

Development of High Fatigue Strength Valve Spring Using Control of White Layer by Nitriding

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ABSTRACT

Elemental addition to a material to reduce its non-dissolved carbide content while increasing its resistance to temper softening has helped to increase internal hardness after nitriding while maintaining its cold-coiling-ability. Conventionally, high strength has been achieved by applying nitriding as a surface treatment to the valve springs, without consideration of the compound layer. However, when the strength of wire coils, the hardness of the nitrogen-diffused layer, and internal hardness are maximally increased, the white layer becomes the points of origin of breakages, and fatigue strength does not increase. The white layer was therefore judged detrimental to fatigue strength, and a nitriding method was developed that attained nitriding without the white layer and the achievement of increased hardness in the nitrogen-diffused layer, which had previously been incompatible.

1. Introduction

Motorcycle valve trains generally use valve lifters or rocker arms to drive the valves, and speeds can exceed 15000 rpm in high-speed engines. As engine speed increases, valve springs experience a resonance phenomenon known as surging, as a result of which the stress on the springs exceeds design stress. For this reason, high-fatigue-strength valve springs are necessary in motorcycles, which are used frequently in the high-engine-speed range. The strengthening of valve springs enables reduced size of valve trains and contributes to weight reduction of the engine and vehicle body. In addition, as strength increases, the loads on the valve springs increase, and a decline in their reaction force (permanent set-in fatigue) occurs under the high-temperature environments generated during high-speed operation. This reduces the range of motion of the valves, and set-in fatigue resistance is therefore also an important characteristic.

The strengthening of materials and the advancement of surface treatment technologies play a significant role in the achievement of high strength in valve springs. The

tensile strength of a material is generally proportional to its hardness, and development projects were therefore conducted in which attempts were made to increase hardness^{(1),(2)}. However, the achievement of a high level of hardness can simultaneously reduce toughness, resulting in a decline in cold coilability. In addition, while a high level of hardness may be achieved, the internal hardness of the material declines when tempered in the nitriding surface treatment process, making it necessary to increase temper-softening resistance. Temper-softening resistance also has a significant effect on the set-in fatigue characteristic, an important factor of the valve spring characteristic. However, elements that increase temper-softening resistance also reduce cold coilability due to the formation of carbides. 0.4% V is added to SWOCN-V, a high-strength material that has been put into practical use, helping to enable good temper-softening resistance to be obtained. However, an increase in the amount of undissolved carbides in the material due to the addition of the V reduces its margin of cold coilability. Nitriding is used as a surface treatment technology for valve springs. Increasing the nitriding temperature promotes the

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diffusion of nitrogen, resulting in increased surface hardness. However, the nitriding conditions affect the material's internal hardness and the thickness of the white layer. Because these changes affect the fatigue strength of the material, the selection of nitriding conditions is important.

This paper will discuss the development of high-strength valve springs, with a focus on alloy composition and nitriding conditions.

2. Material Composition Design

2.1. Aims for Alloy Composition

The development was conducted with consideration of the following points as the design concept for the material:

- (1) Development of a material that balances high strength with cold coilability, and also displays good nitridability;
- (2) Achievement of high level of temper-softening resistance, in order to help prevent a decline in internal hardness under nitriding temperatures; and
- (3) Development of a material that can be produced using existing facilities, with no special treatments, in order to control cost increases.

2.2. Study of Alloy Composition

A study was conducted to determine an alloy composition that balanced high strength with cold coilability. For high-strength valve spring steels, V is important not only in increasing surface hardness during nitriding, but also in helping to maintain internal hardness following heating during the nitriding process. V is generally effective as an additive to heat-treated products, like nitrided spring steel, due to its precipitation hardening effect at temperatures of 400-700°C. However, numerous points must be taken into consideration when using V in industrial applications. If the V added to the material does not dissolve but forms coarse undissolved carbides, not only is the element's precipitation hardening effect reduced, but the material can also be negatively affected, as a result of the reduction of coilability by the coarse undissolved carbides themselves. It is therefore important to employ an effective solution of V or an ultra-fine form of V in order to control the formation of undissolved carbides and help prevent negative impacts on the material, in addition to obtaining a precipitation hardening effect and achieving temper-softening resistance during the nitriding treatment applied in the valve spring manufacturing process.

This can also be predicted from the fact, as shown in Fig. 1, that the effect of V becomes saturated with higher additive amounts. This result was used to find the maximum additive amount of V that could be effectively used in the thermal history of the manufacturing process, from rolling to production of the valve spring, to help ensure that a practically effective rather than an excessive amount could be added.

Other elements were similarly studied from the perspectives of strength and carbide formation. Cr was judged unsuitable for short heat treatments such as high-frequency treatments, because Cr carbides would not readily dissolve.

Si is known as an element that both has a positive effect on the set-in fatigue characteristic of valves and affects carbide formation behavior, and the optimum additive amounts of this element and Cr were therefore studied from the perspectives of strength and carbide formation.

Figures 2(a) and 2(b) show the results of these studies. The amount of undissolved carbides present in the material during coiling and its internal hardness following nitriding were evaluated with actually used materials as the benchmarks. The amount of undissolved carbides was calculated using Thermo-Calc, while the internal hardness of the material was judged using the hardness of previous steels in a hardness database as the criterion. The upper section of each box in Fig. 2 represents hardness, while the lower section represents carbide precipitation behavior. Better performance than previous examples is marked with an A, a decline in performance with a C, and a level of performance close to the critical value with a B. The results indicate that a basic composition of 0.73%C-2.2%Si-1.0%Cr-0.1%V is desirable from the perspectives of carbide behavior following quenching and tempering (which affects coilability and strength following nitriding) and internal hardness following nitriding.

The addition of Mo, which impedes the formation of undissolved carbides and assists in precipitation strengthening, can also be considered to be effective in helping to achieve a high level of strength. However, the addition of excess Mo affects quenchability, and results in production defects such as cracks due to increased hardness as a result of the fact that it promotes the production of super-cooled microstructures such as martensite and bainite during the various heat treatments from rolling to production of the spring. A maximum additive amount for Mo that would not result in the production of super-cooled microstructures in the

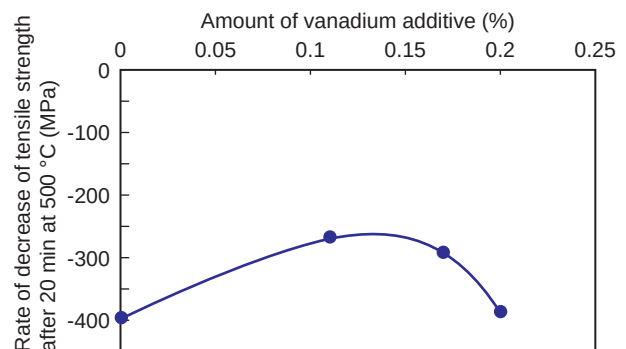


Fig. 1 Relation between vanadium additive amount and temper softening characteristic

projected thermal history of the material was therefore also established.

As in the case of Mo, the addition of W, which dissolves easily under heating during quenching, was also studied. While the precipitation hardening effect of W is not as strong as that of Mo, its effect on quenchability is low, and its addition is not prone to result in production issues due to the formation of super-cooled microstructures. W was therefore added to help ensure increased internal hardness following nitriding.

In this way, the elements related to the achievement of the necessary performance and manufacturability for the springs were comprehensively studied, and the

Table 1 Composition of developed steel

	(mass%)						
	C	Si	Mn	Cr	Mo	V	W
Developed steel	0.75	2.16	0.71	0.98	0.13	0.10	0.15
SWOCN-V (Previous)	0.73	1.67	0.58	0.56	0.15	0.41	–

appropriateness of the composition of the steel was verified in tests. Table 1 shows the composition of the steel, and Fig. 3 shows the material's hardness (temper-softening resistance) and notch-bending angle (coilability) after 3 hr at 500°C. The results indicated that the composition of the developed steel, with Mo and W added to the basic composition, balanced strength with workability.

2.3. Characteristics of Developed Alloy

Figures 4 and 5 respectively show the results of self-diameter winding tests and notch-bend tests on oil-tempered wires produced from wire dissolved in an actual oven. These results provide indices of cold coilability, and

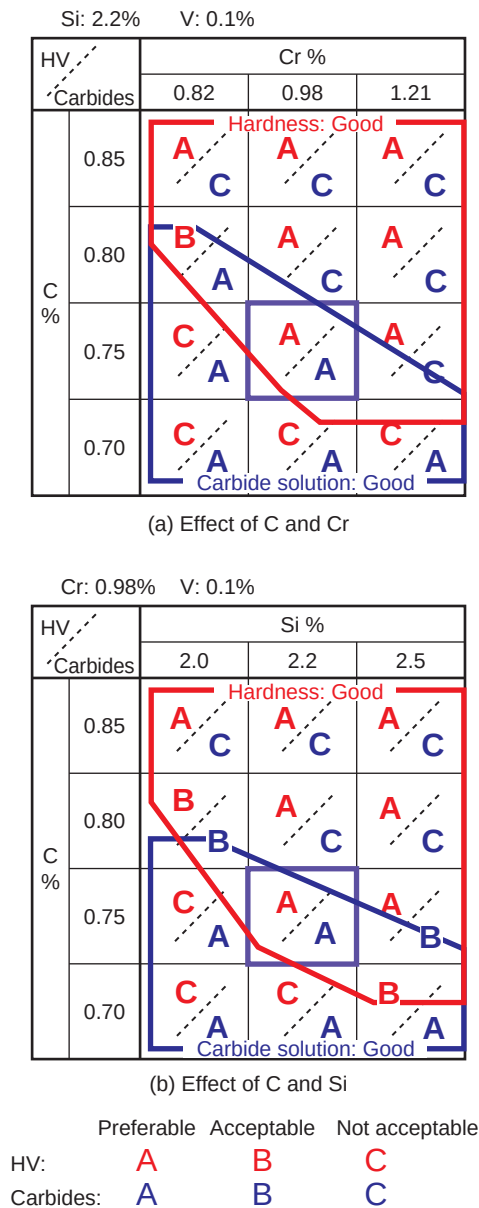


Fig. 2 Example of predicted performance of wires in terms of carbide state and hardness after heat treatments

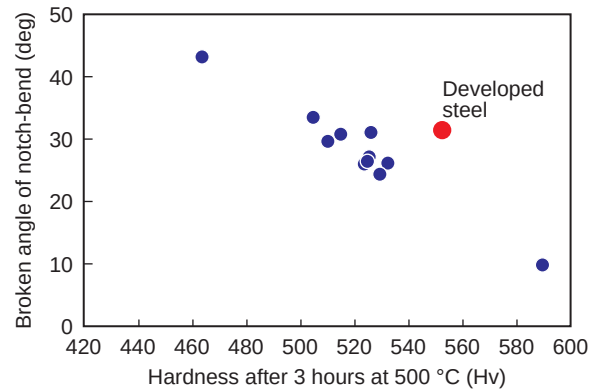


Fig. 3 Results of material composition study

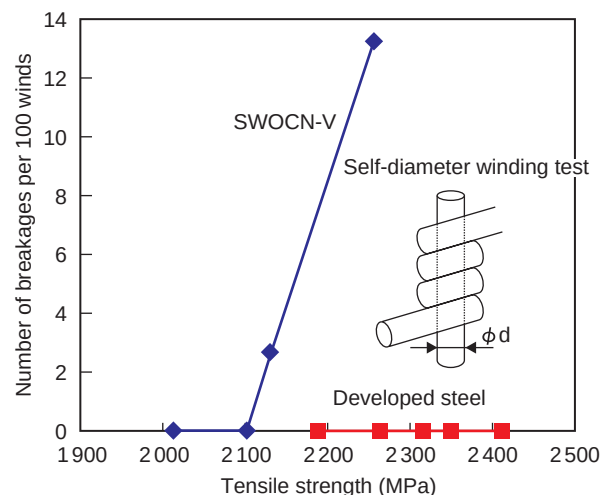


Fig. 4 Result of self-diameter winding test

the developed steel clearly demonstrated better performance than SWOCN-V in terms of coilability against strength. This is thought to be a result of the reduction in the amount of undissolved carbides in the material due to the reduction in V, as shown in Fig. 6.

Figure 7 shows the low-temperature tempering characteristic of the material. Even on the high-strength side, the hardness of the oil-tempered wire was approximately the same at 2250 MPa or more when tempered at a temperature corresponding to the nitriding temperature, and the tensile strength of the oil-tempered wire could therefore be set at 2250 MPa. Figure 8 shows the low-temperature annealing characteristic of the oil-

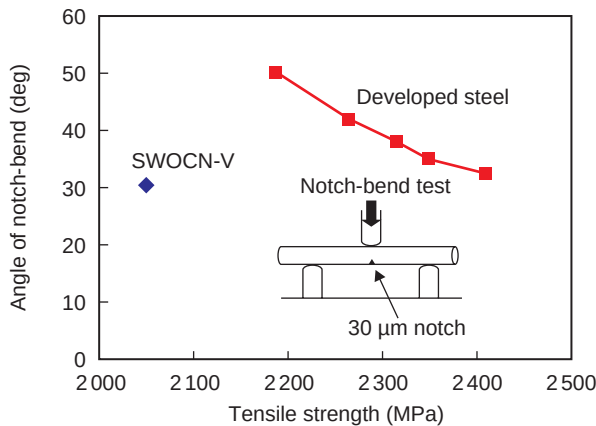


Fig. 5 Result of notch-bend test

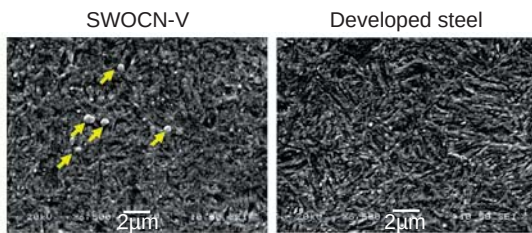


Fig. 6 Identification of non-dissolved carbide

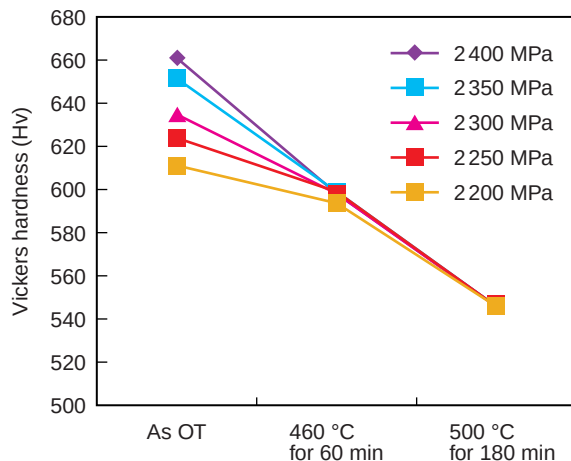


Fig. 7 Results of low-temperature tempering

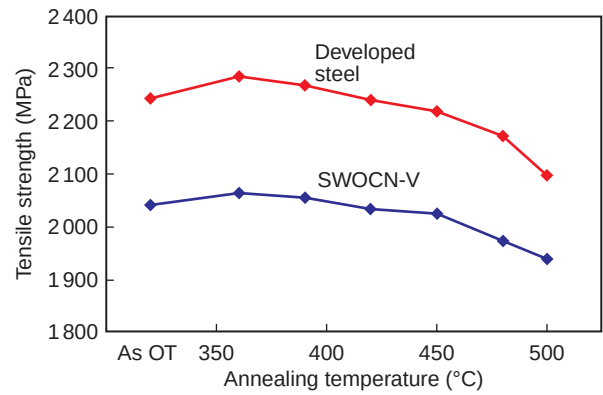


Fig. 8 Results of low-temperature annealing

tempered wire. Tensile strength is increased against SWOCN-V by approximately 200 MPa across virtually the entire temperature range. Existing facilities could also be used for the developed steel from dissolution to oil tempering.

3. Study of Nitriding Treatment for High-strength Valve Springs

3.1. Nitriding Quality Aims

With regard to nitriding conditions, in general when the nitriding temperature is increased the hardness of the nitrogen diffusion layer increases but internal hardness decreases, while the opposite occurs when the nitriding temperature is decreased. The sectional stress on the valve springs is highest on the surface of the internal diameter, and to achieve a high level of fatigue strength it is important to achieve high hardness by forming a high N-concentration nitrogen diffusion layer as the surface layer. However, because the formation of this type of nitrogen diffusion layer using normal gas nitriding necessitates the decomposition of large quantities of NH_3 gas in order to produce large quantities of activated H, a high quantity of N is produced at the same time. Therefore, a high-N concentration white layer is formed on the outermost surface layers of steel materials to which nitriding treatment has been applied. The toughness of this white layer is low, and an excessive white layer would result in reduced fatigue strength⁽³⁾. The aim of the development discussed here was to determine an optimum nitriding quality for fatigue strength by controlling the nitrogen diffusion layer hardness and the white layer⁽⁴⁾.

3.2. Optimization of Nitriding Conditions

Whether or not a white layer is formed on the outermost surface layer of the steel material is determined by the amount of N that penetrates the surface layer of the material; i.e., the balance between the amount of NH_3 that is decomposed and the amount of N that diffuses into the material. In order to control the formation of the white

layer, it is necessary to control the rate of decomposition of the NH_3 gas to attempt to ensure that the concentration of N at the outermost surface of the material, where the concentration is highest, remains below approximately 5 wt%.

The rate of decomposition of the NH_3 gas and the speed of diffusion of N into the steel material are both affected by the temperature. In addition, because the speed of diffusion of N in the steel material is also affected by the composition of the material, it is important to adjust the atmosphere in order to produce an NH_3 decomposition rate suited to different steel materials in order to help prevent the formation of a white layer on the outermost surface layer.

However, by merely adjusting a gas composition and nitriding temperature that help to prevent the formation of a white layer, the oxide film that exists on the surface of the valve spring is insufficiently reduced, and nitriding becomes unstable. The authors therefore decided to conduct the nitriding after replacing the oxide film on the surface of the valve spring with a fluoride prior to the process. Because this fluoridization process would be conducted at a temperature lower than that for low-temperature tempering following cold coiling, there was no concern regarding a decline in hardness. The fluoridized steel surface would be more active in the nitriding atmosphere than a surface covered with an oxide film, and nitriding would therefore be able to proceed even at a comparatively low NH_3 potential without forming a white layer on the outermost surface layer.

In attempting to determine a nitriding treatment applicable to the developed material, it was decided that the nitriding temperature and time should be decided first. Tests were conducted in which valve springs were nitrided at varying temperatures and for varying period of time in a small nitriding oven following replacement of the oxide film with a fluoride. The internal hardness and depth of the nitride diffusion zone were then measured. During the tests, nitriding was conducted with the ratio of NH_3 and H_2 held constant. The results are shown in Fig. 9. The target for internal hardness was set at Hv610 or above, and the nitriding period was set at two hr in consideration of mass producibility. Under these conditions, 470°C was determined to be the optimum nitriding temperature. Figure 10 shows the results for the formation of a white layer on the developed material at different temperatures; if a white layer was formed, the symbol ▲ is used, and if no white layer was formed, the symbol ● is used. The results show that when the temperature is fixed, the formation or non-formation of a white layer depends on the ratio of NH_3 and H_2 in the nitriding atmosphere. Therefore, conducting nitriding at a ratio in the zone where no white layer was formed or close to the boundary line would make it possible to form a high N-concentration nitrogen diffusion layer on the surface of the material with no white layer.

3.3. Study of Effect of White Layer on Fatigue Strength

Two valve spring samples nitrided with different ratios of NH_3 and H_2 were produced in order to clarify the effect of the white layer. The SEM photographs in Fig. 11 show the thickness of the white layer for each sample. Sample A displays a 2 μm -thick white layer, while no white layer can be observed on Sample B. The fatigue strength of these samples was studied using a spring fatigue tester. Figure 12 shows an S-N diagram of the results. The symbol ■ represents a sample in which a crack originated internally, and the symbols □ and ○ represent samples in which cracks originated on the surface. For Sample A

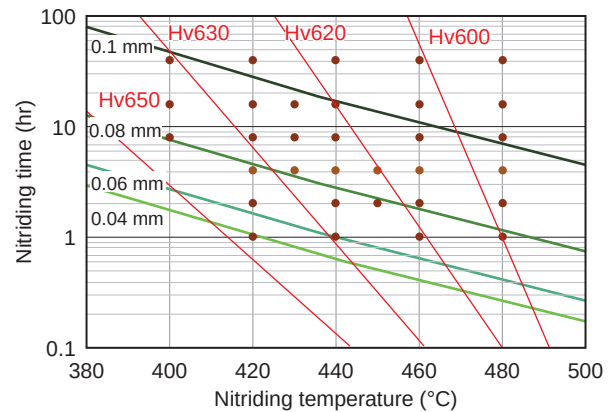


Fig. 9 Relation among temperature, time depth of nitriding, and internal hardness

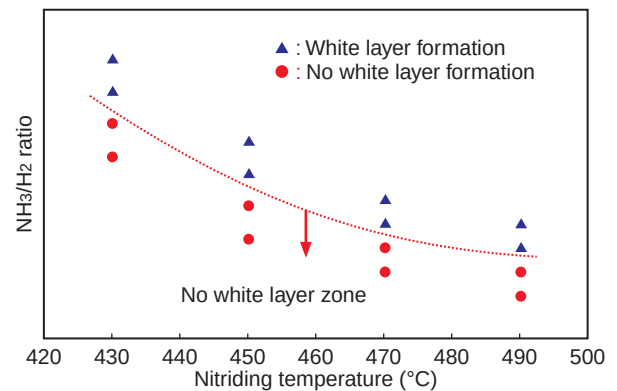


Fig. 10 Relation among gas composition, nitriding temperature, and white layer

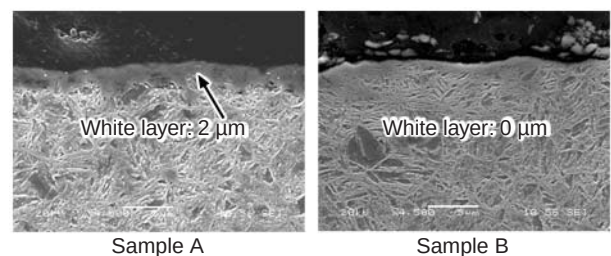


Fig. 11 SEM image of fatigue test specimens

test pieces, which displayed a thick white layer, all cracks originated on the surface. By contrast, for Sample B test pieces, which displayed no white layer, numerous cracks originated internally. Fatigue strength was higher in Sample B test pieces, in which cracks originated both internally and on the surface, than in Sample A test pieces, in which cracks originated exclusively on the surface. This phenomenon is explained in Fig. 13, which shows the stress distribution close to the outermost surface layer of the valve spring. It is conjectured that a high level of hardness due to nitrogen diffusion increases fatigue strength close to the surface of the internal diameter of the valve spring, where stress is highest, but because the white layer (ϵ -Fe₃N) is formed from hexagonal close-packed crystals it is hard but brittle⁽⁵⁾, and when it exists on the outermost surface layer, fatigue cracks spread from

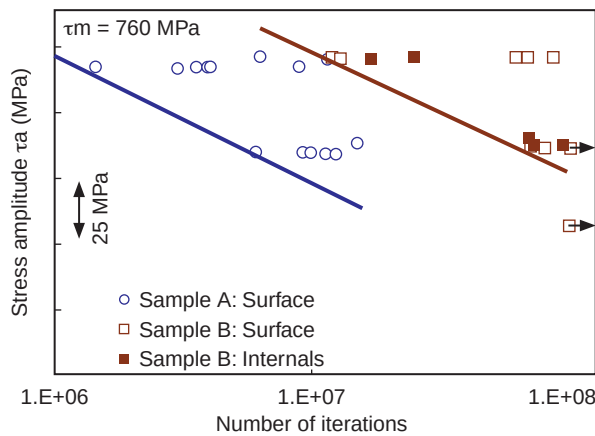


Fig. 12 Fatigue strength effect due to white layer thickness

minute notches. It is thought that in the SWOCN-V, by contrast, while white layers of 2 μ m in thickness were present, because the stress on the outermost surface layer was low in the low-load range, a decline in the strength of the white layer did not become noticeable.

4. Characteristics of High-strength Valve Springs

4.1. Fatigue Characteristic

Figure 14 shows the results of spring fatigue tests on the developed high-strength valve spring material and SWOCN-V. The fatigue tests were initially conducted at $\tau_m=686$ MPa, but no cracks were observed in the developed material, and they were therefore conducted again at $\tau_m=760$ MPa. Because of this, the S-N data for SWOCN-V used as a comparison in Fig. 14 has been reduced by the difference in τ_m .

The developed material clearly performed better than SWOCN-V, displaying a 20% increase in fatigue strength. This is considered to be due to the fact that the hardness curve of the developed material used in the fatigue test valve springs is higher across the entire range than that of the SWOCN-V (Fig. 15), and because the lack of a white layer helps to prevent a decline in surface fatigue strength.

4.2. Set-in fatigue

When valve springs are used in high-load engine environments, high-speed operation exposes them to high temperatures, and declines in their reaction force can occur. This can result in a decline in valve motion, and may lead to the breakdown of the engine. It is therefore

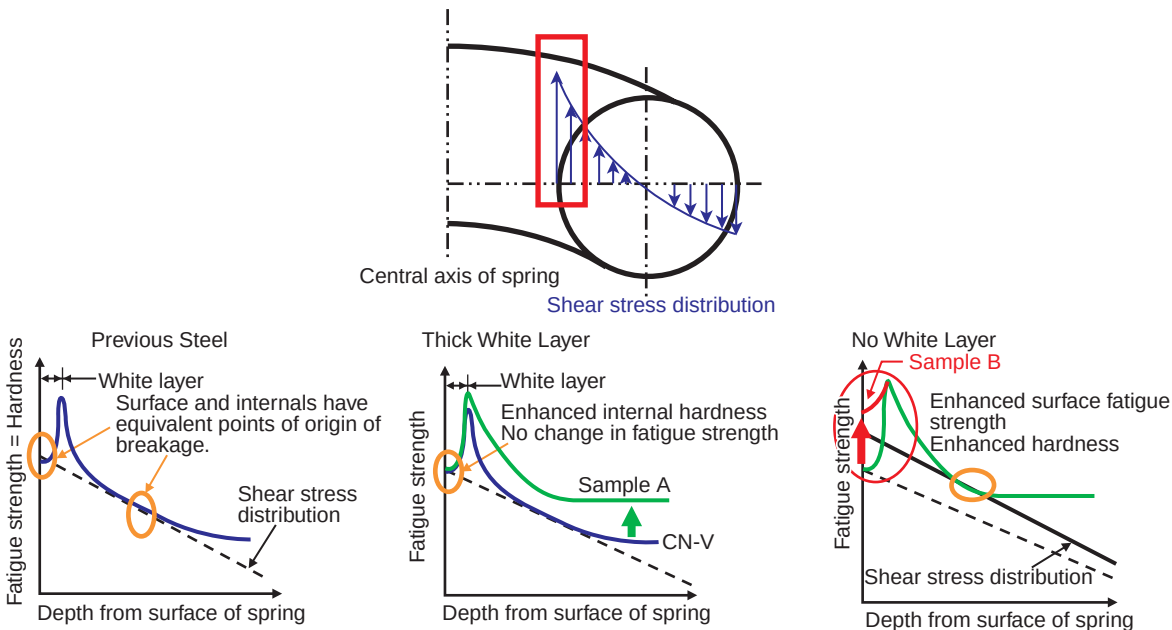


Fig. 13 Schematic diagram of influence of white layer thickness on fatigue strength

necessary to increase set-in fatigue resistance in response to increases in fatigue strength. The set-in fatigue characteristic of the springs was evaluated by measuring the degree of reduction in their reaction force following 100 hr at 150°C at varying constant stresses. Figure 16 shows the results of these measurements. The developed material displays good set-in fatigue resistance, with a

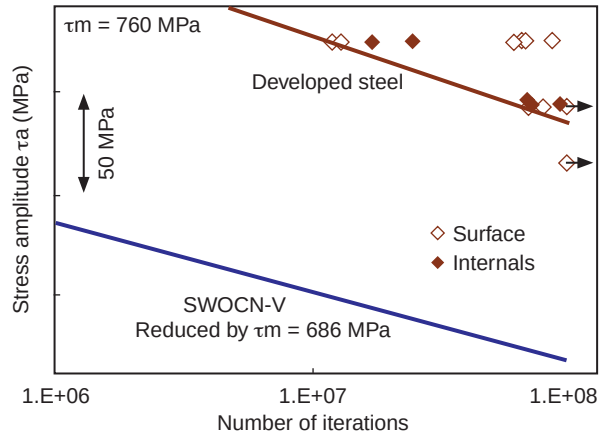


Fig. 14 Fatigue characteristic of developed steel

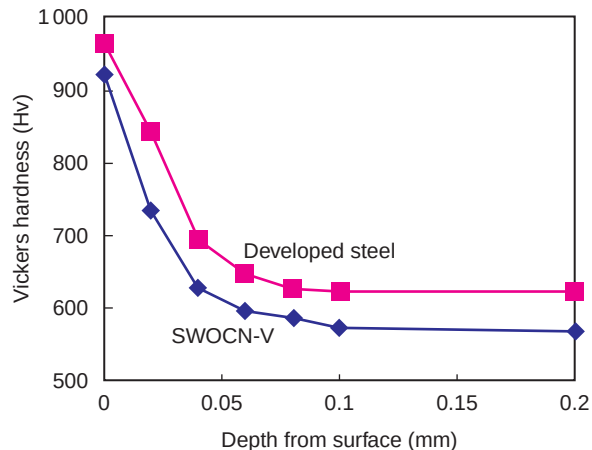


Fig. 15 Results for hardness after nitriding

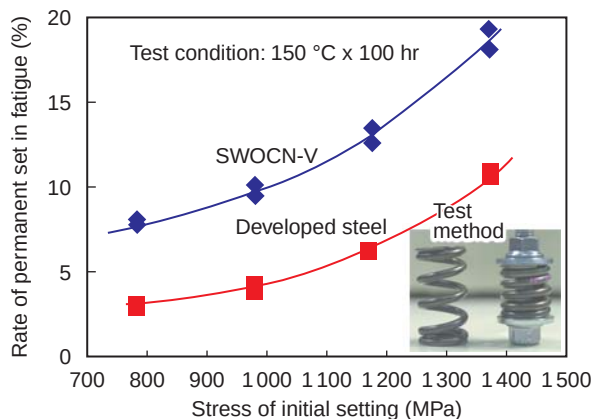


Fig. 16 Permanent set in fatigue characteristic of developed steel

reduction in set-in fatigue of approximately 25% against SWOCN-V. Strengthening of the martensite matrix by Si and Mo and the precipitation of microscopic carbides of Cr, V, and W are thought to be factors in this result.

5. Practical Application of High-strength Valve Spring

The use of the developed high-strength valve spring in the 2006 MotoGP machine helped to enable the height of the cylinder heads to be reduced, maximum engine speed to be increased, and the degree of cam lift to be increased. Riding this machine, Nicky Hayden took the MotoGP world championship in 2006.

Using the know-how gained from MotoGP, the developed valve springs were applied in mass-production for the first time to a motocross racing bike, the CRF250R (Fig. 17). The use of the developed high-strength valve springs helped to enable increased engine speed to be balanced with high durability, resulting in an increase in engine power in the high-speed range. The potential for the application of the developed valve springs to further mass-production models is being examined.



Fig. 17 CRF250R 2010 model using developed valve springs

6. Conclusion

- (1) Using SWOCN-V as a base, a composition that would balance high strength and high toughness was studied, resulting in the selection of 0.73C-2.2Si-1.0Cr-0.1Mo-0.1V-0.15W for the developed steel.
- (2) The necessary hardness following nitriding was achieved while also satisfying demands for cold coilability of oil-tempered wire.
- (3) The effect of the white layer on fatigue strength was clarified, and the necessity for nitriding conditions that would not produce a white layer in order to achieve high fatigue strength was ascertained. Nitriding without the production of a white layer was realized by using an activation reaction produced by fluoridization.
- (4) The high-strength valve springs produced using the developed material display 20% higher fatigue strength and 25% higher set-in fatigue resistance than SWOCN-V.

Afterword

The research conducted by the authors is aimed not only at achieving increased power from high-performance engines, but also, by contributing to the achievement of increased fuel efficiency by reducing the size and weight of automotive engines, to create products that will appeal to Honda's customers.

Acknowledgment

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