High Strength, Oil-tempered Steel Wire for Valve Springs, Manufactured by Rapid Heating Mono-strand Process

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Conventionally, oil-tempered steel wires for valve springs are manufactured in multi-strand type furnaces. This article describes the characteristics of a rapid heating, mono-strand, oil-tempering furnace equipped with a high frequency induction heater. Also discussed are the special features of high strength, oil-tempered wires produced by this new type of furnace. SHINKO WIRE CO., LTD. successfully developed those wires in response to the need for downsizing and weight reduction for automobile engine valve springs. These high quality springs contribute to reduce overall vehicle fuel consumption and thus comply with the growing trend towards improving the environment.

Introduction

Fundamental requirements for springs include not only desired spring characteristics, but also reliability for an extended period of time, especially against breakage and sagging. Valve springs, in particular, require extremely high reliability, since they are subject to cyclic loads of several thousand times a minute for extensive periods of time equal to the lives of vehicles. In addition, downsizing is also required for valve springs, as a part of the effort to reduce weights and improve fuel economics of vehicles for environmental protection and resource saving. In association with this, steel wires for valve springs are required to have even higher strengths, smaller diameters and varied cross-sectional shapes.

Conventional valve springs are manufactured from piano wires, carbon steel oil-tempered wires, Cr-V oil-tempered wires designed specifically for valve springs. In recent years, Si-Cr oil-tempered steel wires are being used more commonly because of their strengths and sag resistances. More recently, high strength Si-Cr-V oil tempered wires are being used widely, not only domestically but also abroad. SHINKO WIRE COMPANY, LTD. manufactures oil-tempered wires for valve springs using a unique rapid-heating mono-strand method, which is employed by no other manufacturers in the world and has lead the development of various high-strength, oil-tempered valve spring wires by exploiting the uniqueness of the method, through collaborations with automakers and spring manufacturers.

This article describes the features of the manufacturing method of oil-tempered wires and the background behind strengthening of oil-tempered wires for valve springs.

1. Manufacture of oil-tempered wires for valve springs using rapid-heating mono-strand process

1.1 The target qualities and the process for achieving target

We strive to provide oil-tempered steel wires that are manufactured into "good springs" at "high efficiencies" at our user's sites, or spring manufacturers. The basic concept of such wire production is summarized in **Figure 1**. Good springs have high reliability with high precision, high fatigue strengths and low rates of sagging. To achieve high fatigue strengths, wires are required to have high strength and toughness without flaws, decarburization and internal defects, such as non-metallic inclusions. For the production efficiencies of springs, steel wires are required to have good workability into coils and lubricity during fabrication. The wires are also required to cause less damage to the tools used for fabrication, have almost no variation of quality in each whole length of wire and to cause no trouble, such as breakage, during fabrication.

SHINKO WIRE COMPANY, LTD. chose a process, best suited for the manufacturing of wires to produce such "good springs", which ensures high strength and toughness, taking into consideration the decarburization, flaws, unstable coiling and twisting

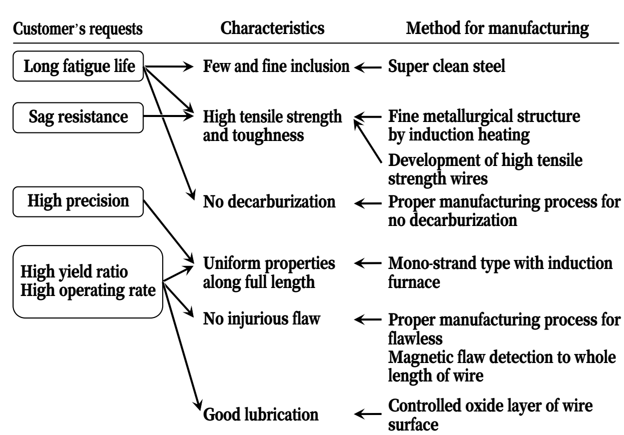


Fig. 1 Important points about production of oil-tempered steel wire for valve spring

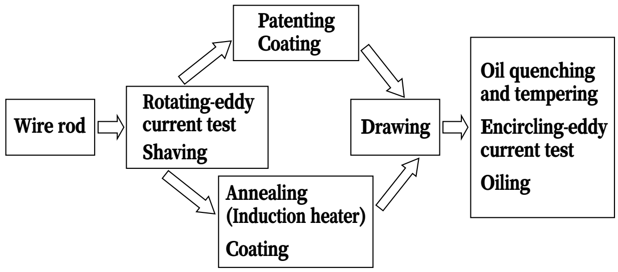


Fig. 2 Manufacturing process of oil-tempered steel wire for valve spring

of ovate wires. **Figure 2** shows the manufacturing process of oil-tempered steel wires for valve springs.

1.2 Manufacturing process of wires before oil-tempering

All the raw material of wires for valve springs are steel wire rods manufactured by the Kobe Works of Kobe Steel, in which special controls are made on non-metallic inclusions to render the inclusions harmless.

In the manufacturing process of wires, longitudinal seams are first detected by a rotary-type, eddy-current flaw detector and the wire surfaces are peeled off along the whole lengths of wires, so that any decarburized layers and seams, including small scratches below the detection limit, are removed. In the next step, the wires are heat-treated (by patenting or high-frequency furnace annealing) to produce homogeneous microstructures, suitable for wiredrawing, and a coating is applied, in-line, which carries the lubricant powder into wiredrawing dies. Then, wiredrawing is carried out through several dies in a continuous wiredrawing machine to produce desired surface roughness, diameters and cross-sectional shapes (for example, ovate). The wires are fed into the next process step of oil-tempering.

1.3 Oil-tempering treatment method

The heat-treatment furnaces, most commonly used, are strand-type furnaces, in which ten or so wires are laid in parallel and are simultaneously heat-treated through heating, quenching and tempering. For the heating process, indirect heating furnaces, having pipes to hold inert atmosphere, are typically used. The heated wires are oil-quenched and then tempered in furnaces, such as molten lead furnaces, atmosphere furnaces and fluidized bed furnaces. The heating speeds of such conventional furnaces, however, are not fast enough to prevent grain growth, which is observed at the end of austenite homogenization.

In order to obtain fine austenite grains, it is essential to rapidly heat the wires to a predetermined

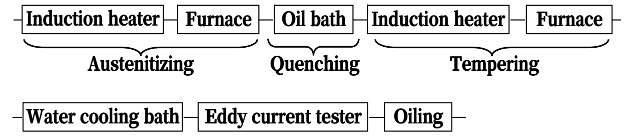


Fig. 3 Rapid heating mono-strand oil-tempering furnace

temperature in the austenite region and to hold the temperature for a minimal amount of time to prevent the grain growth. Such treatment should provide a metallographic structure which is fine and distributed homogeneously, even in the longitudinal directions. Based on the above concept, we applied a mono-strand oil-tempering furnace, using a high-frequency induction heater, for the heating to austenite and tempering, respectively. The outline of the oil-tempering furnace is shown in **Figure 3**. The furnace has the following features.

1) The mono-strand configuration, in which only one wire goes through at a time, allows adjustment of heating conditions for steel types and sizes, easily through adjusting the power of the high frequency induction heater. This makes the furnace flexible to changes, such as in production planning.
2) A holding furnace, installed behind the high frequency induction heater, keeps the wire temperature constant until immediately before the oil-quenching and grows surface oxide films, which play an important role in the lubrication of wires during the coil fabrication, to adequate thicknesses with appropriate compositions.
3) More stringent quality control, per bundle of product wires, is made possible by monitoring not only the production parameters, but also the wire temperatures after the induction heating for quenching and tempering treatments.
4) The process steps are significantly reduced by a through-type, eddy-current flaw detector and a rust inhibiting oil applicator, both installed in the line.
5) The furnace configuration makes the shut-down and launching comparatively easier, allowing short maintenance times for repairs, because of short cooling time and reheating time compared to the conventional furnace.

2. High performance valve springs

2.1 Advancement of valve spring manufacturing technologies

Although large stresses are applied to the wire surfaces of coil springs, the wire surfaces inescapably have some irregularities, such as decarburized layers and flaws, which become weak points. Spring manufacturers have spent a significant effort to improve the wire surface qualities to assure higher qualities of valve springs. The development of the shot-peening process, in particular, has lengthened the fatigue lives of springs remarkably, in which process, compressive residual stresses are introduced to the spring surfaces, which are most likely the weakest points, to reduce the actual surface stresses and harden the surfaces. The shot-peening technology, originally developed by a USA firm in 1930s, was modified and developed into variations, including warm shot-peening, stress-peening, multi-stage shot-peening and hard shot-peening, which result in higher compressive residual stress imparted on the surfaces with deep crossing points (points at which residual stresses change from compressive to tensile) and thus contributed[1)-3)] to the improvement of fatigue strength. In addition, nitriding processes have further strengthened sub-surface layers of the wires and further improved the fatigue properties.

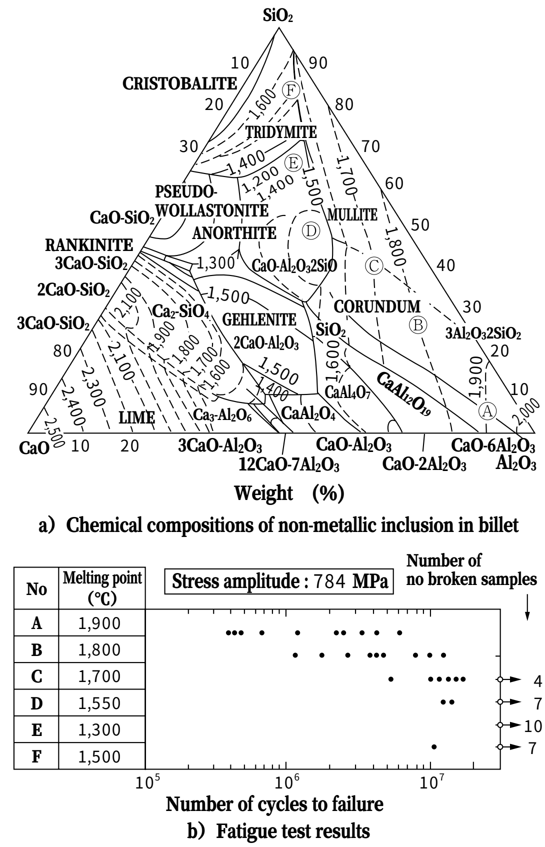
On the other hand, sagging of springs during usage has been reduced by treatments such as setting[4)] and hot-setting, added to the final process step of spring production. There are also instances when springs are broken by excessive stresses cased by a resonance, called surging, when the springs are subject to high speed repeating stresses, in which characteristic frequencies of the springs resonate with driving frequencies. In order to prevent this phenomenon, various modifications have been made in the spring designs, which include development of springs with uneven pitches. Furthermore, development of springs with modified (mainly ovate) cross-sections, in which actual stresses are more evenly distributed in the cross-section, reduced the height of the springs as a result of reduced solid height of the spring.

The performance improvement of valve springs has been made by the collaborative results of various developments made by spring manufacturers, and strengthening of wires, and has contributed to the weight reduction and fuel economy of vehicles.

2.2 Development of ultra-purification technologies for valve spring steel

As the wire surfaces are strengthened by treatments, such as shot peening and nitriding, the maximum points of actual stress are moved to 0.2 to 0.3 mm below the surface of the wires. As a result, non-metallic inclusions existing at these depths, with certain sizes, can initiate fatigue fractures of valve springs.

Kobe Steel tackled the issue and developed a super-clean steel[5)] and technologies, for the first time



a) Chemical compositions of non-metallic inclusion in billet

b) Fatigue test results

Fig. 4 Relationship between chemical compositions of non-metallic inclusion in billet and fatigue life[5)]

in the world, to reduce the non-metallic inclusions and also render the inclusions harmless. **Figure 4** shows the relation between the compositions of non-metallic inclusions and fatigue lives of springs. By shifting the compositions of the non-metallic inclusions to low melting point regions, the non-metallic inclusions are dispersed in smaller sizes during hot and / or cold working and thus immunized.

2.3 Strengthening of oil-tempered wires for valve springs

2.3.1 Product menu of oil tempered wires

Table 1 summarizes oil-tempered wires for valve springs and their chemical compositions produced by SHINKO WIRE COMPANY, LTD. We produce five kinds of steels and six kinds of products, including SWOSC-V, an equivalent of the Si-Cr oil-tempered wire for valve springs specified in JIS G 3561, and five others which have higher strengths. The following is our concept of the strengthening of steel.

1) Strengthening by lowering the tempering treatment temperatures after oil-quenching; SWOSC-VU
   Taking the advantage of the fine grains due to the rapid heating and the easiness of selecting treatment conditions in the induction furnace

Table 1 Chemical compositions of oil-tempered steel wire for valve spring

(mass%)

Product class	Wire name	Steel grade	C	Si	Mn	Cr	V	Ni
Si-Cr steel	SWOSC-VU	SAE9254	0.51-0.59	1.20-1.60	0.50-0.80	0.50-0.80	—	—
High carbon Si-Cr steel	SWOSC-VH	HRS7-V	0.63-0.68	1.30-1.60	0.60-0.80	0.60-0.80	—	—
Si-Cr-V steel	SWOSC-VT	KHV7	0.60-0.65	1.30-1.60	0.50-0.70	0.50-0.70	0.08-0.18	—
High Si-Cr-V steel	SWOSC-VX	KHV10N	0.56-0.61	1.80-2.20	0.70-1.00	0.85-1.05	0.05-0.15	0.20-0.40
Developed Si-Cr-V steel	SWOSC-VXT	KHV12N	0.57-0.63	1.95-2.35	0.30-0.60	1.65-1.85	0.25-0.35	0.10-0.30

line, the tempering treatment temperature is lowered for steel having the same composition as SWOSC-V to increase the strength[6], while maintaining the toughness. Using this material, the fatigue strength of springs can be improved even further, by choosing the low temperature annealing conditions after coiling.

2) Strengthening by increased carbon content; SWOSC-VH
The carbon content of SWOSC-V is increased to raise its tensile strength.

3) Strengthening by alloying and increase of alloying elements; SWOSC-VT, SWOSC-VX, SWOSC-VXT
Several alloys were developed[7)-9)] by increasing Si and Cr contents, and / or by adding other elements to high-carbon steel, in order to maintain high tensile strength, while improving sag resistance, after the low temperature annealing and nitriding treatment. The addition of vanadium causes precipitation of fine vanadium carbide which strengthen the alloy, whereas the addition of nickel improves the toughness. The SWOSC-VX and SWOSC-VXT, in particular, are intended for use with nitriding treatment after spring fabrication. **Figure 5** shows the relationship between low annealing temperatures and the tensile strengths of oil tempered wires. **Figure 6** compares the fatigue strengths of valve springs made of different high-strength oil-tempered wires. The spring made of SWOSC-VXT, a steel developed most recently, has a fatigue strength almost 50% better than that of the conventional SWOSC-V.

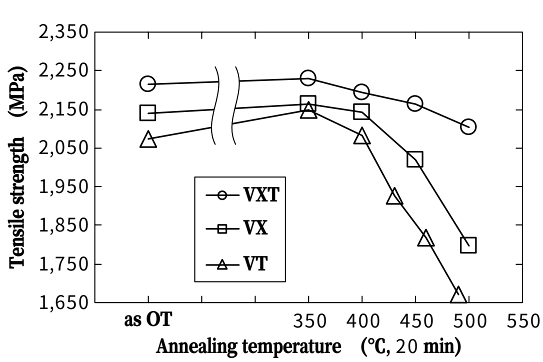


Fig. 5 Relationship between low annealing temperature and tensile strength

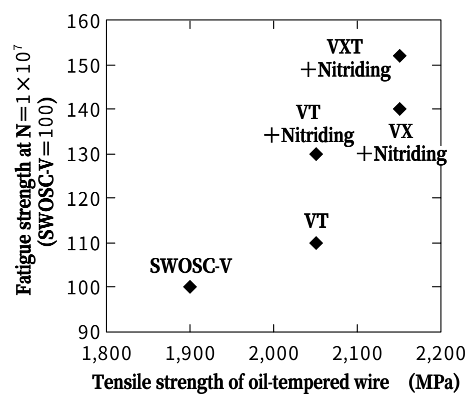
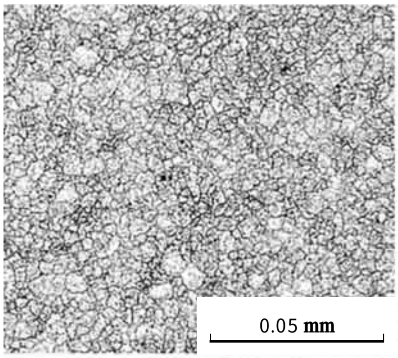


Fig. 6 Relationship between fatigue strength and tensile strength of oil-tempered wire for valve spring

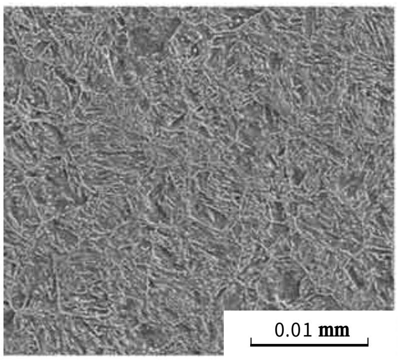
2.3.2 Production technologies for high-strength steel wires

1) Countermeasures against decarburization and surface defects
High strength oil tempered wires generally have high notch sensitivities, because of their high strength with low toughness, and it is important to prevent surface defects from occurring throughout the whole production process. It is also important to prevent defective products shipped out of the manufacturing site (Escape prevention), in case that defects should occur. As for escape prevention of flaws of products, longitudinal seams and spot flaws are inspected and excluded, if any, from the line, by using both the eddy-current flaw detectors of rotary-type and through-type. As a countermeasure against decarburization, the atmosphere and condition, of the heat treatment after peeling, are controlled so as not to cause decarburization. Wires with minimal, if any, decarburization can be obtained, as a result of the short treatment time at the temperatures at which decarburization tends to occur, which is an advantage of applying a rapid heating method for the final oil-tempering treatment.

2) Refining of metallurgical microstructure



a) Austenite grain size



b) Micro structure

Photo 1 Micro structure and austenite grain size of oil-tempered wire (SWOSC-VXT)

The mono-strand process allows easy changes of process conditions, for each steel type and wire diameter, enabling operations for which conditions are optimized for each product. In this way, process conditions are controlled for each coil, in which the process features of producing wires with fine and homogeneous microstructures, are fully exploited. **Photo 1** shows the old austenite grain size and the microstructures of a rapidly heated oil-tempered wire made of SWOSC-VXT. The rapid heat-treatment results in a finer microstructure (with grain size number; average #12.0, as specified by JIS G 0551) compared to the conventional atmospheric furnaces and an ultra-fine microstructure (with grain size number; average #13.5 to 14.5), especially in case of a Si-Cr-V steel, or SWOSC-VXT, wherein vanadium also acts as a grain refiner.

3) Countermeasure against increased delayed fracture sensitivity
   High-strength oil-tempered wires are heat treated to have tensile strengths up to 2,200 MPa, and minute existence of hydrogen is reported to increase the delayed fracture sensitivity[10]. Because of this, dehydrogenation treatment is optionally carried out after the oil-tempering treatment.

4) Effort to improve coiling workability
   When springs are made of a high-strength oil-tempered wire, the product springs tend to have a small D / d ratio with large pitch angle. Because of this, the lubiricity between tools and wire surfaces becomes an important factor. Especially when using wires with modified cross-sections, the lubiricity becomes more important, because the wires are even more strongly restrained by tools having holes matching the desired wire cross-sections. Various improvements have been made to control the composition and thickness of the wire surface oxide layers, to improve the abilities of lubricant oils and to coat lubricant films on the wire surfaces.

Conclusions

In the process of developing high-strength wires, valve springs made of them are used for racing cars. All the parties involved in the development have experienced the feel of "swing from joy to sorrow" by the results of the racing. Now, such high performance valve springs are used for popular cars all over the world. Looking back on such accomplishments, the challenges for even higher strengths are considered to be inescapable to achieve vehicles' downsizing, weight reduction and longer operating lives and to contribute to global environmental preservation including resource saving and CO_2 emission reduction. Evolution of our technologies is also expected to contribute to increasing demand for safety measures, such as pedestrian protection.

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