Improved Fatigue Strength of Valve Springs and Sheet Springs by Applying a New Surface Treatment Technology

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ABSTRACT

The peening of fine steel beads with the diameter less than 80 micrometers onto spring surface (SS Treatment) was found to improve the fatigue limits of the spring effectively since the surface compressive residual stress and surface hardness were improved significantly. As an example, by applying this technology to the non-nitrided valve springs made from the so-called high tensile oil tempered wire, the fatigue limit was increased to the nearly equivalent level as the nitrided and conventionally shot-peened valve springs made from the same high tensile wire. This means that the SS Treatment can be used as a substitute to the nitriding process in order to improve the fatigue property of valve springs. The improved fatigue strength by applying this technology to nitrided valve springs is also described in this article.

INTRODUCTION

For the increasing demand for better fuel economy and lighter weight car production, automotive engine valve springs and transmission springs with better fatigue limits have been asked from car-manufacturers. The development of the super-clean chrome silicone valve spring steel by Kobe Steel Ltd.[1], and other steel mills introduced the car-manufacturers in the western countries to use this grade for the engine valve springs and contributed to the above mentioned purposes in the past. Following this development, the so-called high tensile grade oil tempered valve spring wires were developed in Japan[2 & 3]. In order to apply the high tensile valve spring wires to the high strength valve springs as an improved substitute to the conventional chrome silicon valve spring quality oil tempered wire, its higher fatigue fracture sensitivity to defects such as non-metallic inclusions and surface flaws due to its higher tensile strength, compared with the conventional chrome silicone grade wires, should be overcome either by giving the spring surface layer larger compressive residual stress or by reducing the size of the defects in the wire. Since the remarkable improvements of the latter, may take some time and be difficult to realize in the steel mills and wire manufacturers now, the former remedies shall be provided. Suncall and Kobe Steel already presented a paper[4] on the effect of surface flaw depth on the fatigue strength of valve springs made from the high tensile grade wire SOTHN which was developed by Kobe Steel and Suncall. It is reported in this paper, that the surface seams with the depth of 0.05mm and less, do not deteriorate the fatigue strength of the valve springs made from the high tensile wires when compressive residual stress is added properly on the surface layer by conventional shot peening process or by nitriding followed by the similar shot peening process.

At the first part of this paper, the features of the SS treatment technology are briefly introduced, taking as an example, the application of this technology to the wave springs produced of flat cold-rolled chrome silicon alloyed steel wires. At the latter part of this paper, the application of this technology to the high strength valve springs produced of the high tensile grade valve spring wires, are reported.

FEATURES OF THE NEW SHOT PEENING TECHNOLOGY : SS TREATMENT

Apparatus and shot particles

The apparatus used for the SS treatment is an air-blast type machine, which utilizes compressed air to propel the shot particles. The apparatus was produced by Fuji Seisakusho Ltd., Tokyo and is called pneuma-blaster, type SG-4BL, which is a tumbler type machine and is operated automatic, and the shot particles are circulated repeatedly. In order to select the most appropriate shot particle size on the fatigue strength, shot particles with different average diameters were bombarded on the wave springs(Fig.1). All the shot particles were composed of either high carbon steel or high speed steel.

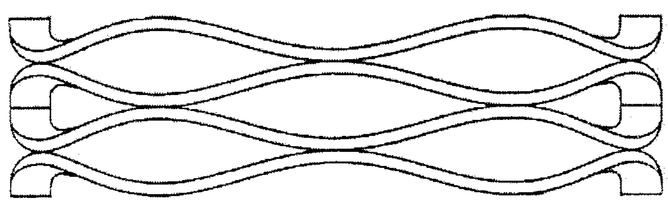

Fig. 1

Fig.1. Schematic view of wave spring tested

The wave springs used at this experiment were made of valve spring quality chrome silicon alloyed steel (Table 1). The steel rod was surface shaved, heat-treated to fine pearlite microstructure, acid pickled, phosphate-coated, cold drawn and then cold rolled to the final flat section of 5.5mm width and 0.97mm thickness. The flat rolled wire was cold-formed to wave spring shape, stress relief tempered to get rid of surface residual tensile stress,

Table 1. Chemical composition of wave springs

Element	C	Si	Mn	P	S	Cr
Mass %	0.57	1.50	0.70	0.013	0.01	0.68

shot-peened with different conditions, cold-set and finally heated at 230C for 20 min. and cooled.

The wave springs thus prepared were fatigue tested and the fatigue limits at the stress repetition of 10^7 times were experimentally obtained. The maximum average stress on the spring surface σ_m ,was 785MPa in all the fatigue tests. Each fatigue limit or the critical stress amplitude σ_{aw}, below which no fatigue fracture took place, was obtained. The fatigue test results are plotted in Fig. 2.

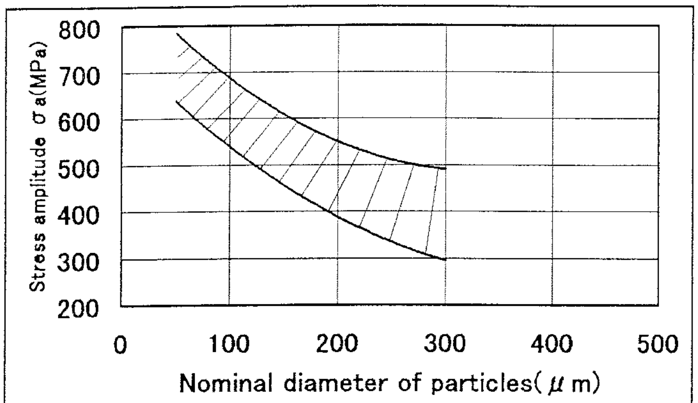

Fig.2

Fig. 2. Effect of nominal shot particle size on fatigue strength of wave spring

This figure indicates that the fatigue strength is improved with the reduction of shot particle size and the best result is obtained when shot particles with the nominal average diameter of 50 micrometers or less is bombarded at the most suitable speed. The shot particles used for the SS treatment are steel beads with the nominal diameter of 50 micrometers or less, which actually have average diameter from 65 to 35 micrometers. Figure 3 is a scanning electron photograph showing the new shot particles with the nominal diameter

Fig.3. New steel beads with the nominal diameter of 50 micrometers.

of 50 micrometers. The actual average size of these particles was 37micrometers and the maximum and the minimum sizes were 75 micrometers and 10 micrometers, respectively, when 60 particles were measured arbitrarily. The average hardness of the new particles was Hv 860 to 865.

Based on these investigation results, it was decided to use the steel beads with the nominal diameter of 50 micrometers or the smaller one for the SS treatment. All the SS Treatment in this investigation to be described below, used steel beads with the nominal diameter of 50 micrometers.

Improved fatigue strength and its mechanism

In order to clarify the mechanism of the drastically improved fatigue strength of the wave springs by applying the SS Treatment, as described above, some investigations such as residual stress distributions by X-ray method, X-ray diffraction of the spring surfaces, surface roughness measurements, TEM (transmission electron microscopy) and micro-hardness distributions, were conducted. Three kinds of wave springs, i.e., (i) SS treated, (ii) conventionally shot-peened with steel balls of 0.3mm dia., and (iii) the non-shot-peened, were fatigue-tested. The S-N curves obtained are plotted in Fig. 4.

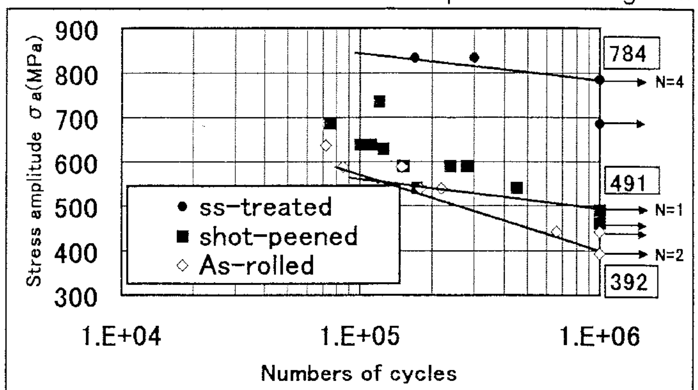

Fig.4 Fatigue test results

Fig.4. S-N curves of three kinds of wave springs.

Figure 5 shows the surface residual stress distributions. The SS - treated wave springs are seen to have higher compressive stress on the surface than conventionally shot-peened ones. It is a normal characteristic of conventionally shot-peened springs that their maximum compressive stresses are obtained not at the surface but several tens micrometers beneath the surface.

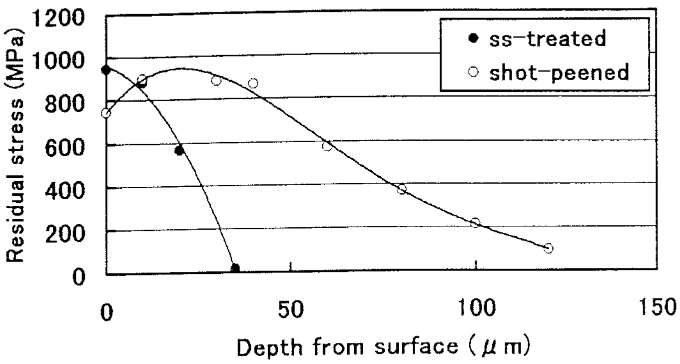

Fig.5 Residual stress distribution

Fig.5. Residual stress distribution

On the contrary, the SS - treated springs have such a characteristic residual stress distribution that it has the largest value at the surface vicinity and gradually decreases with the depth until about 30 to 50 micrometers, where the effect of the SS Treatment is almost vanished. The micro-hardness distributions of these springs are plotted in Fig. 6. It is clearly seen that the springs subjected to the SS Treatment, gives the largest hardening at the surface.

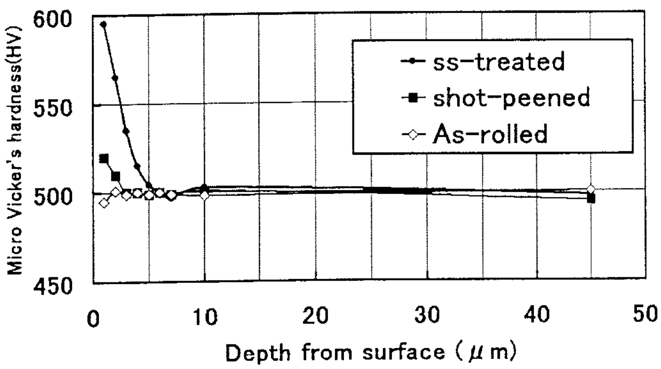

Fig.6 Hardness distribution

Fig. 6. Micro-hardness distributions of wave springs

According to the X-ray diffraction of the three kinds of spring surfaces, the SS - treated surface and the conventionally shot-peened surface have the similar texture, but are different from the as-rolled texture(Fig. 7). Namely, the as-rolled spring has the (200) [110] texture on the rolled surface along the rolling direction. On the other hand, the former two kinds of springs have preferred ferrite crystal plane (110) but no preferred orientation on the rolled and peened surface layer with the thickness less than 5 micrometers. This means that the SS Treatment and the conventional shot-peening gave the

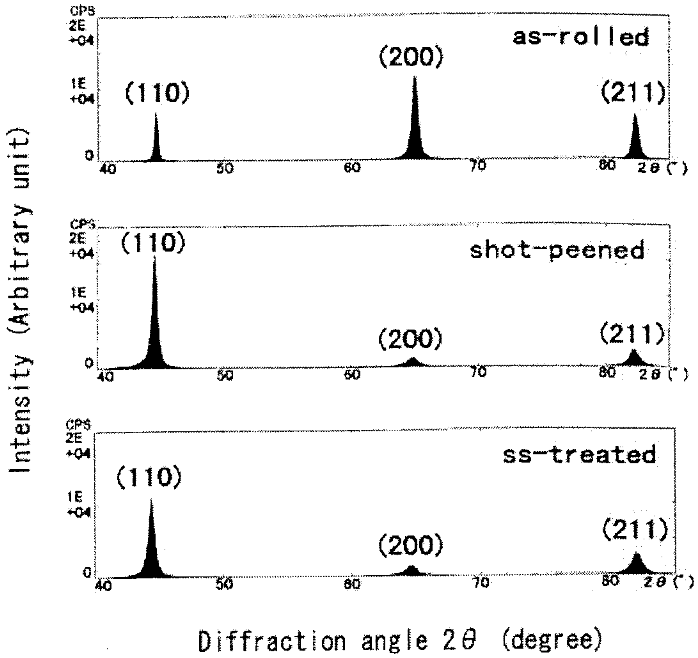

Fig. 7. X-ray diffraction of spring surfaces. X-ray: Cu Kα

quite similar plastic deformation on the spring surface layer, at least the deformation of ferrite is concerned. Each half value width of (110), (200) and (211) peaks of the SS treated spring was found to be larger than the corresponding each half value width of conventionally shot-peened one. This means the degree of deformation was stronger in the SS Treatment than in the conventional shot-peening.

Fig. 8. Microstructure of surface layer, as-rolled(A), as-conventionally shot-peened(B) and as-SS treated(C) by TEM.

The microstructure of the surface region of these three kinds of wave springs was investigated in terms of TEM. The observations were conducted with the sliced film prepared parallel to the transverse section of the rolled flat wire. Compared with the as-rolled micro-structure(Fig. 8A) and as-conventionally shot-peened one(Fig. 8B), the micro-structure of the SS treated spring(Fig. 8C) have at least two unique features: (i) Sub-grain or cell size, most of them are separated by cementite lamellae, is apparently reduced by the SS Treatment. And, (ii) some of the cementite(Fe_3C) lamellae between the neighboring cells seems to have disappeared in the SS treated springs, in contrast to the as-rolled and as-conventionally shot-peened ones. When spring surface region is strongly deformed by the bombarded SS steel beads, high density dislocations are produced in the ferrite matrix, and strongly deformed cementite lamellae tends to dissolve I ferrite and furnish diffusible carbon atoms to dislocation cores, assisted with both (a) the temperature rise[5 & 6] due to deformation and (b) probably extremely refined cementite grains due to heavy deformation[7]. According to the X-ray diffraction analysis of these spring surfaces, the cementite peaks which were apparently observed on the as-rolled spring surface layer and on the conventionally shot-peened spring surface layer, disappeared on the SS treated springs, supporting the refining and/or the dissolution of the strongly deformed cementite lamellae in matrix ferrite.

The reduced cell size and the dislocation locking by carbon atoms thus trapped around dislocation core, raise the yield strength of the surface zone of the springs which were SS treated. The higher yield strength of the SS treated surface zone helps formation of higher compressive residual stress at this surface region. The temperature rise of the spring surface region, caused by shot bombardment, is supposed to be larger as the shot particle size is decreased, according to F.P. Bowden and D. Tabor [8]. The higher temperature of the surface layer is supposed to help deforming the surface layer more heavily because of the temperature dependence of flow stress. The actual temperature rise during deformation by the collision of the steel beads to spring surface, is supposed to be below 400 to 500C, above which work hardening is weakened due to recovery and recrystallization.

Fig. 9. Surface roughness of wave spring

Another merit of the SS Treatment, compared with the conventional shot peening, is better surface roughness (Fig. 9). The fatigue fracture initiation site of the wave springs was always surface region. The higher compressive residual stress, the higher hardness and the smaller surface roughness are thought to be the causes of the improved fatigue strength of the wave springs by suppressing the micro-crack formation and its propagation.

IMPROVED HIGH STRENGTH VALVE SPRINGS BY APPLICATION OF SS TREATMENT TO HIGH TENSILE STRENGTH OIL-TEMPERED WIRE

Non-nitrided high strength valve spring

In this chapter, a high tensile strength grade valve spring quality oil tempered wire, SOTHN, was used, of which chemical composition is in Table 2. The wire diameter was 3.19 mm and the tensile strength and the reduction of area at tensile fracture was 2091Mpa and 51.5%, respectively. The addition of small amount of V is to refine austenite grain size, which improves ductility and toughness of oil-tempered wire. The addition of approximately 0.3 percent Ni is to improve toughness and decrease the micro-crack propagation rate under repeated stress.

Table 2. Chemical composition of high tensile wire

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

The valve springs were produced as-follows: The coiling was made at room temperature. Then, the springs were stress relief tempered, their coil-ends were ground to make flat and parallel seats, shot-peened with steel cut-wires with 0.6mm diameter, and tempered at 230C for 20min.. A half of the springs were then SS-treated for 20min., again tempered at 230C for 20min., and finally cold-set. The rest half springs were finally just cold-set with the same condition as for the SS treated springs.

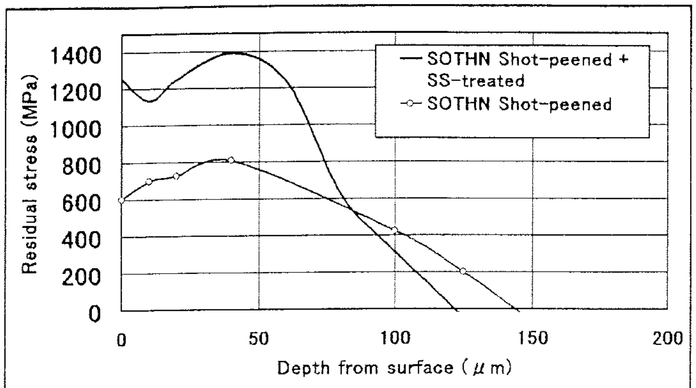

Fig.10 Residual stress distribution

Fig. 10. Distributions of Compressive residual stress

Normally, at the shot peening process in the production of automotive engine valve springs, cut wires or steel balls with the diameter from 0.6mm to 0.8mm, are bombarded onto valve spring surface. In this investigation, cut wires made from high carbon steel wire with the diameter of 0.6mm, were bombarded onto the tested valve springs for 40min, at the speed of 70m/sec. This conventional shot peening process was conducted using an impeller type machine. The residual stress distributions of these two kinds of high strength springs are shown in Fig. 10. It is clear that the SS - treated spring has higher compressive residual stress than the conventionally shot-peened one, at the spring surface region. The hardness distributions at the surface region were measured (Fig. 11) and the higher hardness of the SS treated springs, compared with the conventionally shot-peened ones, was found at the surface region.

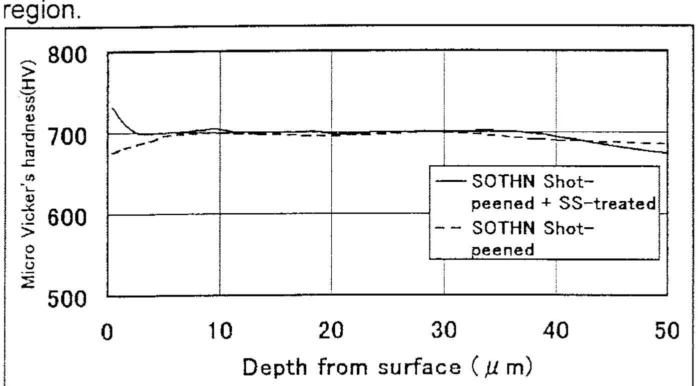

Fig.11 Hardness distribution

Fig. 11. Hardness distributions of a SS-treated high strength spring and a conventionally shot peened one.

The improved surface roughness was obtained by SS-Treatment, compared with the conventionally shot-peened springs.

In these experiments, the highest fatigue strength was obtained with the valve springs which were SS treated, following conventional shot-peenning. In Fig. 12, fatigue strength curves of these two kinds of valve springs are plotted with that of the conventionally shot-peened chrome silicone alloyed valve springs, taking the mean stress τ_m as abscissa and amplitude stress as ordinate at the stress repetition of 5 x 10^7. This figure indicates the drastic improvement of the SS-treated springs compared with the conventionally shot-peened ones. For example, the fatigue strength τ_a of the SS treated springs obtained, is 500MPa, when the fatigue test is made at the average stress, τ_m, of 588MPa. Although this fatigue strength, 588 ± 500 MPa, is a little inferior to that of the nitrided and conventionally shot-peened valve springs produced of the same grade of steel, which is reported to be 588 ± 529 MPa[4], it is far better than conventionally shot-peened high tensile strength valve springs or conventionally shot-peened chrome silicon valve springs, of which fatigue strength are reported to be 588 ± 441 MPa or 588 ± 412 MPa[4], respectively. Therefore, it may be possible to use the SS Treatment as a replacement of the nitriding, which is popularly utilized in the valve spring manufacturers in Japan but a costly process.

Application of SS Treatment to high strength nitrided valve spring

As described in the previous section, the high strength valve springs produced of SOTHN, nitrided and conventionally shot-peened, are reported to have fatigue strength of 588 ± 529 MPa[4]. The same grade of nitrided and conventionally shot-peened valve springs were prepared and then SS - treated. The springs were fatigue tested and the remarkable improvement of surface residual stress and fatigue strength of the SS - treated springs was obtained. Namely, surface residual stress of 1650 MPa and fatigue strength at 5 X 10^7 cycles of 588 ± 549 MPa were obtained. In this case, SS Treatment condition was not the best condition. When the best SS Treatment condition was applied, the surface residual compressive stress of 1985 MPa and the fatigue strength of 686 ± 559 MPa (this value might change in the final manuscript) were obtained.

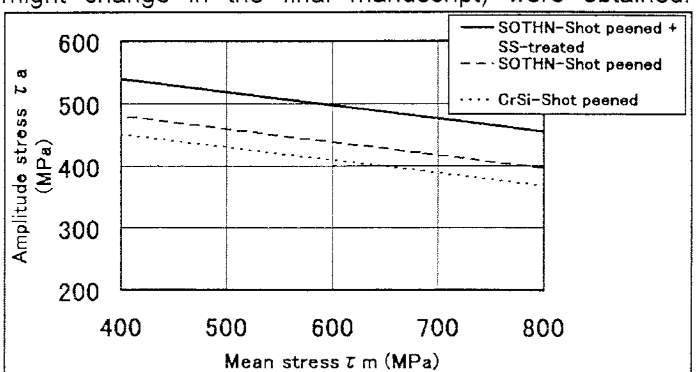

Fig.12 5 × 10^7 cycles fatingue stregth diagram for valve spring

Fig. 12. Fatigue curves of the three kinds of valve springs

Consideration on sensitivity to defects

The roll of the residual compressive stress is reported, not able to stop the generation of a micro-crack from a defect but to arrest its propagation[9]. Namely, large enough residual compression stress can stop the final fracture of a metallic part, even if it has a certain constant size defect in it. In order to get enough residual compressive stress on the spring surface layer, the surface zone should have high yield stress or high hardness. The SS Treatment can effectively increase the hardness of the surface layer of 10 to 50 micrometers depth below surface, contributing to the increased surface compression stress building without resorting to costly process such as gas-nitriding. According to our experiences, the improvement of fatigue property by applying the SS Treatment to various springs, seems to be more prominent as the hardness of the spring surface increases.

According to the fatigue crack propagation tests using WOL type spring steel specimens, the critical K_I value, below which the fatigue micro-crack stops, is supposed to be within 3 to 7 MPa X square root m[10]. K_I is expressed as $(2/\pi)\sigma$ times square root(π a), where σ is effective stress and is approximately obtained by subtracting residual compressive stress from the repeated maximum torsion stress, since the figure of torsion stress is nearly the same as that of the principal tension stress on the twisted round wire surface. Since the shot-peened and then SS treated springs had the surface residual stress of 1250 MPa or more, the springs were expected to endure the maximum repeated stress, (τm ± τa) of more than 1250 MPa, according to the micro-mechanics described above. Actually, however, the fatigue limit was 588 ± 500 MPa, which indicates the maximum stress of 1088 MPa. This indicates a stage II micro-crack (in stage II, fatigue crack propagates perpendicular to the tension stress), which propagated either from a wire surface flaw, from a non-metallic inclusion or from a stage I micro-crack (in stage I, micro-crack is produced along shear stress plane) below surface, was arrested at the wire surface region less effectively than the prediction based on KI theory described above. This discrepancy of the theoretical prediction and the actual fatigue test result may have been caused, at least, by the relaxation of the residual stress at the propagating crack front or by the condition tri-axial stress condition was not met at the crack front.

CONCLUSION

The new surface treatment technology called SS Treatment, is a method to bombard round steel beads onto spring surface at a suitable condition. This was applied to a wave spring, a kind of sheet spring and to a high strength valve spring. Drastic improvement of fatigue strength was obtained for both springs. The mechanism of the improved fatigue strength was investigated.

1. The fatigue strength of wave springs, in terms of amplitude stress, was increased two times that of non-peened ones, by applying the SS Treatment.

2. This improvement is considered to have been achieved by high surface compressive residual stress, by high hardness due to heavy deformation and by smooth surface.

3. SS treated wave spring surface layer was Investigated with TEM. The refined cementite lamellar distance and sell size, heavily deformed and thinned cementite lamellae and disappearance(dissolution) of some part of cementite lamellae were apparently observed.

4. It was suggested that the high compressive residual stress and high hardness were caused by interaction between dislocations and carbon atoms during the SS Treatment.

5. Significant effects of the SS Treatment, as concluded in 1 to 4, were also obtained, though qualitatively, when applied to high strength valve springs which had been conventionally shot-peened with 0.6mm diameter steel cut wires,.

6. This improvement obtained by the SS Treatment is estimated to be about 13 % higher fatigue strength in terms of the amplitude stress than conventionally shot-peened high strength ones, and 21 % increased fatigue limit than the chrome silicone steel springs conventionally shot-peened, respectively.

7. The SS Treatment was found to improve the fatigue strength of the nitrided and then conventionally shot-peened springs remarkably.

8. The high fatigue strength of the high strength valve springs which were SS - treated following conventional shot-peening, is supposed to be, at least, due to high arresting capacity of micro-crack propagation by high residual compressive stress at the spring surface layer.

CONTACT

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Suncall (previous name : Sanko Senzai Kogyo) has been a maker of spring wires, springs and other parts used for auto-industry, computers, communications etc. Its web site is "http://www.suncall.co.jp".

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