History and Future of High-Fatigue-Strength Steel Wire for Automotive Engine Valve Spring

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Valve springs are one of the automobile engine components that require a very high degree of fatigue strength and heat resistance. With the recent trend toward lighter cars and smaller engines, oil tempered wire used for valve springs needs to be smaller in diameter and higher in strength. About 80 years ago, Sumitomo Electric Industries, Ltd. started the production of piano wire, and has since been working hard to develop new materials and techniques for manufacturing steel wire for valve springs. This paper describes the history of the development of high-strength steel wire and its future.

Keywords: valve spring, oil-tempered wire, higher fatigue strength

1. Introduction

The valve actuation system for automobile engines (Fig. 1), which is the mechanism that actuates intake and exhaust valves, has played an important role in complying with stricter emission standards in recent years, responding to needs for better fuel economy, and improving the maneuverability of automobiles. One of the key components in the system is valve springs, which are used to convert rotary motion from the power transmission shaft into reciprocating motion using a cam mechanism, and must have an extremely high degree of durability and heat resistance (sag resistance). In line with the recent trend toward lighter cars and space-saving engines, oil-tempered wire*1 used for valve springs is required to be smaller in diameter and higher in strength. For valve springs, oil-tempered chromium silicon (Cr-Si) alloy steel wire has generally been used. In response to the need for higher strength steel wires, several materials have been developed such as high C-Cr-Si steel with a higher content of carbon, vanadium (V)-added high C-Cr-Si steel, high Si oil-tempered steel wire[(1),(2)] with high heat resistance, and high Cr V-added oil-tempered steel wire[(3)] with high nitriding performance. This paper describes the history and prospects of Sumitomo Electric Industries, Ltd.'s development of high-strength steel wires for valve springs.

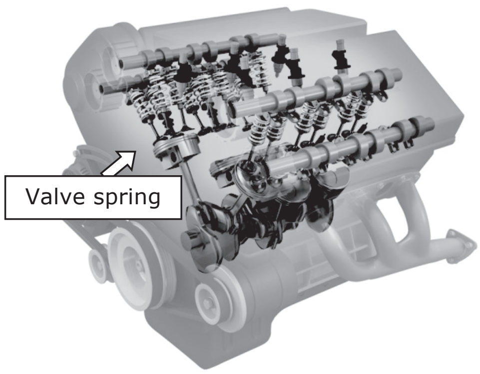

Fig. 1. Valve actuation system for automobile engines and valve springs

2. History of Strengthening Steel Wire for Valve Springs

Sumitomo Electric has a long history of developing materials for valve springs. It started when piano wire*2 for valve springs of aircraft engines, which had been mostly imported from Sweden, was produced domestically in 1932. After the war, piano wire started to be used for automobile engines, and the production volume continued to increase. However, after the manufacturing technology of oil-tempered wire was introduced from Western countries, the major material for valve springs shifted from piano wire to oil-tempered wire. Oil-tempered wire is steel wire that has the features of higher strength, higher heat resistance, and higher fatigue strength than piano wire. In 1954, our company produced Japan's first prototype furnace with a molten lead bath as a heating system. In the following year of 1955, it started the experimental production of oil-tempered wire of carbon steel. After presenting the results at the Japan Society for Spring Research (currently the Japan Society of Spring Engineers), it started full-scale production and sales.

Since the mid-1960s, Cr-Si oil-tempered steel wire (SAE9254, JIS SWOSC-V) with more excellent features has been used, and in the 1980s, high C Cr-Si steel and V-added high C-Cr-Si steel were developed. These have been the major materials for valve springs.

Conventionally, the fatigue strength of oil-tempered wire has been estimated[(4)] using the size of internal defects (inclusions*3) and hardness, and there has been concentrated efforts toward reducing the size of inclusions and increasing the hardness of materials. However, this approach seems to have limitations toward further improvement of fatigue strength.

Since the successful commercialization of Cr-Si oil-tempered steel wire for valve springs using our molten material in 1981, Sumitomo Electric has been promoting the development of material design technology. Centering on material design technology, this paper looks back on the major events regarding the development of steel wire with high fatigue strength at Sumitomo Electric and discusses the prospect of development.

3. Development of High Strength Steel Wire at Sumitomo Electric

3-1 High Si oil-tempered steel wire

In the mid-1990s, we developed VHS, a high Si Cr-Si oil-tempered steel wire (hereinafter referred to as "VHS"), which has higher fatigue strength and heat resistance.(1) During the development, we broke free of the conventional idea that the high strength material leads to springs with high fatigue strength. There were two development concepts: one is the higher strength and toughness for springs, and the other is higher fatigue strength with finer grains.

The general manufacturing process from steel wire to springs is shown in Fig. 2. Heat treatment is performed throughout the process. A high amount of Si, which increases resistance to temper softening, is added to VHS to improve its strength during low temperature annealing after coiling. The chemical compositions of VHS are shown in Table 1.

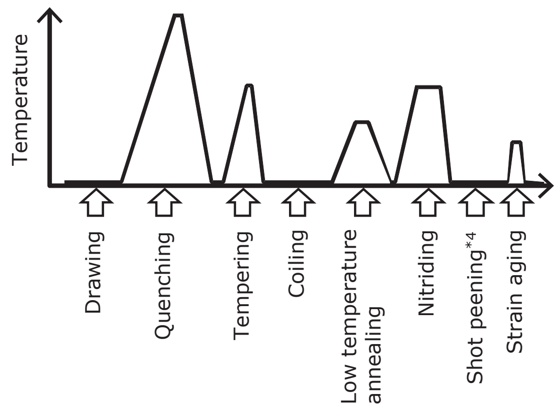

Fig. 2. General manufacturing process from oil-tempered steel wire to springs

Table 1. Chemical compositions of VHS, high Si Cr-Si oil-tempered steel wire (mass%)

	C	Si	Mn	Cr	V
VHS	0.63	1.95	0.77	0.71	0.08
Conventional	0.66	1.41	0.75	0.71	0.14

Compared with conventional material (V-added Cr-Si steel), VHS contains about 1.5 times the amount of Si and two-thirds the amount of V. The effects of each composition are shown below.

First, the increased amount of Si, the element that increases resistance to temper softening, is expected to increase the heat treatment temperature as follows:

(1) Higher temperature of tempering: Dislocation relaxation reduces microscopic defects and improves toughness, resulting in easy coiling.

(2) Higher temperature of low temperature annealing: Residual stress developed during the coiling process is sufficiently lowered. Reducing microscopic defects, which can be the origin of fatigue fracture, improves the fatigue limit.

(3) Higher temperature of the nitriding process: Easily diffused nitrogen makes a thicker layer of nitrogen and minimizes the decrease of the hardness of the inside, which is not nitrided, resulting in a higher fatigue limit.

Second, the addition of V, whose fine precipitation during the tempering process leads to a secondary hardening phenomenon, helps form V carbide that has high heat resistance and is relatively stable under a high temperature, resulting in a fine grain. However, too much added V decreases the toughness due to V carbide. Since the increased Si mentioned above can increase heat resistance, the amount of V was minimized.

Examining the composition of these two elements and optimizing the manufacturing processes, we have developed VHS. Regarding the refinement of the grain, the prior γ grain size*5 has become about 3–4 μm (13 in JIS grain size number*5) from about 10–11 μm (10–11 in JIS grain size number) due to lower temperatures and shorter heating time than under conventional heating conditions during the quenching process.

The tensile strength of VHS with various grain sizes and conventional material after low temperature annealing is shown in Fig. 3. The numbers in the legend of the figure are the grain size numbers. There is no difference between the tensile strength of oil-tempered wire made of VHS and conventional material, but after being tempered at temperatures higher than 400°C,

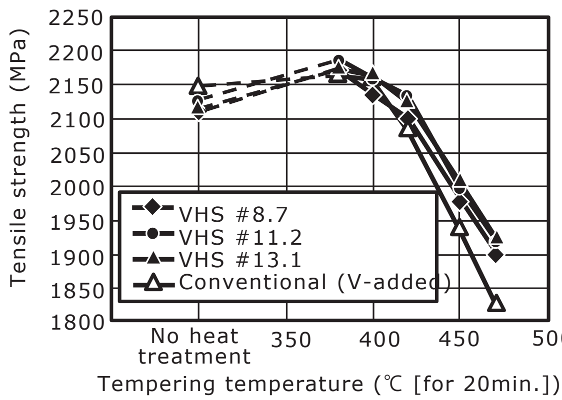

Fig. 3. Tensile strength of VHS and conventional material after low temperature annealing

the tensile strength of the conventional material decreases by a greater amount. The figure also shows that the grain size of VHS little affects the resistance to temper softening.

The results of our original Charpy V-notch impact test*6 on VHS with various grain sizes and conventional material are shown in Fig. 4. In comparison of the minimum depth of the notch when a fracture was initiated during the test, while the conventional material was broken with a notch of 40 µm or less in depth, VHS was broken with a much larger notch regardless of the grain size number. This shows that VHS has higher toughness than conventional material.

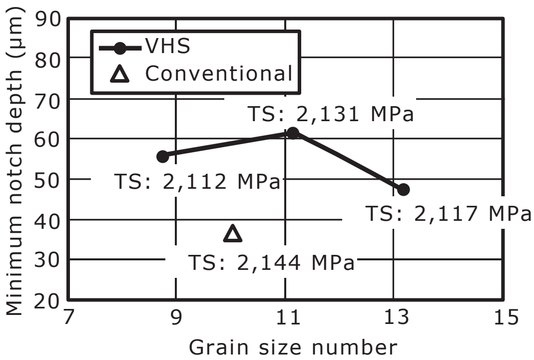

Fig. 4. Minimum notch depth when the Charpy impact test on VHS and conventional material initiates a fracture

The fatigue strength of VHS with various grain sizes and conventional material is shown in Fig. 5. The test was performed using a Nakamura-type rotating-bending fatigue test machine,*7 and the fatigue limit was determined after 1 x 10^7 cycles of repeated bending test without fatigue failure. The fatigue limit of VHS increases as the grain size number increases, and compared with conventional material of the same grain size, the fatigue limit is about 10% higher. The r values in the figure are fatigue strength divided by tensile strength. The figure reveals that the r values increase as the grain size number increases or the grain size decreases. The improvement in the fatigue strength is caused by other parameters than the material strength.

r = fatigue strength/tensile strength after tempering

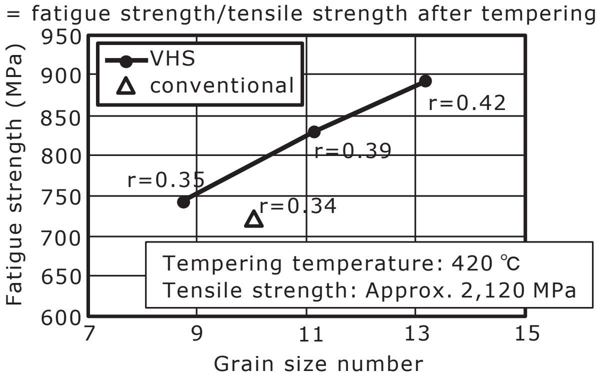

Fig. 5. Relationship between grain size number of VHS and fatigue limit

3-2 High Cr and V-added oil-tempered steel wire

In the 2000s, we developed VHR, a high Cr and V-added oil-tempered steel wire (hereinafter referred to as "VHR"), which has a higher fatigue strength than VHS. To take the development concept of VHS even further, we carried out the development with the users' manufacturing process in mind. Under practical use conditions, fatigue fractures are usually observed near the surfaces of springs because the stress loaded on a spring is the highest at the spring's surface. Therefore, the following processes are generally applied during the manufacture of springs: (1) nitriding treatment for hardening the wire surface, and (2) shot peening (SP) treatment for applying compressive residual stress on the wire surface to lower the actual stress (Fig. 2).

However, a high temperature of the nitriding treatment causes the internal strength of the spring to decrease, resulting in fatigue fractures (Fig. 6). The other problem is that strengthening steel wire deteriorates the wire's toughness and impedes the mass production of valve springs. Therefore, before developing VHR, we had set the target of promoting nitriding on the surface of springs during the nitriding process, which determines the properties of high-strength springs, not deteriorating the internal hardness, and achieving strength and toughness equivalent to those of conventional steel.

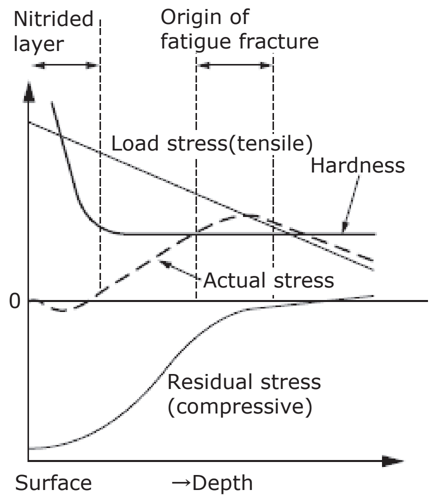

Fig. 6. Internal stress state of spring

The chemical compositions are shown in Table 2. Compared with the composition of VHS, a high Si oil-tempered steel wire, the developed steel has increased the amounts of Cr and V to improve nitriding performance. The increased amounts of Cr and V, which provide precipitation strengthening, and also increased amounts of Si and Co, which provide solid solution strengthening, improve heat resistance. Cr, which is more prone to be distributed in carbide than in ferrite during the tempering process, can restrain the enlargement of carbide due to its low diffusion rate.[5],[6] Furthermore, the decreased amount of Mn decreases hardenability and ensures toughness (workability) with consideration for mass production.

Table 2. Chemical compositions of high strength oil-tempered wire made by Sumitomo Steel Wire Corp. (mass%)

	C	Si	Mn	Cr	V	Co
VHR	0.64	2.2	0.55	1.2	0.15	0.2
VHS	0.63	1.95	0.77	0.71	0.08	-

* VHS is Si-added material with high resistance to temper softening. Regarding VHR, the VHS development concept and increased amounts of Cr and V improve the nitriding performance.

The tensile strength of VHR and VHS after low temperature annealing is shown in Fig. 7.

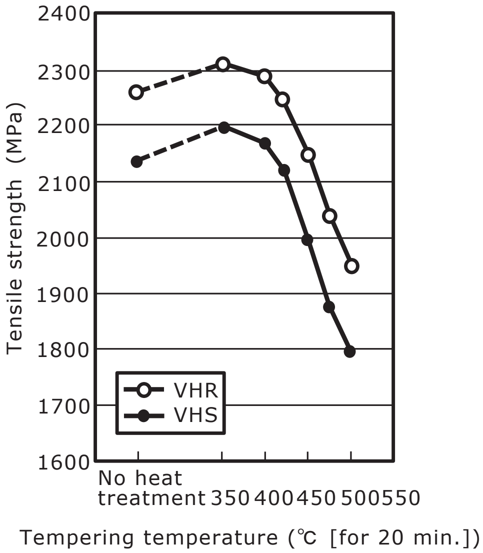

Fig. 7. Tensile strength of VHR and VHS after low temperature annealing

The tensile strength of VHR is higher than that of VHS under all temperature conditions. In addition, the tensile strength of VHS decreases by a greater amount after tempering than is the case with VHR. After tempering at 450°C, the difference between the tensile strengths of VHS and VHR is about 150 MPa.

The Vickers hardness profiles of VHR and VHS after nitriding at 450°C for two hours are shown in Fig. 8.

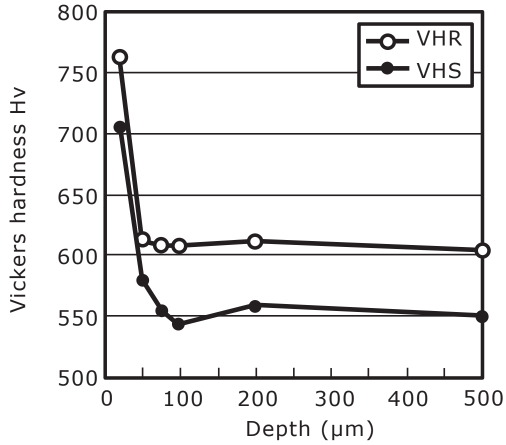

Fig. 8. Vickers hardness profile of VHR and VHS after nitriding process

The Vickers hardness of VHR at a depth of 20 μm from the wire surface is 770 HV, which is higher than that of VHS. At a depth of 200–300 μm from the wire surface, which is likely to be the origin of a fatigue fracture, the Vickers hardness of VHR is higher than that of VHS.

The fatigue strength of VHR after heat treatment that is intended to represent nitriding (at 450°C for two hours) is shown in Fig. 9.

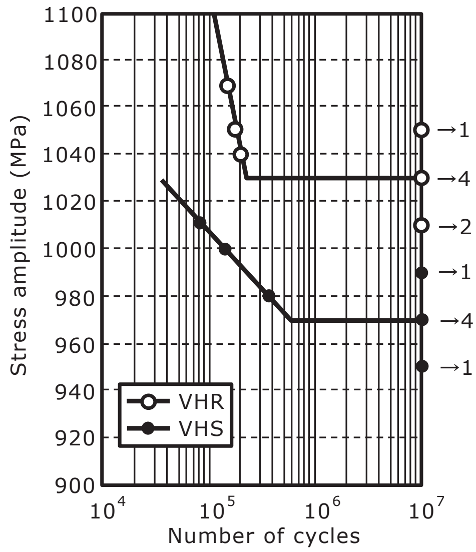

Fig. 9. Fatigue strength of VHR after heat treatment that is intended to represent nitriding (at 450°C for two hours)

The samples were not nitrided in reality. The purpose of the test was to evaluate the internal fatigue strength of the material softened by the heat of the nitriding process. The figure shows that VHR has higher fatigue properties than VHS even when the inside of the softened material is the origin of a fracture.

4. Development of Further High Strength Material

There has still been a strong need for higher strength material because valve springs for automobile engines are important components for improving maneuverability and fuel economy.

When VHR was developed, finer sizes of carbide were observed in the grain. (Photo 1. Transmission Electron Microscope (TEM) images. Carbide in the grain is shown by the black spots in the photo.) Image processing revealed that the average carbide size of VHR was 20.8 nm. VHR's high fatigue strength is likely to be ascribable to this size, which was about two-thirds that of VHS (27.8 nm). It is thought that the diffusion rate of Cr in the material causes the suppression of carbide growth. Using this idea, the refining technology of carbide in the grain can be established by optimizing conditions for heat treatment such as rapid heating and cooling, which control the diffusion rate of elements composing carbide.

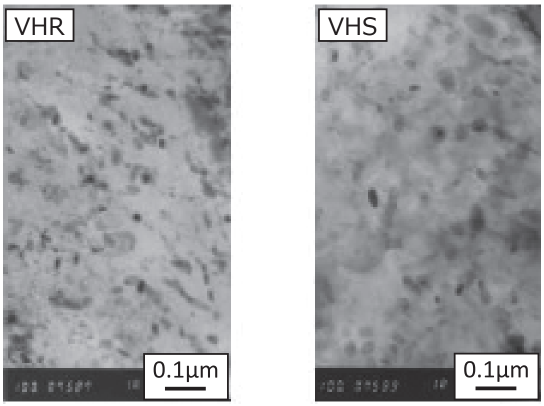

Photo 1. TEM images of VHR and VHS grain after nitriding process

Sumitomo Electric believes that the material design technology consists of alloy design, heat treatment, and machining technology. In 1994, we introduced the high-frequency induction furnace and water quenching method, which were revolutionary at that time, to a new quenching production line and started the development of steel refining technology using rapid heating and cooling processes. We are developing a high-strength material that is exceeding expectations from phase diagrams of conventional metals under nanometer-order structural control.

5. Conclusion

Having an unparalleled degree of fatigue strength, toughness, and heat resistance compared to other steel materials, oil-tempered wire for valve springs has contributed to improving engine performance and fuel efficiency in the automobile industry. There has been a strong need for higher spring performance. With users' spring manufacturing processes in mind, Sumitomo Electric will strive to design and propose new materials with higher performance and lower costs by combining its alloy design, wire drawing, and heat treatment technologies.

Technical Terms

*1 Oil-tempered wire: Oil-tempered wire is heat treated steel wire that has a tempered martensite structure produced by a quenching-tempering process. It has the features of high (fatigue) strength and high heat resistance.

*2 Piano wire: Piano wire is high-strength steel wire that has a high content of fibrous iron carbide (Fe_3C) in the longitudinal direction. The piano wire is formed by drawing pearlite steel, which is obtained by isothermal transformation at a temperature of 500°C to 600°C after heating steel until it is austenitized. The name derives from music wire used for piano strings.

*3 Inclusion: Inclusions or nonmetallic inclusions are small numbers of particles present in steel. During steel manufacturing, some inclusions cannot be removed by deoxidizers, which react with the oxygen and form oxide to be removed. Adjusting components and other measures are implemented to lower the melting point, resulting in softened and detoxified steel during the rolling process.

*4 Shot peening: Shot peening is a spring manufacturing process of hitting a surface of springs at high speed with a large number of small balls made of steel or nonferrous metal or steel wire cut to lengths approximately the same size as the width of a wire. This process causes plastic deformation that results in surface smoothing, strain hardening, and compressive residual stress, as well as improving the fatigue strength of springs.

*5 Prior austenite (γ) grain size, grain size number
Recently, grain size refinement has become a keyword in material development. Discussions on oil-tempered wire are often focused on the grain sizes (prior γ grain size) of austenitized structures while being heated during a quenching process. The grain size number, an index of the grain size, is specified as follows (according to JIS G0551):
$b = 2^{(n+3)}$
n: grain size number; b: the number of grains per square millimeter of a material cross section

*6 Charpy V-notch impact test: General steel wire for springs tends to induce fractures from small cracks when high tension is applied while springs are formed. Therefore, our company conducts our original Charpy V-notch impact tests to evaluate the notch sensitivity of material. The notch sensitivity is evaluated by determining the minimum depth of a notch that causes a fracture after hitting the back side of the notch on the steel wire made by a cutting tool with the hammer of a Charpy impact test machine. The hammer release angle is adjusted to make the strain rate (the impact speed when the hammer hits the test specimen) as close as possible to the strain rate employed when springs are formed.

*7 Nakamura-type rotating-bending fatigue test: Actual springs are used after a low temperature annealing or nitriding process. Therefore, to grasp the properties under conditions as close as possible to the actual conditions, the fatigue tests for steel wire are conducted after heat treatment (at 420°C for 20 minutes), which is intended to represent low temperature annealing after forming springs, heat treatment (at 430°C for three hours), which is intended to represent nitriding, and selective shot peening to steel wire for the purpose of eliminating impact with the rough surface.

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