# Development History of Wire Rods for Valve Springs

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*To reduce fuel consumption, automotive valve springs need to be made lighter. Kobe Steel has developed high strength steel for valve springs to meet this requirement. Furthermore, by continuously developing technology for the control of internal defects, such as non-metallic inclusions, high strength valve spring steels with good robust quality have been provided. This paper describes the development history of wire rods for valve springs with high fatigue strength.*

## Introduction

Valve springs (**Fig. 1**) are used in the valve actuation mechanisms of internal-combustion engines. A valve spring serves to move an intake, or an exhaust, valve according to the head-discharge curve of a cam such that the valve is in contact with its seat to prevent compression leakage. In the meantime, a valve spring is required to impose appropriate tension on the valve so as not to increase the friction loss of the valve operating system. The environmental regulations for automobiles are becoming more stringent in order to further reduce $CO_2$ emissions. To achieve this and to improve fuel economy, valve springs are required to be lighter and smaller. Such downsizing improves followability with cams, reduces the inertia weight of valve operating systems, and helps to reduce the size of engines. However, as valve springs become lighter and smaller, more stress is imposed on spring wires. In addition, the spring wires must withstand repeated loading at a frequency of several thousand cycles per minute for extended periods of time. Furthermore, aging degradation can cause shortening of the spring, a phenomenon called "sag"; hence valve springs are also required to have improved sag resistance under high stress. Until the late 1970s, valve springs had been made of hard-drawn wire of high carbon steel having a tensile strength of about 1,700MPa. Then oil-tempered wires of 1,900MPa grade began to be used. Nowadays, oil-tempered wires of 2,100~2,200MPa grade are commonly used[1), 2)]. Furthermore, nitriding treatment is being applied to the surfaces of wires to increase durability (**Fig. 2**).

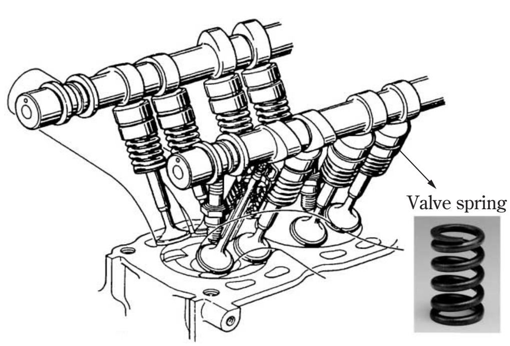



**Fig. 1** Valve spring in automobile engine

Billet — Hot-rolling — Shaving — Patenting — Drawing — Oil-tempering —
— Eddy-current Testing — Cold Coiling — Stress Relieving — Coil-end Grinding —
— ( Nitriding ) — Shot Peening — Strain Aging — Setting

**Fig. 2** Manufacturing process of valve spring

This paper introduces Kobe Steel's history of strengthening valve spring steel and newly developed materials.

## 1. Strengthening of valve spring steel at Kobe Steel

### 1.1 History of strengthening steel for valve springs

Wires used for valve springs include piano wires (i.e., as-drawn high-carbon steel wires) and oil-tempered wires (i.e., wires that are drawn, oil-quenched and tempered).

Until World War II, piano wires had been made in Sweden. Kobe Steel started producing wire rods made of high carbon steel in 1930. The company successfully developed wire rod for valve springs and inaugurated the production of piano wires for valve springs in 1941. Around that time, the piano wires were first used for the valve springs of aircraft engines and then started to be used for the valve springs of automobile engines[3)]. In 1952, Kobe Steel succeeded in developing a wire rod (KPR: Kobe Piano Wire Rod) that was comparable with Swedish steel[4)].

After the war, oil-tempered wires were introduced from the USA. In 1955, Kobe Steel began producing oil-tempered wires of carbon steel and also of Cr-V. These wires gradually came to be used in automobile engines[5)].

Since around 1964, wires with excellent heat resistance (SAE9254, JIS SWOSC-V), made of oil-tempered steel containing Si and Cr, have been used to increase fatigue strength and improve sag resistance. This steel has become a de facto standard.

**Table 1** shows the chemical compositions of wire rods used for valve springs, i.e., the compositions specified by SAE (SAE steels) and the ones developed by Kobe Steel. **Fig. 3** depicts the development trend of the wire rods. Kobe Steel's technologies include techniques for reducing surface scratches and decarburized layers, both of which can adversely affect the fatigue strength of oil-tempered wires, and a method[6] for peeling the wire rod surface over its entire length. In the early 1980s, the company developed and implemented technologies[7] for evaluating and cleaning off harmful inclusions. Adopting this technology to the SAE9254 steel has significantly improved the fatigue strength of valve springs.

Studies have been conducted aiming at optimizing chemical compositions for higher strength. In the mid-1980s, a new composition, KHV7, was developed and implemented. This composition was based on SAE9254 and has a higher content of C for increased tensile strength and an additional content of V, which refines austenitic grain and improves softening resistance. Oil-tempered wires of SAE9254 have a tensile strength of about 1,900MPa, while those of KHV7 have a tensile strength around 2,050MPa. The developed steel has an increased fatigue strength that is about 1.1 times higher than that of the conventional SAE9254. Furthermore, applying nitriding treatment has increased the fatigue strength by a factor of about 1.3.

In the early 1990s, a new alloy, KHV10N, containing 2.0% of Si, was developed to increase resistance against temper softening. This steel has raised the tensile strength of oil-tempered wires to the 2,200MPa level. Combined with nitriding treatment and modified shot peening, KHV10N has achieved a fatigue strength about 1.4 times higher than that of SAE9254.

To further improve the fatigue strength and sag resistance of KHV10N, larger amounts of Cr and V were added to make the crystal grains ultrafine. The developed alloy, KHV12N, was commercialized in 2006.

**Fig. 4** shows the ratio of high and super-high strength steels occupying the valve spring steels produced by Kobe Steel. In recent years, the adoption of high-strength steel has been increasing rapidly. High-strength steel currently accounts for about 60 percent of the valve spring steel shipped by Kobe Steel, and this rate is expected to increase.

### 1.2 Means for strengthening

Assuming no defect, the following relationship[8] generally exists between the fatigue limit, $\sigma_w$, and Vickers hardness, $HV$:

$$\sigma_w = 1.6HV \quad \cdots\cdots\cdots (1)$$

wherein the units are in MPa for $\sigma_w$ and kgf/mm$^2$ for $HV$.

**Table 1** Chemical compositions of wire rod for valve spring (mass%)

| Steel grade | | C | Si | Mn | Ni | Cr | V |
|---|---|---|---|---|---|---|---|
| KHV12N | Ultra high tensile | 0.60 | 2.15 | 0.45 | 0.20 | 1.75 | 0.27 |
| KHV10N | Super high tensile | 0.58 | 2.00 | 0.85 | 0.30 | 0.95 | 0.10 |
| KHV7 | High tensile | 0.62 | 1.45 | 0.60 | — | 0.60 | 0.12 |
| SAE9254 | SWOSC-V | 0.55 | 1.40 | 0.65 | — | 0.65 | — |
| SAE6150 | SWOSV-V | 0.50 | 0.25 | 0.80 | — | 0.95 | 0.20 |
| SAE1070 | SWO-V | 0.70 | 0.25 | 0.80 | — | — | — |

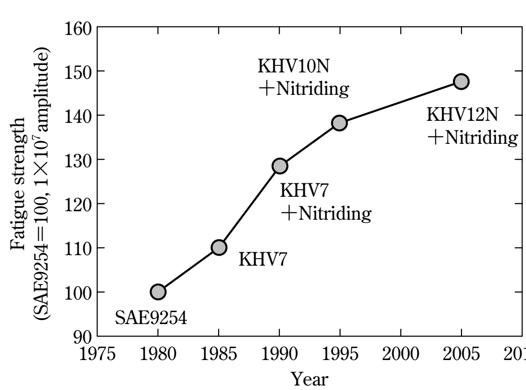



**Fig. 3** Trend of high strength steel grades for valve spring in KOBE STEEL

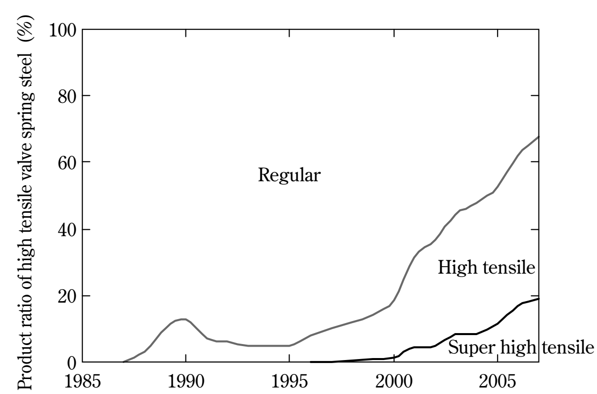



**Fig. 4** Product ratio of valve spring steel grades in KOBE STEEL

Valve springs for automobile engines are used over an extended period of time in a severe environment of high temperature and high stress. In such an environment, a non-metallic inclusion larger than about 10$\mu$m can initiate fatigue fracture.

Murakami estimated the fatigue limit, $\sigma_w$, when internal defects such as inclusions were present, as follows[8].

$$\sigma_w = \frac{1.56(HV+120)}{(area)^{1/2}} \cdot \left[\frac{(1-R)}{2}\right]^{\alpha} \quad \cdots\cdots\cdots\cdots\cdots\cdots (2),$$

where $R=(\sigma_m-\sigma_a)/(\sigma_m+\sigma_a)$,

$\alpha = 0.226 + HV \times 10^{-4}$,

$area$: Area of defect [$\mu$m$^2$],

$\sigma_m$: Mean stress [MPa],

$\sigma_a$: Stress amplitude [MPa],

in which the units are in MPa for $\sigma_w$ and kgf/mm$^2$ for $HV$

According to this formula, hardness must be increased and the defect size decreased to improve fatigue strength. A conventional method of improving fatigue strength is to increase the strength of wire by oil tempering; however, when the tensile strength exceeds 1,800MPa, fracture is initiated at non-metallic inclusions, causing the fatigue strength to vary[1] as shown in **Fig. 5**. Thus, there is a limit to improving fatigue strength by increasing the tensile strength of wires. To overcome this issue, several approaches have been undertaken, such as increasing surface hardness by nitriding treatment and applying compressive residual stress by shot peening. Compressive residual stress can be treated as mean stress that reduces the effective stress.

Sag resistance, on the other hand, can effectively be improved by increasing the tensile strength (internal hardness) of spring wires[9].

The following outlines the treatment and technology for strengthening.

### 1.2.1 Nitriding treatment

Nitriding treatment is generally applied at a temperature from 400 to 600℃. This treatment hardens the surface layers of springs, increases compressive residual stress and significantly improves fatigue strength. However, the treatment reduces internal hardness, making it difficult to satisfy both fatigue strength and sag resistance at the same time. To resolve this issue, oil-tempered wires with softening resistance are very important.

### 1.2.2 Shot peening treatment

Shot peening is effective in improving the fatigue strength of parts such as valve springs. This treatment increases the compressive residual stress and hardness of the treated surfaces so as to increase fatigue strength. Multi-stage shot peening has been employed for increasing the fatigue strength[10]. Methods reported more recently include fine shot peening to improve residual stress[11), 12)] and enhanced shot peening for nano-sizing surface crystals to improve fatigue strength[13]. These shot peening technologies should be combined with other surface modification technologies to achieve further strengthening.

### 1.2.3 Inclusion control technology

Non-metallic inclusions, which mainly consist of $SiO_2$, can cause breakage of valve springs. These non-metallic inclusions are rendered harmless by lowering their melting point by controlling their compositions in the direction indicated by the arrow[2] in **Fig. 6**.

To control the composition in the direction of

| Material | Initiation of Fracture | | Chemical Compositions (wt%) | | | | |
|---|---|---|---|---|---|---|---|
| | Inclusion | Surface | C | Si | Mn | Cr | V |
| Si-Cr Steel | ● | ○ | 0.55 | 1.40 | 0.70 | 0.70 | — |
| Cr-V Steel | ▲ | △ | 0.67 | 0.25 | 0.75 | 0.50 | 0.20 |
| Plain Carbon Steel | — | □ | 0.82 | 0.25 | 0.45 | — | — |

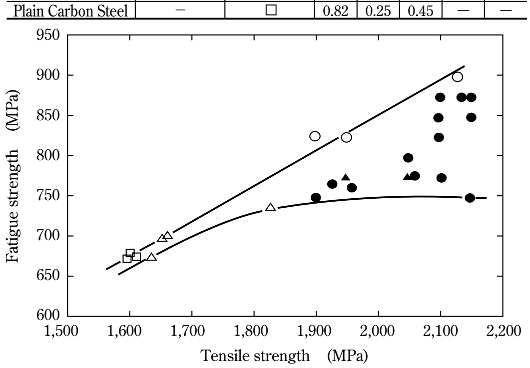



**Fig. 5** Effect of tensile strength of steel wire for valve spring on fatigue strength

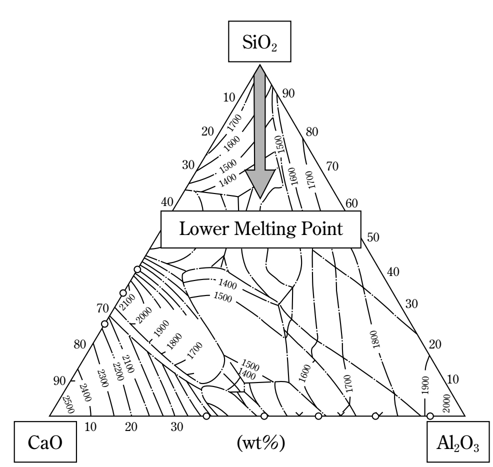



**Fig. 6** Composition of inclusion[9]

the arrow, the processing parameters, such as slag basicity during secondary melting, must be controlled more accurately.

## 2. Characteristics of ultra-high strength wire rod for valve springs

Kobe Steel developed, and commercialized in 2006, an ultra-high strength wire rod, KHV12N, for valve springs; this wire rod has the world's highest fatigue strength. This chapter introduces the characteristics of KHV12N.

### 2.1 Concept of composition design

To improve the nitriding property and refine crystal grains, larger amounts of Cr and V are added than was the case with the previously developed KHV10N. In addition, an increased amount of Si was added to improve temper softening resistance in order to prevent a reduction in internal hardness during nitriding treatment and thus to enhance sag resistance.

### 2.2 Characteristics of oil-tempered wires

**Table 2** shows the mechanical properties and grain size numbers of oil-tempered wires. An ultrafine grain structure (austenite grain size number 14) was obtained for KHV12N. This oil-tempered wire was subjected to low temperature annealing for 20 minutes for stress relieving after cooling. **Fig. 7** shows the mechanical properties after annealing at different temperatures. KHV12N exhibits improved softening resistance and less strength reduction at elevated temperatures even when compared with another high-strength valve spring wire, KHV10N.

### 2.3 Fatigue characteristics of springs

**Fig. 8** shows the fatigue and sag characteristics of springs made of three different wires. Nitrided KHV12N exhibits a fatigue strength about 1.6 times higher than that achieved by SAE9254. This enables the spring weight to be almost halved. **Fig. 9** shows an example of a spring made of KHV12N.

**Fig.10** shows the sag resistances of springs made of various materials. KHV12N exhibits the highest resistance against sag. The austenitic grain size number turns out to correlate well with the tensile strength of spring wires. The sag for KHV12N is decreased by about 60% compared with that for SAE9254, and by about 20% compared with that for KHV10N. This is regarded as attributable to the refinement of crystal grains. **Fig.11** shows the

Table 2 Properties of oil-tempered wire

| | Tensile strength [MPa] | Reduction of area [%] | $\gamma$ grain size No. |
|---|---|---|---|
| KHV12N | 2,157 | 46.4 | 14.0 |
| KHV10N | 2,155 | 52.4 | 12.0 |

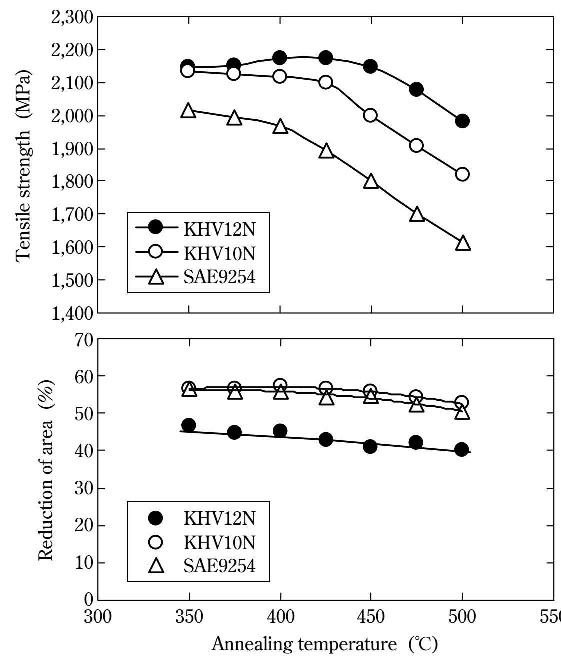



Fig. 7 Relationship between annealing temperature and mechanical properties

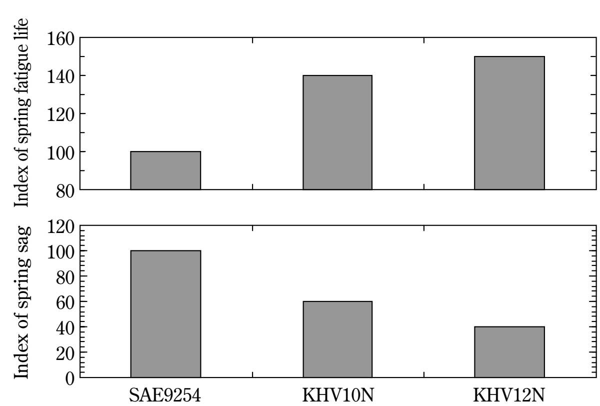
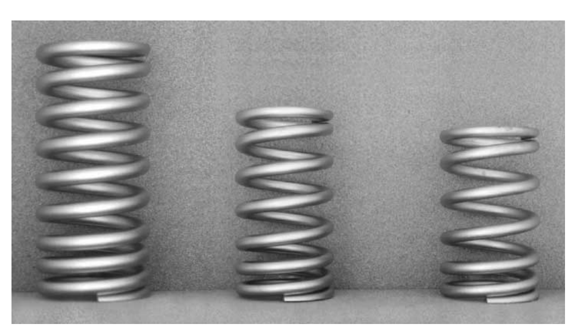



Fig. 8 Fatigue life and sag index of high-tensile valve spring



SAE9254 KHV10N KHV12N

Fig. 9 Comparison of valve spring height

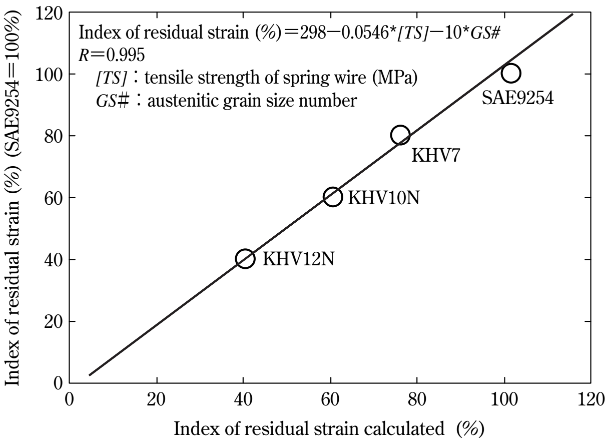



**Fig.10** Sag resistance with a function of tensile strength and austenitic grain size number

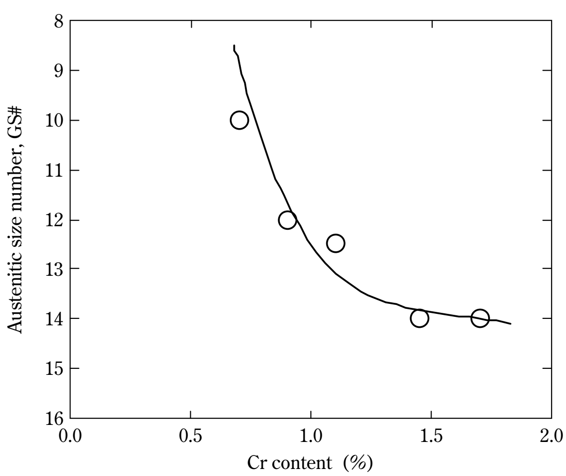



**Fig.11** Relationship between austenitic grain size number and Cr content

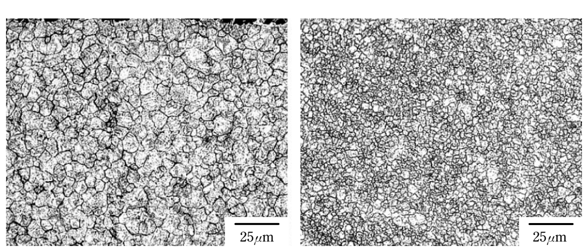



**Fig.12** Etched austenitic grain of ultra-high tensile valve spring

relationship between the amount of Cr added and grain size. **Fig.12** are micrographs of KHV12N and KHV10N after grain boundary etching. The increased amount of Cr added in KHV12N improves the thermal stability of carbide, making the carbide more effective in preventing crystal grains from coarsening. Furthermore, the increased addition of V increases the amount of carbide containing V, enabling the ultra-refinement represented by grain size number 14. These are considered to be the reasons for the improved sag resistance.

## Conclusions

Kobe Steel developed wire rods for valve springs earlier than any other company and has supplied them to the market. The wire rods are characterized by good robust quality and high strength, which enable the steel to be used under high stress. After 2015, the production volume of hybrid vehicles (HV) using both gasoline engines and electric motors is expected to increase rapidly. Kobe Steel's high strength wire rods for valve springs, including the ultra-high strength series, are effective in downsizing HV engines and in improving the fuel economy of gasoline engines. Kobe Steel will strive to contribute to the growth of the automobile industry and help to resolve global environmental problems.

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