

# The Past and Future of High-strength Steel for Valve Springs

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*For reduced fuel consumption, there is a rising demand for downsizing and weight reduction in automobile engine valve springs. Corresponding to this demand, Kobe Steel has developed a high tensile strength steel for the valve springs and has greatly improved upon the conventional manufacturing process of the springs. This article describes the current trends in high strength steels for valve springs and the latest development status of the super-high strength steels.*

## Introduction

There is an increasing demand to reduce the size of the valve train in automobile engines. Part of the demand is due to environmental concerns and part is because of passenger safety. The environmental aspect is caused by the need to reduce CO<sub>2</sub> emissions by improving fuel consumption. In an automobile engine approximately 40% of energy loss, other than direct heat loss, is due to friction and 15%-50% of this is believed to be due to the valve train. A reduction in size of the valve train should reduce the friction loss and reduce fuel consumption. The passenger safety aspect follows from the increasingly stringent standards for passenger head protection in a collision. In order to meet these standards, further down-sizing of the engine is desirable since it gives more collision-absorption space in the engine compartment.

The downsizing and strengthening of automotive valve springs (**Figure 1**) have been pursued for the purposes described above. Valve springs weigh only 20 to 50 grams each, but are subject to several thousands cycles per minute of repeated stress and are required to have extremely high reliability over extended period of times.

The increasing stress applied to the valve springs has led to the development of steels with

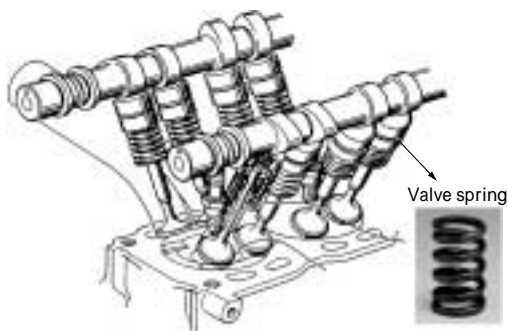


Fig. 1 Valve spring in automobile engine

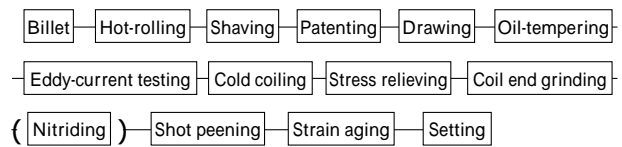


Fig. 2 Manufacturing process of valve spring

higher fatigue strength and high sag resistance.<sup>1), 2)</sup> Surface modification technologies have been applied also to increase fatigue strengths. The general process of spring production includes nitriding and shot peening as shown in **Figure 2**.

This article describes the history and current status of our development in the strengthening of steels for the valve springs.

## 1. Strengthening of steels for valve spring

### 1.1 History of strengthening

There are two kinds of wires used for valve springs: piano wires drawn from high-carbon steel wire rods and oil-tempered wires quenched and tempered after drawing.

Piano wires made in Sweden were widely used for valve springs before the World War II. We began development of high-carbon steel wires in 1930 and started the production of piano wires for automotive valve springs after successful developments in 1941. Our wires were used mostly for the valve springs of aircraft engines in the early days and came to be used in automobiles later.<sup>3)</sup> In 1952 we succeeded in developing a wire rod (KPR; Kobe Piano wire Rod) that compared well with the piano wires made in Sweden.<sup>4)</sup>

After the war oil-tempered wires were introduced from the USA. Oil-tempered carbon wires and oil-tempered Cr-V wires were first produced domestically in 1955 and were used gradually in automobile engines.<sup>5)</sup>

The Si-Cr oil-tempered wire (SAE9254, JIS SWOSC-V), having higher heat-resistance, began to be used in 1964 for higher fatigue strength and sag resistance, and has come to be used as today's standard.

**Table 1** compares the chemical compositions of the spring wire steels for JIS and of the ones developed by us. The progress of the development is summarized in **Figure 3**. Flaws and decarburization on wire surfaces are known to

Table 1 Chemical compositions of wire rod for valve spring

		(mass%)						
		C	Si	Mn	Ni	Cr	V	Steel grade
High Si-Cr-V steel	Super high tensile	0.56 - 0.61	1.80 - 2.20	0.70 - 1.00	0.20 - 0.40	0.85 - 1.05	0.05 - 0.15	KHV10N
Si-Cr-V steel	High tensile	0.60 - 0.65	1.30 - 1.60	0.50 - 0.70	-	0.50 - 0.70	0.08 - 0.18	KHV7
Si-Cr steel	SWOSC-V	0.51 - 0.59	1.20 - 1.60	0.50 - 0.80	-	0.50 - 0.80	-	SAE9254
Cr-V steel	SWOCV-V	0.45 - 0.55	0.15 - 0.35	0.65 - 0.95	-	0.80 - 1.10	0.15 - 0.25	SAE6150
Carbon steel	SWO-V	0.60 - 0.75	0.12 - 0.32	0.60 - 0.90	-	-	-	SAE1070

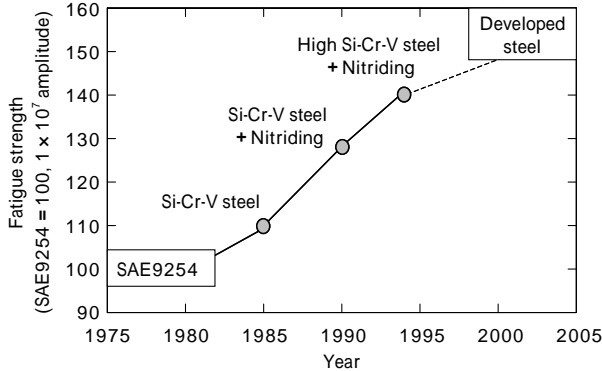


Fig. 3 Trend of high strength steel for valve springs in Kobe Steel

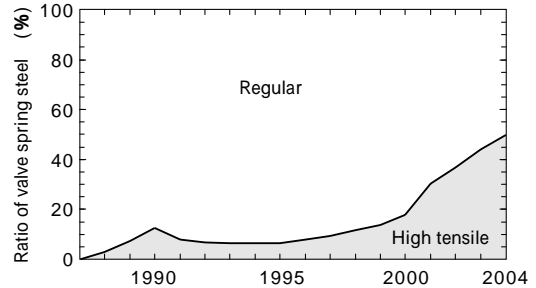


Fig. 4 Ratio of valve spring steel in Kobe Steel

affect the fatigue strength of oil-tempered wires and we have developed technologies to reduce flaws and decarburization, and to remove the surface layer completely along the whole length of the wire by shaving.<sup>6)</sup> In the early 1980s we established technologies to evaluate and control inclusions.<sup>7)</sup> The technologies were applied to SAE9254 wire to improve the fatigue strength of valve springs.

Further study on the optimization of chemical composition led to the development of Si-Cr-V steel in the mid 1980s, in which higher C content increases the strength, and an addition of V increases the softening resistance and refines the austenite grain size. The Si-Cr-V oil-tempered wire has a tensile strength of 2,050MPa class, while the standard oil-tempered wire of SAE9254 has strength of about 1,900 MPa. The use of this steel has improved fatigue strength by a factor of 1.1 compared to SAE9254. Additional nitriding treatment improves fatigue strength by a factor of approx. 1.3.

High Si-Cr-V steel containing 2.0% Si was developed in the early 1990s to improve the softening resistance. As a result, the tensile strength of the oil-tempered wire was increased to 2,200MPa class and additional improvement of nitriding and shot-peening improved the fatigue strength of the SAE9254 by a factor of 1.4.

Figure 4 shows the ratio between the high tensile-strength and regular steels for valve springs made in our production. The use of high-tensile strength steels has increased to occupy about half

of the world wide usage of steel for valve springs and will continue to increase in the future.

### 1.2 Strengthening method

Assuming no defect, the fatigue strength is calculated by the following equation.<sup>8)</sup>

$$\sigma_w = 1.6HV \dots\dots\dots (1)$$

Valve springs are subject to severe working conditions at high temperatures under high stresses and for extended period of times. This results in fatigue fracture of the valve spring by initiation at non-metallic inclusions larger than 10 μ m. Murakami estimated<sup>8)</sup> that the fatigue strength  $\sigma_w$  in the presence of internal defects such as inclusions to be,

$$\sigma_w = \frac{1.5\alpha(HV + 120)}{\sqrt{area}^{1/6}} \left( \frac{1 - R}{2} \right) \dots\dots\dots (2)$$

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

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

$area$  = defect area,  $\sigma_m$  = average stress

The formula indicates that an increase in hardness and reduction in defect-size are required to improve fatigue strength.

Improvements of fatigue strength have been achieved mainly by increasing the strengths of oil-tempered wires, however, this approach has a limit at a tensile strength of 1,800 MPa, above which the fatigue strength tends to deteriorate<sup>1)</sup> due to the fracture at non-metallic inclusions as shown in Figure 5. Further improvement of fatigue strength employs surface treatments such as nitriding to increase surface hardness and shot-peening to add compressive residual stress. The compressive residual stress counteracts as the

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	-	-

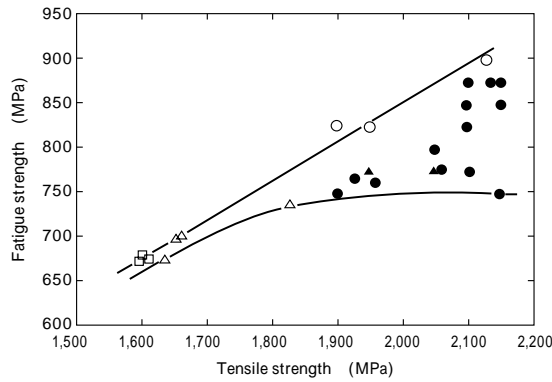


Fig. 5 Effect of tensile strength of steel wire for valve spring on fatigue strength and on initiation site of fracture

average stress, thus reducing the effective stress.

On the other hand, increase of the tensile strength (increase of the core hardness) is effective in improving the sag resistance as shown in **Figure 6**.

The following describes the detail of each strengthening method.

1) Application of nitriding

**Figure 7** shows the effect of nitriding temperature on the surface hardness and core hardness. Nitriding, generally processed at 400 to 600 °C, increases the surface hardness and compressive residual stress of the spring, which improves the fatigue strength significantly. However, the treatment tends to reduce the core hardness, making it difficult to improve both the fatigue strength and sag resistance simultaneously. The improvement in the softening resistance of the oil-tempered wire is effective in solving this problem.

2) Application of shot-peening

Shot-peening, which increases the compressive residual stress and surface hardness, is effective in improving the fatigue strengths of valve springs. Multi-step shot peening has been applied for the improvement of fatigue strength.<sup>9)</sup> Recently, several technologies have been reported including a method to increase fatigue strength by improving the residual stress by using fine shots<sup>10), 11)</sup>, and a method to increase fatigue strength by inducing nanocrystals at the surface through a severe shot-peening. Such technologies might be combined to achieve even higher strengths.

3) Control of inclusions

Inclusions of Al<sub>2</sub>O<sub>3</sub>, MgO-Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> are known to cause breakage of valve springs. The

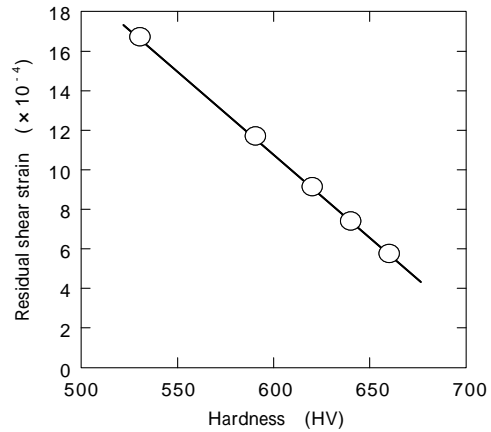


Fig. 6 Relationship between core hardness and residual shear strain

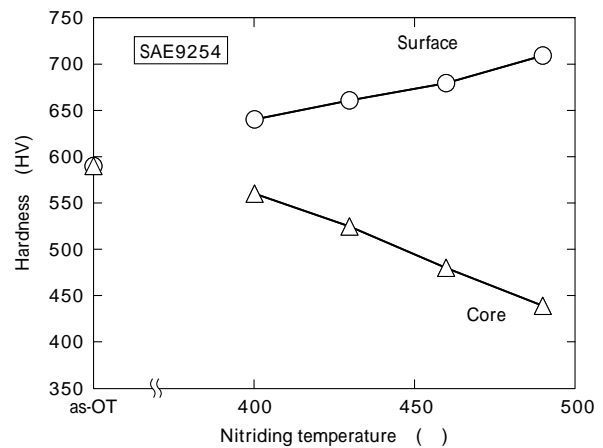


Fig. 7 Relationship between nitriding temperature and hardness

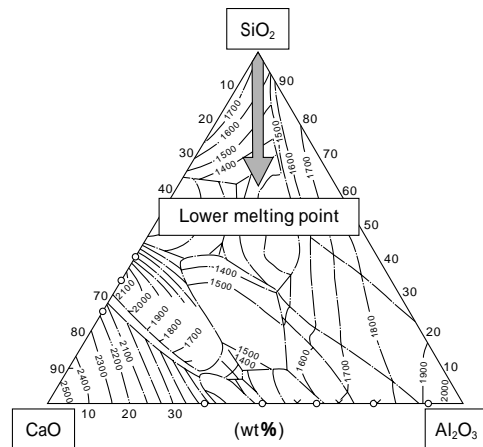


Fig. 8 Composition of inclusion

compositions of the inclusions should be controlled to become lower melting point as shown in **Figure 8**.<sup>12)</sup>

In order to control the compositions in the region, the basicity of slag should be controlled according to the amount of Si and a minute amount of Al should be added in optimum

concentrations.

## 2. Properties of the super-high strength steel for valve springs

We have developed a super-high strength valve spring steel for the next generation, which has fatigue strength even higher than that of high Si-Cr-V steel. The following describes the properties of the steel.

### 2.1 Concept of the composition design

Further additions of Cr and V to the high Si-Cr-V steel improve nitriding and refine grain size. Increased amount of Si improves sag resistance by increasing temper softening resistance and by inhibiting reduction of core hardness during the nitriding process.

### 2.2 Properties of oil-tempered wire

Table 2 shows the mechanical properties and grain size of an oil-tempered wire. A super-fine microstructure of austenite grain-size No.14 was obtained. Oil-tempered wires, including the one made of newly developed steel, were annealed at low temperatures for 20 min for stress relief and the results are shown in Figure 9. The newly developed steel shows a higher softening resistance compared to the high Si-Cr-V steel and shows a smaller decrease in strength at higher temperatures.

### 2.3 Fatigue properties of the spring

The fatigue strengths of the springs made of different steels are shown in Figure 10. The newly developed steel with nitriding can achieve a fatigue-strength higher by a factor of 1.55 compared to the SAE9254. This allows the reduction of the spring weight by half (Photo 1 shows examples of valve springs made of conventional and newly developed steels).

## 3. The future perspective and conclusions

The global issues on environment and safety call for safer automobiles with lower environmental burden. The demand for high-strength spring steel is becoming higher because valve springs are effective in cutting CO<sub>2</sub> emissions, in improving fuel-consumption, and in downsizing of engines. The strengthening of the valve spring, which originally started in Japan, is accelerating both in

Table 2 Properties of oil-tempered wire

	Tensile strength (MPa)	Reduction of area (%)	grain size No.
Developed	2,157	46.4	14.0

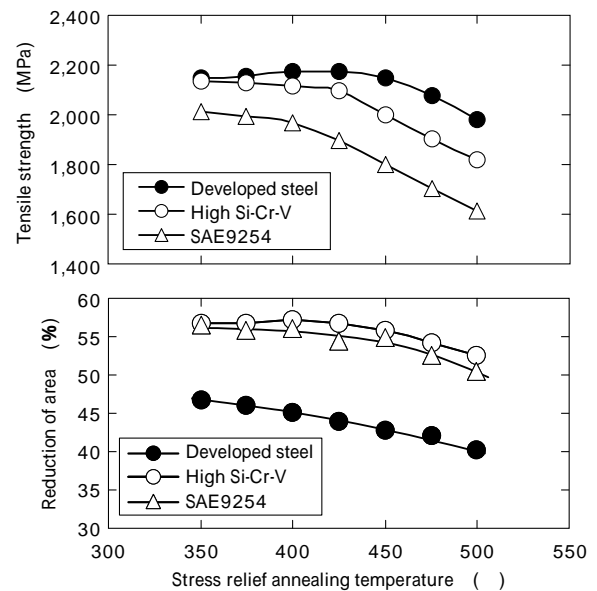


Fig. 9 Relationship between stress relief annealing temperature and mechanical properties

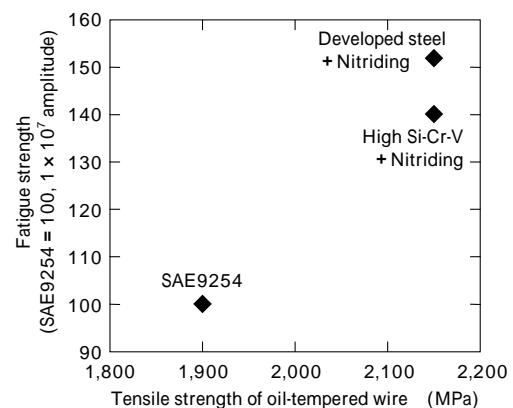


Fig.10 Relationship between fatigue strength and tensile strength of oil-tempered wire for valve spring

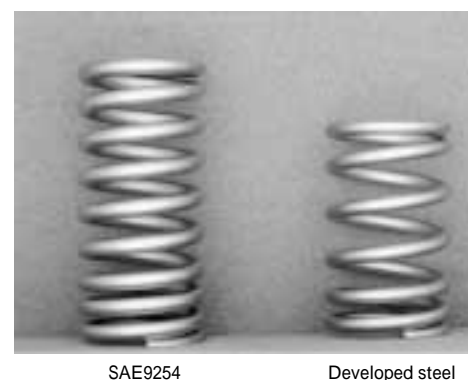


Photo 1 Valve springs made of SAE9254 and developed steel

Europe and in the USA and further improvements will proceed more rapidly.

The modifications of the spring processing technologies, including improved shot-peening and application of new surface treatments, will be needed for the further improvements.

Further improvements of reliability are required for the application of the super-high strength valve spring and it is essential to reduce non-metallic inclusion sizes. Even higher strength will be obtained with advancement of steel making technologies which limit the size of non-metallic inclusions to less than 10 to 20  $\mu\text{m}$ .

We will continue to play a role in environmental protection and contribute to society by providing high-strength steels for valve spring with high reliability.

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