTHS wire valve springs nitrided had the highest surface layer and core hardness among these three grades of wires, and as a result gave the best resistance to the stress relaxation of the nitrided springs, only the high strength SOTHS wire valve springs were used for the following fatigue research. However, in the last paper by the present authors [2], since the gas-nitrided and two stage shot-peened high strength SOTHS wire valve springs (i.e., conventional shot-peening followed by SS-Treatment) were reported to be free of fatigue-fracture even after repetition in the highest stress range as high as τm 686MPa (τm: mean shear stress) +/- τa 667MPa (τa: amplitude shear stress), the so-called S-N curve and the fatigue limit stress could not be obtained. The hardness and residual stress distributions in these nitrided and two stage shot-peened SOTHS wire springs, which were not included in the previous paper [2], are reported in the present paper. Then, in the present fatigue research, the wire diameter and the dimensions of the SOTHS wire springs to be used for fatigue testing were selected so as to allow fatigue-testing at higher stress levels than the ϕ 3.2mm SOTHS wire nitrided springs reported in the previous paper [2], and at the same time, in order to successfully obtain an S-N curve. Also in the present study, the nitriding condition was modified to such an extent that higher core hardness can be obtained compared with the springs reported in the previous paper. Specifically, the nitriding temperature was decreased to 703K and the time was shortened to 3hrs in the present research, compared with 723K and 7hrs in the previous investigation [2]. In the previous paper by the present authors [2], the first-step shot-peening after gas-nitriding was performed using cut steel wires with a diameter of ϕ 0.6mm. The shot-peening condition was also modified in the present study from the condition adopted in the last paper [2] in order to get compressive residual stress deeper in the spring surface layer. In the final stage, the SS-Treatment was applied. As a result, at the stress repetition of 5×10^7 cycles, fatigue limit stress as high as 736MPa +/- 687MPa or 736MPa +/- 665MPa was obtained from the

S-N curve or by the Probit method, respectively. The residual stress and hardness distributions, and also the surface roughness were measured. Based on these investigations, the reasons for the high fatigue strength obtained are discussed in the latter part of this paper.

TESTED MATERIALS AND EXPERIMENTAL METHODS

TESTED MATERIALS

The wire grades used in the first part of this study were conventional grade wire JIS SWOSC-V, two high strength grade SOTHN and SOTHS wires. All of these wires were manufactured on the normal valve spring wire production line in the Kyoto Plant, Suncall Corp. as valve spring quality wires, i.e., hot rolled wire rods (raw materials) were surface shaved, heat-treated, acid-pickled, wire-drawn to final diameters and oil-tempered. The chemical compositions of these wires are listed in Table 1. The supplied SWOSC-V and SOTHN wires had a diameter of ϕ3.2mm and the SOTHS wire ϕ 4.0mm. In addition to these wires, the chemical composition of another SOTHS wire with a diameter of ϕ 3.2mm, which was studied in a previous report [2], is listed in Table 1. The tensile strengths of these wires as-supplied are given in Table 2 except the ϕ 3.2mm SOTHS wire.

Table 1. Chemical compositions of wires used Mass %

Wire Grade	C	Si	Mn	Ni	Cr	V
SWOSC -V (9254)	0.55	1.40	0.70	0.03	0.65	-
SOTHN	0.58	1.49	0.70	0.29	0.84	0.07
SWOHS ϕ4.0mm	0.60	1.98	0.87	0.26	0.98	0.09
SWOHS ϕ3.2mm	0.56	2.06	0.91	0.29	0.97	0.11

Table 2. Tensile strengths of different grade wires used

Wire Grade	Wire Diameter mm	Tensile Strength MPa	Reduction of area at tensile fracture %
SWOSC-V	3.2	1,943	56.5
SOTHN	3.2	2,091	51.5
SOTHS	4.0	2,164	38.6

EXPERIMENTAL METHODS

Gas-nitriding characteristics of springs made from three grades of steel wires

In order to study the effect of steel wire grade on gas-nitriding characteristics, three kinds of wires listed in Table 2 were cold-wound to helical springs, stress-relief tempered at 708K for 20min, descaled, gas-nitrided at 703K for 180min, shot-peened and tempered for strain aging at 493K for 20min. The dimensions of the springs produced are listed in Table 3. The shot-peening condition for the SWOSC-V, and SOTHN wire springs was as follows: Cut steel wires with a diameter of ϕ 0.6mm and a hardness of HV 550 were shot on the spring surface at a speed of 72m/sec for 40min. For the ϕ 4.0mm SOTHS springs, more intense shot-peening was applied by using ϕ 0.8mm round cut steel wires with high hardness, and in the final-stage, the SS-Treatment was practiced for 20min. After the shot-peening, all the springs were tempered at 493K for 20min for strain aging and then cold pre-set at 1,294MPa. Using these finished springs, the hardness and nitrogen distributions at the surface layers were investigated, and the stress relaxations were tested by spring clamping tests. In measuring hardness distributions, the chord method [3] was applied and a micro-Vickers hardness tester was used for hardness measurement. The load applied for the hardness indentation was 2.94N (300grf) except for the outermost surface indentation where a 0.98N (100grf) load was applied. The nitrogen distributions in the surface layer were analyzed using an X-ray micro-analyzer, type JXA-8800RL from JEOL. The measurement of the nitrogen content in the spring

Table 3. Dimensions of springs tested

Wire grade	SWOSC-V SOTHN	SOTHS
Wire diameter (mm)	3.2	4.0
Mean coil diameter (mm)	21.2	22.0
Total number of coils (turns)	6.5	6.5
Active number of coils (turns)	4.5	4.5
Free height (mm)	53	53

surface layer was made on a polished cross section of each spring in terms of the line analysis method starting from the spring surface to a depth of approximately 0.14mm below the surface, under the condition of the electron beam acceleration voltage of 15kV and a current of 0.3 μA. The spring clamping tests were conducted as-follows: The test springs were compressed to a predetermined height with a steel nut and bolt, were then held in an oven kept at 393K for 48hrs and then cooled to room temperature. After that, the load loss ΔP of the tested spring brought about by the heating at 393K for 48hrs was measured and the γ (in Japan, γ is called "residual shear strain", that is proportional to the load loss ΔP and means the elastic shear strain caused by the load loss ΔP if it occurred all due to elastic deformation, or the shear stress relaxation divided by shear modulus.) was calculated as follows;

$$\gamma = 8D\Delta P/ (\pi d^3 G) X100 (\%)$$

Where D: Mean spring diameter

ΔP: Load loss

d: Wire diameter

G: Shear modulus

Spring fatigue test

Following the experimental studies to compare the properties of the nitrided springs described above, the most heat resistant ϕ4mm SOTHS wire nitrided springs with the best characteristics were fatigue-tested, of which the production processes were the same as those explained in the previous paragraph. The spring fatigue tests were performed using hydraulic servo-pulser type machines. The speed of stress cycling was 1,200rpm. Each fatigue test was conducted until $5X10^7$ cycles when no fracture took place during the test.

Hardness measurement by Nano-Indenter

In the measurement of hardness distributions across an adiabatic shear band using a nano-indenter XP from MTS systems Corp., each hardness was determined at an indentation depth of 300nm below the specimen surface during indentation of a diamond triangular cone (called Berkovich indenter) under vibration [4].

Residual stress distributions

Residual stresses were measured using a PSPC micro-area X-ray residual stress analyzer from Rigaku Corporation. Chromium Kα irradiation and (211) α–iron X-ray diffraction peaks were used for the analyses.

EXPERIMENTAL RESULTS

STEEL WIRE GRADES AND THE NITRIDING CHARACTERISTICS

Nitrogen content in the surface layer in each gas-nitrided spring is shown in Figure 1. It was found that the depth of the nitrogen penetration beneath the spring surface or the thickness of the nitrided layer is around 80 μm irrespective of the wire grades tested. The nitrogen contents in the outermost surface layers were found to be approximately 1.9, 3.0, and 6.9 mass % for the SWOSC-V, SOTHN, and SOTHS wire springs, respectively. This indicates that in the outermost surface layers of all the nitrided springs in Figure 1, iron nitride (probably *ε-iron nitride* $Fe_{2\text{-}3}N$) particles and/or layers were formed (pure ε iron nitride contains approximately 7.7 to 11.1 mass % nitrogen, according tothe chemical composition ranging from Fe_3N to Fe_2N) since percentage of nitrogen in solid solution in α iron is far less than 1.9 mass%. The hardness distributions measured for different steel wire grade springs nitrided

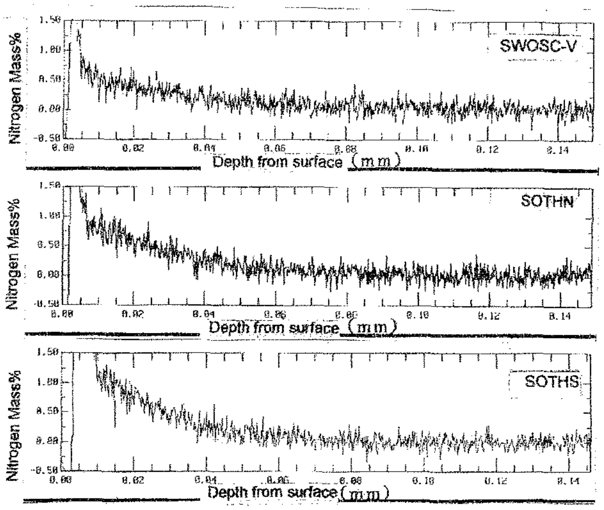

Figure 1. Nitrogen contents in the surface layer by linear analysis with an X-ray micro-analyzer

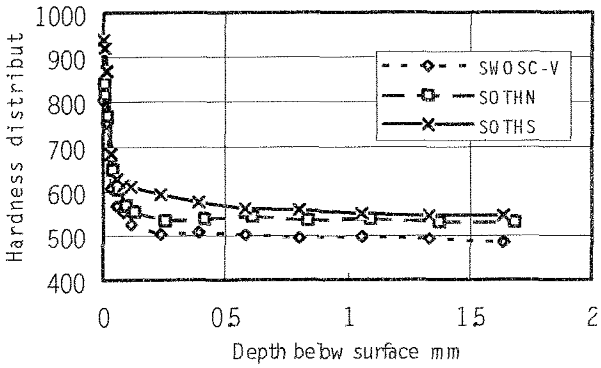

Figure 2. Micro Vickers hardness distributions in gas-nitrided springs. (Nitriding condition: 703K for 3hrs, load: 0.98N for the outermost surface indentations, and 2.94N for other indentations)

at 703K for 3hr, shot-peened, tempered for strain aging, and pre-set are shown in Figure 2. It was found that the SOTHS, the SOTHN, and the SWOSC-V (CrSi steel) wire springs have core hardnesses of approximately HV550, HV530, and HV490, respectively. When comparing the surface hardness among these three kinds of springs, the SOTHS spring has the highest value and the SWOSC-V spring has the lowest value. It should be noted that the hardness near the spring surface is influenced not only by the nitrogen content but also by the shot-peening condition. According to Y. Oki et al [5], of all the tensile strengths obtained after heating, quenching to oil, and tempering at a certain condition, the highest tensile strength obtained was in the steel grade equivalent to the SOTHS wire, followed by the high-carbon SAE 9254 steel wire that was not tested in the present study, and the SAE9254 wire that is equivalent to the SWOSC-V wire, had the lowest tensile strength among the three grades of steels tested. The increased amount of carbon, chromium, vanadium, and silicon in SOTHS wire compared with the other steel wires is reported to contribute to the increased high hardness [5]. Some of these nitrided springs made from the three kinds of wire grades in this study were subjected to the spring clamping test at 393K for 48hrs and their stress relaxation properties were checked. Figure 3 shows the results obtained. Plotted data in this figure clearly indicate the superiority of the nitrided SOTHS wire springs compared with the other grades of wire springs. Preserving a high hardness in the core portion in the gas-nitriding process is considered to be an important factor to attain an excellent resistance to stress relaxation in nitrided springs.

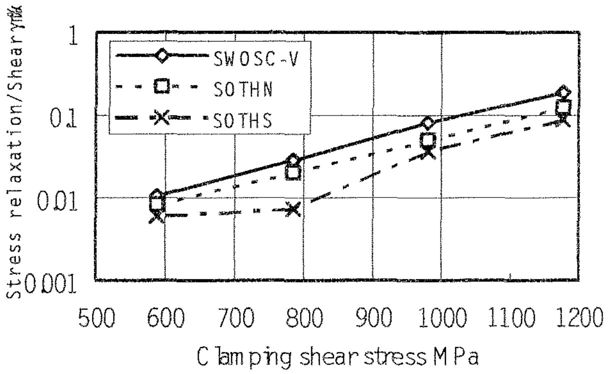

Figure 3. Spring clamping test results for gas-nitrided springs made from different wire grades (393K, 48hrs)

PREVENTION OF MICRO CRACKS FORMATION IN SHOT-PEENING

It is well known among engineers specializing in spring technology that springs shot-peened with particles with an excess kinetic energy normally end up with inferior fatigue strength and rougher spring surface than springs shot-peened under proper conditions. Such an over-intense shot-peening is sometimes called over-peening. Figure 4 shows an example of a cross section of an over-peened SOTHS wire spring. It clearly shows a micro-crack generated along an white-etching adiabatic shear band [6, 7], existent in the non-nitrided spring surface layer. This kind of adiabatic shear band is a trace of localized shear deformation in metals and alloys as a result of high-strain-rate cold working to large plastic strain. Hardness traverses by a nano indenter were made across an adiabatic shear band in an over-peened SOTHS wire spring, and the results are plotted

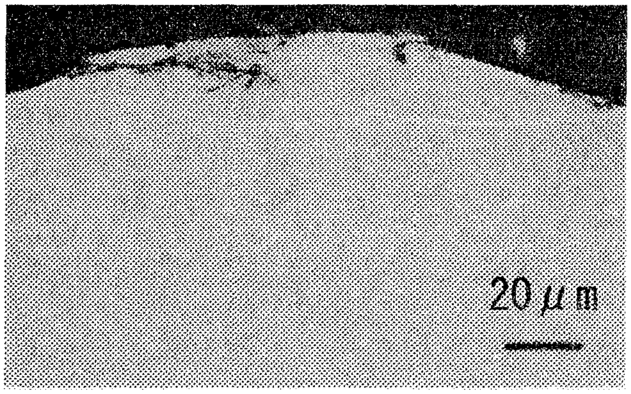

Figure 4. An example of a micro-crack produced in a SOTHS wire spring by over-peening (an optical micrograph of a wire cross section nital-etched).

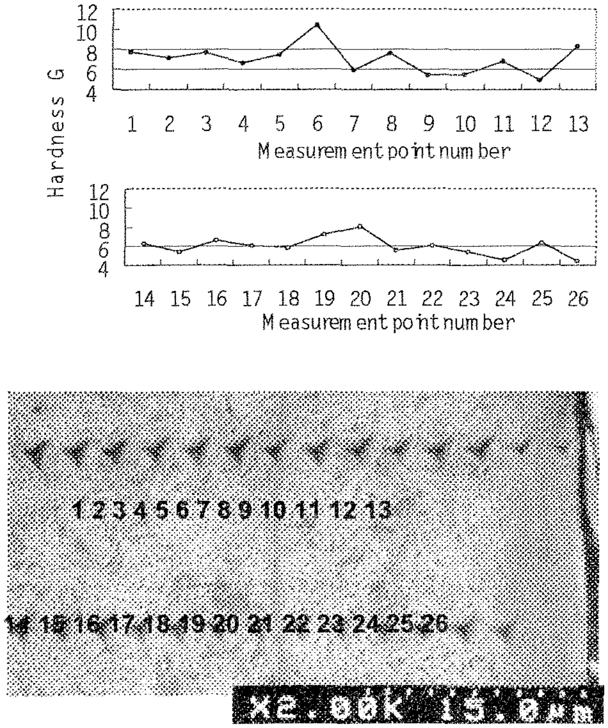

Figure 5. Hardness distributions across a shear band by a nano indenter (upper figures) and the corresponding SEM image with indentations for the hadness measurements (lower photo.). A dark-colored vertical line crossing the point 6 is the shear band. The right hand side in the SEM image is the surface.

along with an SEM image in Figure 5. The numerical numbers in the SEM image indicate indentations corresponding to the measurement point numbers in the hardness distribution figures. In this case, the shear band at the measurement point 6 is found to have very high hardness i.e. 10.37GPa (equivalent to HV 964), which was caused by strain hardening in the localized narrow heavy shear band, rather than hardening by martensite transformation, according to SEM observations with higher magnifications (for example, Figure 6).

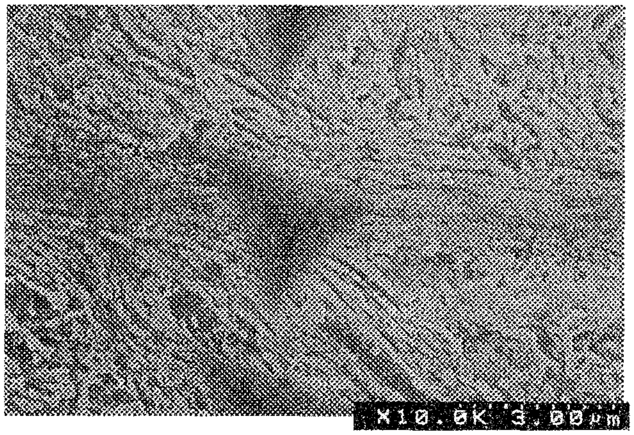

Figure 6. An SEM image showing a shear band and an indentation impressed on the band (corresponds to the measurement point 6 in Figure 5).

It is plausible that such a shear band with extremely high hardness is easily cracked, because of its brittleness due to excess plastic working suffered by the band. In fact, the non-nitrided SOTHN wire shot-peened under the same shot-peening conditions as those given in Figures 4 and 5 had an inferior fatigue strength than those shot-peened with the most appropriate intensity according to the rotating beam type wire fatigue testing. Even such a micro-crack in surface layer, which does not have a detrimental effect on the fatigue properties of the non-nitrided valve spring used under rather low applied stress repetition, can possibly propagate and cause fatigue fracture if it exists in a nitrided valve spring on which is exerted such a high applied repeated stress that does more than cancel the compressive residual stress, since a micro-crack tends to propagate more easily as the hardness in the spring surface layer is increased. Specifically, in the case of nitrided valve springs, since their surface layer hardness is much harder than non-nitrided valve springs, the critical micro-crack size above which fatigue fracture takes place or the critical ΔK value [1] for fatigue crack propagation is inversely proportional to the matrix hardness around the micro-crack, although higher compressive residual stress in the nitrided spring surface layer tends to decelerate or stop the crack propagation by decreasing the actual tensile stress around the micro-crack [8]. It is important to note that not all shear bands adjacent to spring surfaces generate surface micro-cracks, but excessively intense shot-peening seems to generate micro-cracks along with shear bands. However, with the conventionally produced valve springs used under normal stress conditions, the effect of adiabatic shear bands on the fatigue strength is thought to be harmless or unimportant. In the previous papers, it was also reported that carburized alloy steel specimens shot-peened under extremely high intensity conditions with adiabatic shear bands in their surface layers do not deteriorate the fatigue strength [9], or the effect of shear bands is minimal on the fatigue strength of a titanium alloy [10]. In preparing both the ϕ 3.2mm and ϕ 4.0mm SOTHS wire springs in this study, shot-peening was conducted so as to produce surface compressive residual stress as high and deep as possible, but not to produce surface micro-cracks and to minimize the generation of adiabatic shear bands.

PROPERTIES OF GAS-NITRIDED SOTHS SPRINGS

SOTHS springs gas-nitrided at 723K for 7hrs

In the previous paper by the present authors [2], fatigue test results were reported on ϕ3.2mm SOTHS wire springs gas-nitrided at 723K for 7hrs. In the present paper, the same figure is presented again in Figure 7, according to which no fatigue fracture took place even at the highest repeated stress of τm 686 +/- τa 677MPa fatigue-tested. The hardness distribution in this spring is shown in Figure 8. The hardness at a depth of

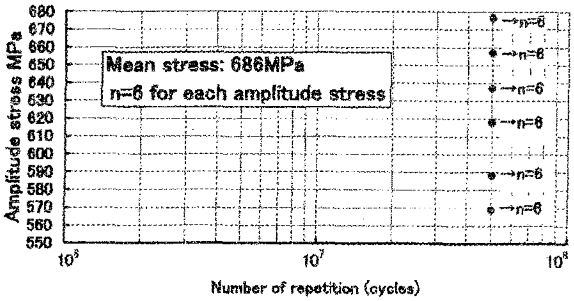

Figure 7. Fatigue test results on ϕ 3.2mm SOTHS springs gas-nitrided at 723K for 7hrs, shot-peened, SS-treated, tempered for strain aging and cold pre-set.

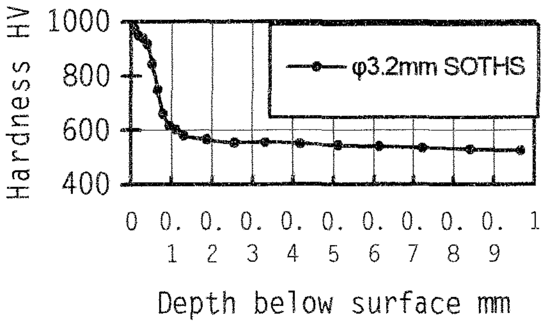

Figure 8. Hardness distribution in a ϕ3.2mm SOTHS wire spring gas-nitrided at 723K for 7hrs, shot-peened, and SS-treated.

0.97mm below the surface is HV524, which is lower than the hardness HV550 obtained at a depth of 1.05mm below the surface in the ϕ4mm SOTHS wire springs nitrided at 703K for 3hrs (Figure 2). The residual stress distribution measured for the ϕ 3.2mm SOTHS wire gas-nitrided springs is shown in Figure 9. The data in Figure 9 were obtained for the ϕ 3.2mm SOTHS wire gas-nitrided spring as SS-treated and non strain-aged. The sharp rise in compressive residual stress in the vicinity of the spring surface was caused by the SS-Treatment. After tempeing a ϕ 3.2mm SOTHS nitrided, shot-peened and SS-treated spring at 493K for 20min, the outermost surface compressive residual stress measured was decreased to around 1,600MPa from 2,035MPa (Figure 9) obtained for an as-SS-treated spring.

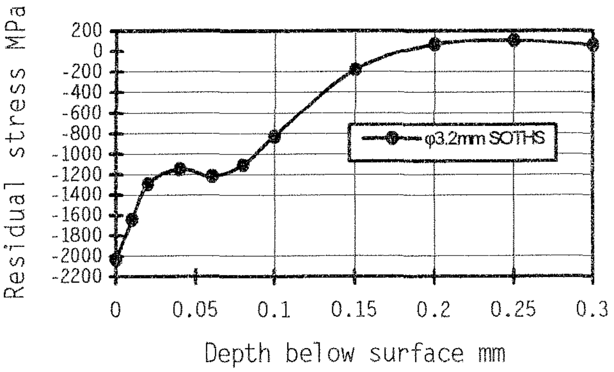

Figure 9. Residual stress distribution in a gas-nitrided ϕ 3.2mm SOTHS wire spring as-SS-treated. The nitriding condition: 723K for 7hrs

ϕ4mm SOTHS wire springs gas-nitrided at 703K for 3hrs

It is recognizable that the ϕ4mm SOTHS wire gas-nitrided spring has a lower surface layer hardness (Figure 2) than that of the 3.2mm SOTHS wire gas-nitrided spring (Figure 8). This difference in surface layer hardness between them was primarily caused by the differing nitrogen contents in the nitrided layer owing to the differing nitriding conditions. Figure 10 shows the residual stress distribution in the surface layer in the ϕ 4mm SOTHS wire spring which was nitrided at 703K for 3hrs, shot-peened, SS-treated, tempered at 493K for 20min, and then cold pre-set. The compressive residual stress of 1,700MPa in the outermost surface layer in this spring is noted to be smaller than that of 2,035MPa obtained for the ϕ3.2mm SOTHS spring plotted in Figure 9 but larger than that tempered for strain aging at 493K for 20min. The residual stress distribution at the outermost surface layer are considered to be influenced by various factors: First, higher nitriding temperature and longer nitriding time both increase the surface compressive residual stress, second, shot-peening condition also affects it, and third, tempering for strain aging after shot-peening decreases the surface compressive residual stress. The ϕ 3.2mm SOTHS spring of which residual stresses were plotted in Figure 9 was nitrided at a higher temperature and for a longer time but shot-peened less intense than the ϕ4.0mm SOTHS wire nitrided spring, and not tempered after the SS-Treatment. The ϕ 3.2mm nitrided springs non-tempered for strain aging at 493K for 20min, also did not fatigue fracture at all (tested spring numbers n=6) under the stress repetition at 686 +/- 677MPa until to the $5X10^7$ stress cycles, probably because of very high compressive residual stress in the surface layer. This seems to suggest that the tempering for strain aging at around 500K for the SS treated nitrided springs does not deteriorate the fatigue life or strength, probably because the decreased compressive residual stress in the spring surface layer is compensated by the stronger dislocation locking in α iron by enriched nitrogen atoms in solid solution, which is expected to prevent slip band formation that causes micro-crack generation under tensile stress. In Table 4, the surface roughness measured by a surface measuring instrument with a stylus on the spring inside surface, is presented. All the fatigue tests were conducted under a mean stress τm= 736MPa at room temperature. Fatigue test results for the ϕ 4mm SOTHS wire gas-nitrided springs are plotted in Figure 11. In the fatigue test conducted at the amplitude stress τa=726MPa, all four springs fatigue-fractured from their surface. In the fatigue test at the amplitude stress τa=706MPa, a spring fractured starting from a sub-surface non-metallic inclusion at $1.5X10^7$ cycles, other two springs fractured starting from their surface at $1.5X10^7$ cycles and at $3.0X10^7$cycles respectively, and the remaining three springs did not fracture until $5X10^7$ cycles. At the lowest amplitude stress fatigue-tested, i.e., τa=667MPa, no spring fracture took place among 6 springs fatigue-tested. From these results, the fatigue limit stress at $5X10^7$

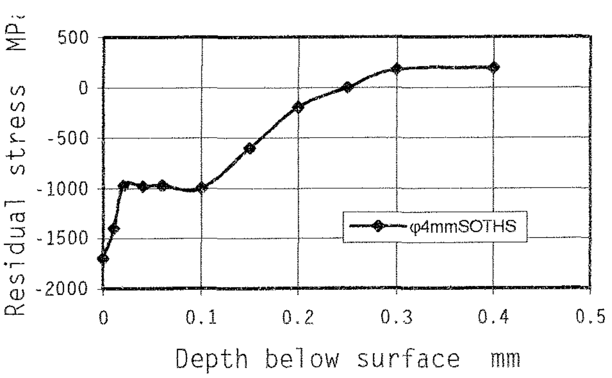

Figure 10. Residual stress distribution in ϕ 4mm SOTHS wire gas-nitrided spring

Table 4. Surface roughness of a ϕ4mm SOTHS gas-nitrided spring (Mean value from six measurements)

Ry	Rz
7.83μ m	3.05 μm

cycles is determined to be 736MPa +/- 687MPa, according to the method (b) in 6.11(2) in JIS Z2273 "General rules for fatigue testing of metals", by which rule, fatigue limit amplitude stress is determined as the mean value of the maximum amplitude stress where no fatigue fracture took place and the lowest amplitude stress where at least one specimen fatigue fractured. In order to statistically determine fatigue limit stress at 5X10^{7}cycles of stress repetition, analysis of fatigue data by the Probit method was also made. As a result, fatigue limit stress was determined to be τm 736MPa +/- τa 665MPa at μ - 4σ, or 99.994% survival, where μ is the mean amplitude stress and σ is the standard deviation.

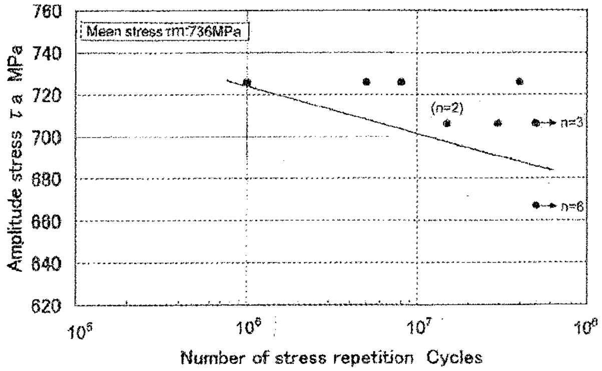

Figure 11. Fatigue test results on 4mmSOTHS wire springs gas-nitrided, shot-peened, SS-treated, tempered and cold pre-set.

DISCUSSION

CAUSES OF HIGH FATIGUE LIMIT STRESS OBTAINED

Factors to improve fatigue strength

There are many factors to be considered in obtaining very high fatigue strength in valve springs. Generally, in order to avoid fatigue fracture from sub-surface hard non-metallic inclusions, it is necessary to add high compressive residual stress deep or high in the spring surface layer. In realizing this, improved shot-peening utilizing shot particles with a rather large diameter and/or higher hardness and in some cases gas-nitriding is applied in valve spring production. Figure 12 is a SEM image indicating the sub-surface fracture origin in the fish-eye pattern, taken on the fatigue fracture surface from a spring stressed at the amplitude stress τa=706MPa and fractured at 1.5X10^{7} cycles. The depth and the size of the non-metallic inclusion at the fracture origin were 0.35mm and 30μm respectively. It seems to be important to recognize that the crossing point in residual stress distribution where the residual stress becomes zero (in the fatigue tested ϕ4mm SOTHS wire gas-nitrided springs, it is around 0.23mm below the surface) is far deeper than the thickness of the nitrided layer (in this study, it is around 80 μm below the surface as is shown in Figure 1). The crossing point depth can be further increased by the improvement of nitrided spring production process though not reported in the present paper. To enhance compressive residual stress in the spring surface layer including from the surface to the crossing point, is another countermeasure to prevent fatigue fracture from sub-surface harmful non-metallic inclusions and from surface micro-cracks [8] by stopping or decelerating fatigue crack propagation there. Nitriding and the SS Treatment are examples of such measures. Of course, it is also necessary to decrease the size and quantity of harmful non-metallic inclusions in steel making and solidification processes in steel mills.

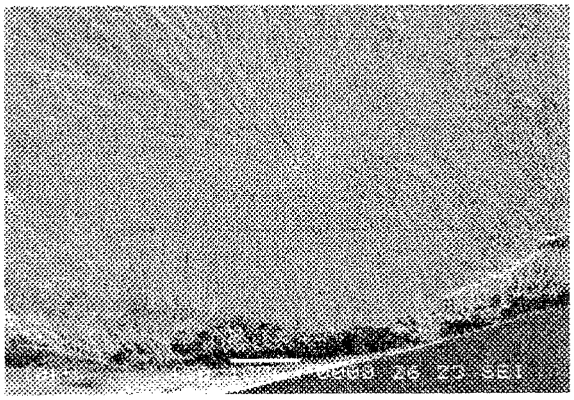

Figure 12. SEM image showing fatigue fracture from a non-metallic inclusion. Specimen: ϕ4mm SOTHS gas-nitrided spring fatigue fractured at the amplitude stress 706MPa and 1.5X10^{7} cycles. The length of the white bar in the image is 100μm.

It is also very important to avoid producing harmful defects such as surface micro-cracks or notchs in spring production processes, e.g. spring coiling and shot-peening. In the normal shot-peening process applied to non-nitrided springs, adiabatic shear band formation is known to occur frequently and its formation in the spring surface layer does not inversely affect the spring fatigue characteristics as far as their micro-crack size is smaller than a certain value. Even if shear band formation occurs in the surface layer by shot-peening, it may not be harmful in fatigue of the spring when no micro-crack(s) is (are) produced at the end(s) of the band. In this study, especially in preparing ϕ4mm SOTHS wire gas-nitrided springs for fatigue testing, such adiabatic shear bands with micro-cracks were prevented by adjustment of the shot-peening conditions. According to the authors' experiences on the SS-treatment, it can be quite an excellent process in that it can add high compressive residual stress in the surface layer without producing any micro-cracks caused by the SS-Treatment. The effect of the SS-Treatment on non-nitrided valve springs and on nitrided valve springs is considered firstly to prevent fatigue fracture from surface and secondly to delay or stop the crack which has progressed to the surface layer from a sub-surface inclusion as was already reported in previous papers [1 & 2].

STRESS RELAXATION

Factors to improve stress relaxation property

Chemical compositions in steel, especially carbon and silicon are known as elements which improve resistance to stress relaxation. Vanadium is known to be an austenite grain size refiner and through refinement of prior austenite grain size can contribute to improved resistance to stress relaxation. It is also important not to hold so called retained austenite in a spring, which is caused by excessive amounts of alloying addition in steel, since it accelerates spring stress relaxation. In the SOTHS wire nitrided springs, no retained austenite remained according to an analysis by X-ray diffraction. The clamping test was conducted at 393K for 48hrs for a 4.0mm SOTHS wire gas-nitrided (at 703K for 3hrs) spring. The result is plotted in Figure 13. In this figure, the clamping test result obtained for the ϕ 3.2mm SOTHS gas-nitrided spring is also plotted for comparison. When comparing these two springs, no big difference in stress relaxation is recognized between them, in spite of the higher core hardness in the ϕ 4.0mm SOTHS gas-nitrided spring than the ϕ 3.2mm SOTHS gas-nitrided spring. The lower core hardness in the latter spring might be counter-balanced by the higher hardness, higher diffusible nitrogen content in the surface layer in the latter compared with the former.

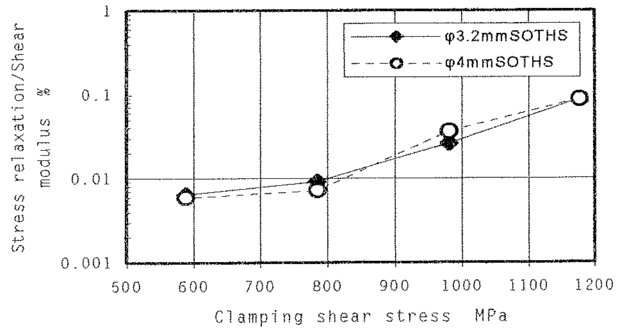

Figure 13. Comparison of warm clamping test results between ϕ 4.0mm SOTHS wire gas-nitrided spring and ϕ 3.2mm SOTHS wire gas-nitrided spring. Testing temperature and time: 393K and 48hrs.

Nitrogen in steel has higher solid solubility in α iron than carbon and can anchor dislocations at room temperature and at around 393K, resulting in smaller relaxation caused by dislocation motion. Another important method to improve the resistance to stress relaxation is applying hot or warm pre-setting instead of applying cold pre-setting.

CONCLUSION

1. The stress relaxation properties of springs gas-nitrided at 703K for 3hrs, made from three kinds of valve spring quality wires (SOTHS, SOTHN, and JIS SWOSC-V) were compared. It was found that the SOTHS wire spring gave the best resistance to stress relaxation. The JIS SWOSC-V (SAE9254) had the worst resistance to it.

2. The core hardness after the gas-nitriding was the highest in the SOTHS wire springs and the lowest in the JIS SWOSC-V spring.

3. The nitrided layer thickness of the three grades of wire springs gas-nitrided at 703K for 3hr, was found to be approximately 80 µm in each case.

4. The depth of the compressive residual stress layer below the gas-nitrided spring surface (=depth to crossing point) after shot-peening was found to be more than 150 µm, indicating the depth to crossing point was increased by shot-peening condition.

5. By the SS-Treatment applied after conventional shot-peening for the SOTHS wire gas-nitrided springs, compressive residual stress as high as 1,700 (for ϕ 4mm spring) to 2,035MPa (for ϕ 3.2mm spring) was obtained at the spring surface.

6. The fatigue limit strength at $5X10^7$ cycles obtained for the ϕ 4mm SOTHS wire gas-nitrided springs was τm 736MPa +/- τa687MPa from the S-N curve and when the fatigue life data were statistically treated, it was τm736 +/- τa 665MPa.

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