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PRECIPITATION STRENGTHENED SPRING STEEL FOR AUTOMOTIVE SUSPENSIONS

Toshiro Yamamoto
Research Department
Aichi Steel Works, Ltd.
Aichi, Japan

Ryohei Kobayashi
Research Department
Aichi Steel Works, Ltd.

Toshio Ozone
Research and Development Division
Chuo Spring Co., Ltd.
Aichi, Japan

Mamoru Kurimoto
Research and Development Division
Chuo Spring Co., Ltd.

ABSTRACT

A spring steel with a small amount of niobium and vanadium added simultaneously into AISI 9260 or SUP7 of the Japanese Industrial Standards is found to have a good sag-resistance or resistance to a small deformation during service for automotive suspension springs. The two alloying elements bring about a retarded softening when quenched and tempered, which is the result of the precipitation of carbides of the two elements. Besides good sag-resistance which is evaluated by two methods, the steel has comparable characteristics to SUP7 in many respects such as hardenability, fatigue properties and so on. Losing the weight of the suspension springs by about 15%, the new spring steel has been used for some Japanese new models since last year and the application is increasing.

WHILE current trend toward lighter automotive suspension springs requires higher working stresses on them, the sag is the primary obstacle for suspension designers. Precedented researches (1,2,3)* revealed that silicon has an advantageous effect of reducing sag on spring steels. That is why a higher silicon steel such as AISI 9260 or JIS-SUP7 (0.6%C-2.0%Si-0.85%Mn) has become widely used as a sag-resistant spring steel in place of JIS-SUP6 (0.6%C-1.65%Si-0.85%Mn) in Japan. Since much improved sag-resistance was needed especially for the suspension springs for modern lightweight FF cars, we investigated every strengthening effect of steels and have come up with the precipitation strengthened spring steel.

PREPARATION

From preliminary experiments, we selected niobium and vanadium as precipitation strengthening elements and added them separately and simultaneously into SUP7. The chemical compositions of the steels we investigated are shown in Table 1. They were induction melted in the atmosphere and poured into 300 kg (660 lb) ingots followed by billeting to 95 mm (3.7 in) square bars. The final products were 12.2 mm (0.48 in) diameter bars, which were then centerless ground to 12.0 mm (0.47 in) to be used mostly for experiments on coil springs, and 30 mm (1.18 in) diameter bars, which were used for hardenability test, fracture toughness test and so on.

RESULTS

AS-ROLLED CONDITION - Microscopic structures of as rolled 12.2 mm (0.48 in) diameter bars of SUP7 and SUP7-Nb-V are shown in Fig. 1. The grain size of SUP7-Nb-V is about one quarter as that of SUP7 in as-rolled condition. On the non-etched polished surfaces of as-rolled SUP7-Nb, SUP7-V and SUP7-Nb-V, i.e., steels with niobium or vanadium, there were rock-shaped constituents of about 1 to 5 μm in diameter. X-ray diffraction analysis performed on the remnant extracted from the steels by chemical solution consisting of phosphoric acid and water identified that they were NbC in case of SUP7-Nb , V_4C_3 in case of SUP7-V and both in case of SUP7-Nb-V.

Table 1 - Chemical Compositions of the Steels Investigated

	C	Si	Mn	P	S	Cu	Cr	Al	Nb	V
SUP7	0.58	2.09	0.83	0.014	0.008	0.09	0.14	0.025	0	0
SUP7-Nb	0.58	2.16	0.86	0.026	0.010	0.15	0.14	0.022	0.19	0
SUP7-V	0.58	1.98	0.81	0.013	0.008	0.09	0.09	0.032	0	0.29
SUP7-Nb-V	0.56	1.94	0.79	0.014	0.008	0.09	0.09	0.021	0.15	0.18

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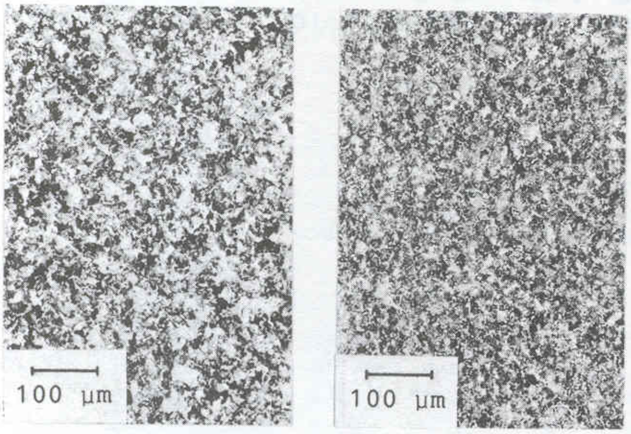
* Numbers in parentheses designate References at end of paper.

As for the precipitation strengthening, it is usual to make use of such metallic carbides as M_3C, M_2C and MC types. Of these carbides, MC type to which NbC and V_4C_3 belong is the most effective in strengthening the steels. These carbides of niobium and vanadium must be resolved into austenite phase upon austenitizing to give rise to the precipitation during tempering.



SUP7 SUP7-Nb-V

Fig. 1 - Microscopic structures of as-rolled 12.2 mm diameter bar

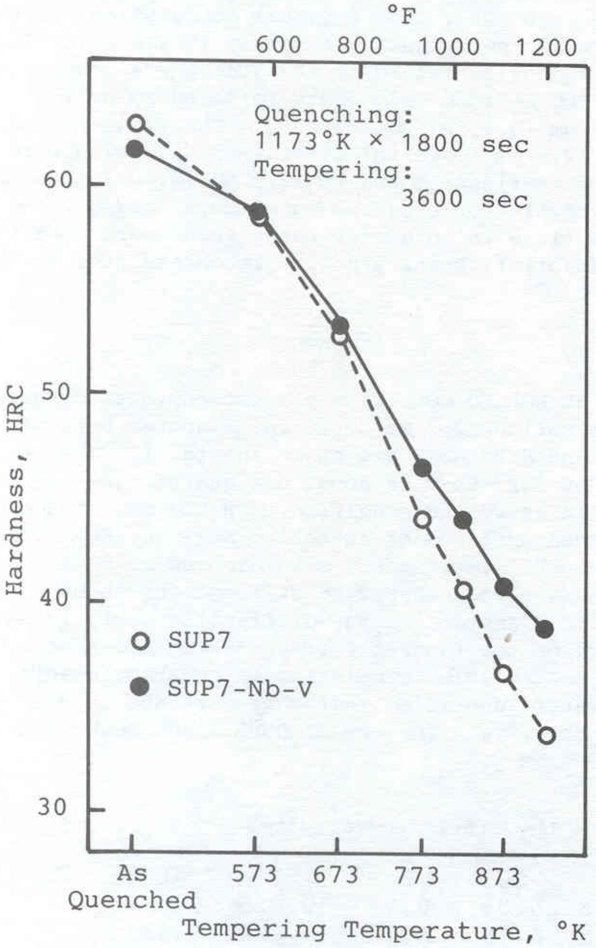


Fig. 2 - Tempered hardness when quenched from 1173°K (1652°F)

PRECIPITATION EFFECT - Fig. 2 shows the tempered hardness of two of the steels quenched from 1173°K (1652°F) into oil. There is a distinct difference in tempered hardness between SUP7 and SUP7-Nb-V at austenitizing temperatures from 673°K (752°F) and higher. SUP7-Nb made just the same curve as SUP7, and SUP7-V as SUP7-Nb-V.

As the effect was at its culmination at the tempering temperature of 823°K (1022°F), we investigated the influence of austenitizing temperature on the precipitation of the added elements by means of the tempered hardness at 823°K (1022°F). Fig. 3 shows the result and one can see

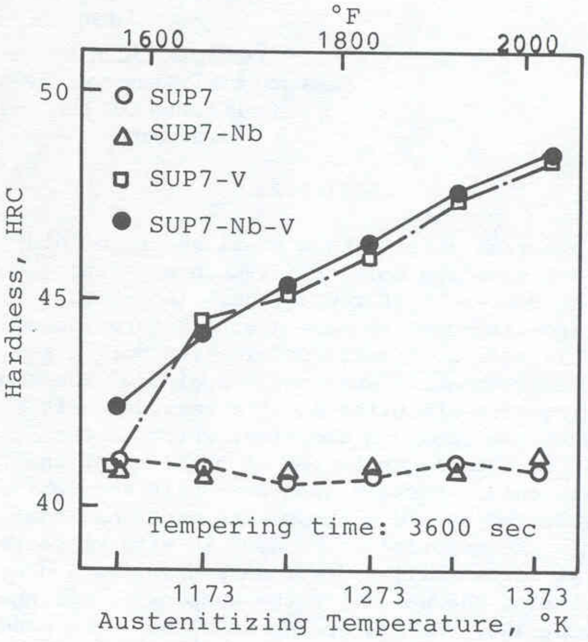


Fig. 3 - Relationship between austenitizing temperatures and 823°K (1022°F) tempered hardness

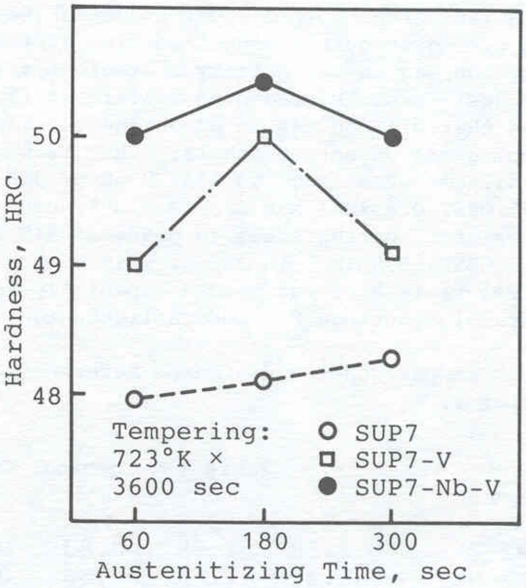


Fig. 4 - 723°K (842°F) tempered hardness when austenitizing time is short at 1173°K (1652°F)

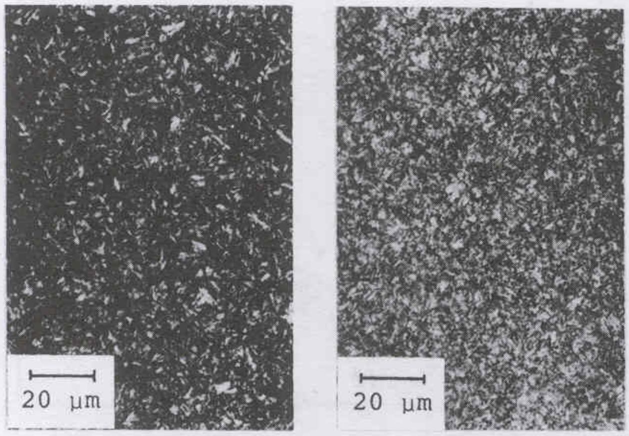
that niobium has little effect on the precipitation even when quenched from austenitizing temperatures of up to 1373°K (2012°F) in case it is added solely into SUP7. While there seems no significant difference in precipitation performance between the steels alloyed by V-only and Nb-V from Fig. 3, another experiment revealed that the steel with V-only cannot yield enough precipitation when the austenitizing time is not sufficient, which is often the case in actual production lines. Fig. 4 shows the hardness of SUP7, SUP7-V and SUP7-Nb-V when they were quenched from 1173°K (1652°F) and tempered at 723°K (842°F) and the holding time at the austenitizing temperature is shorter than that of the case in Fig. 3.

From the facts revealed as above, we made SUP7-Nb-V the candidate for the new sag-resistant spring steel.

As for the heat treatment, higher quenching temperature is preferable from the viewpoint of precipitation. On the other hand, heating at high temperature is a cause of surface decarburization which is harmful to the fatigue life of the spring products. Taking these conditions into consideration, we selected 1173°K (1652°F) for the quenching temperature of SUP7-Nb-V hereafter, which was the same as that of the production line of SUP7.

Fig. 5 is the microscopic structures of SUP7 and SUP7-Nb-V when quenched and tempered at 723°K (842°F). SUP7-Nb-V has a finer structure than SUP7 as seen in as-rolled condition. As will be mentioned later, this is the result of the grain refining effect of the carbides of the two allying elements.

Thin foil specimens of quenched and tempered SUP7-Nb-Vwere subjected to electron microscopy. This time the quenching temperature was 1143°K (1598°F) and the tempering temperature was 783°K (950°F). Fig. 6 is the transmission electron microscopy and Fig. 7 is the diffraction pattern and the key diagram. These figures show that vanadium carbides exist along with theta carbides, Fe_3C, when austenitized at as low as 1143°K (1598°F).



SUP7 SUP7-Nb-V

Fig. 5 - Microscopic structures of 1173°K (1652°F) quenched and 723°K (842°F) tempered specimens

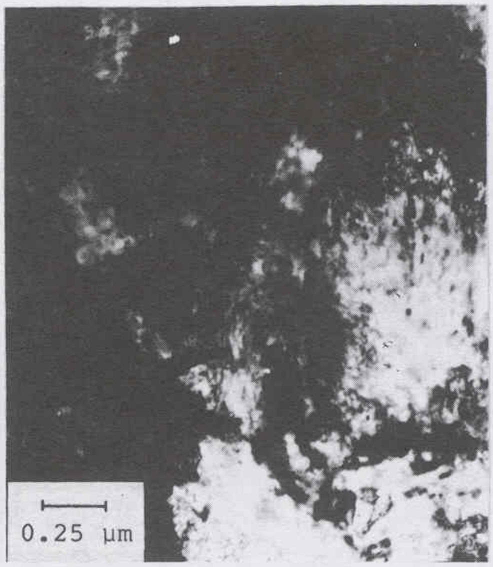


Fig. 6 - Transmission electron microscopy of quenched and tempered SUP7-Nb-V

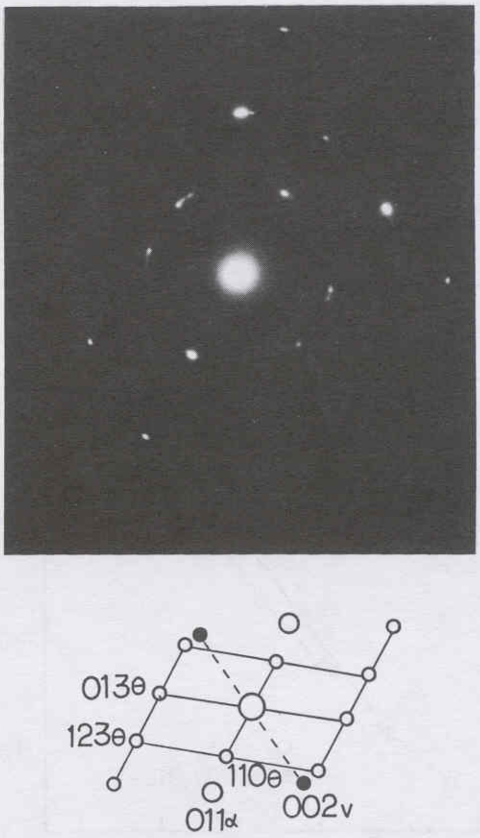


Fig. 7 - Diffraction pattern of Fig. 6 and its key diagram

AUSTENITE GRAIN SIZE - Because grain boundaries play a role of obstacles for travelling dislocations, finer grains are preferable for sag-resistant spring steels. Fig. 8 presents the change in grain size of SUP7 and SUP7-Nb-V as austenitizing temperature is varied from 1173°K (1652°F) to 1373°K (2012°F). The austenite grains were revealed by the oxidation method in accordance with ASTM E 112. The grains of SUP7-Nb-V were about one fourth as that of SUP7, in grain size number the difference being about 2, in the austenitizing temperature range below 1123°K (1742°F). The refinig effect by niobium and vanadium is believed to be due to the carbides remaining unresolved at the austenitizing temperature to impede the growth of the austenite grains. From this condition, as well as the limitation by the surface decarburization, quenching temperature should be lower than 1223°K (1742°F).

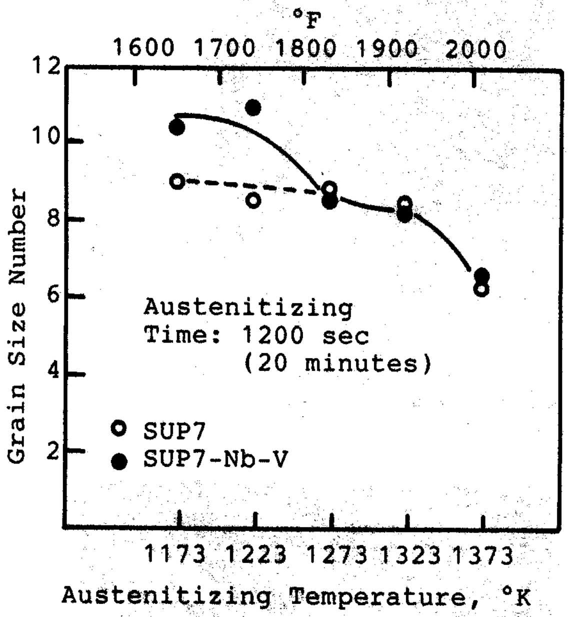


Fig. 8 - Austenitizing temperature vs. austenite grain size number

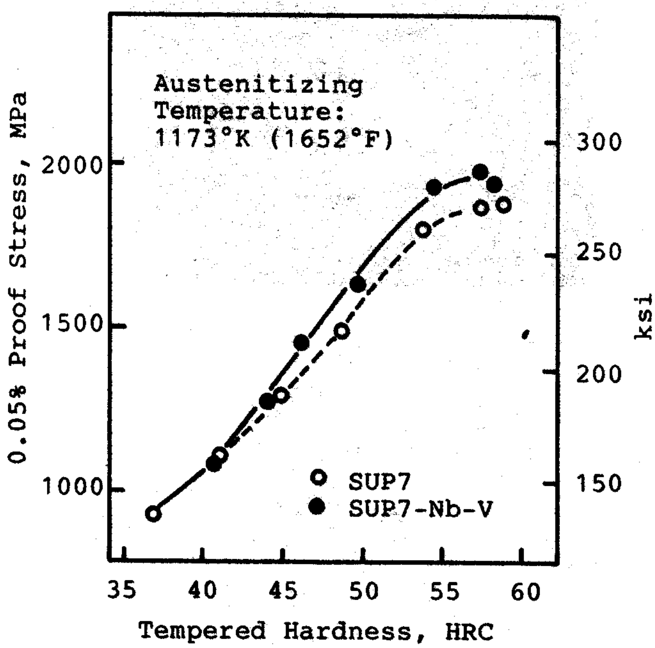


Fig. 9 - 0.05% proof stress vs. tempered hardness

TENSILE CHARACTERISTICS - Tensile specimens were quenched into oil and tempered at temperatures ranging from 573°K (572°F) to 873°K (1112°F) followed by surface grinding to eliminate surface defects and decarburization. From every tensile test, 0.05% proof stress, 0.2% proof stress, tensile strength, elongation and reduction of area were derived and hardness of the specimen was measured afterward. When tensile strength, elongation and reduction of area were plotted against the hardness, the two steels, SUP7 and SUP7-Nb-V, fell almost on one line. On the other hand, when 0.05% proof stress was plotted against the hardness, as in Fig. 9, SUP7-Nb-V showed higher stress values than SUP7. As for 0.2% proof stress, though the difference was smaller, similar figure was taken. Since proof stress is the stress at which a small plastic deformation begins, SUP7-Nb-V is expected to be more sag-resistant than SUP7.

SAG-RESISTANCE - Sag-resistance was evaluated by two methods: coil spring squeezing test and torsion creep test. The former was performed on the actual coil springs to simulate actual sag.

Table 2 - Dimensions of the Coil Springs

Bar Diameter	Ø12.0	mm
Bar Length	1950	mm
Coil Diameter	Ø100	mm
Free Height	350	mm
Spring Rate	38.8	N/mm
Number of Turns	6.21	
Number of Effective Turns	4.71	

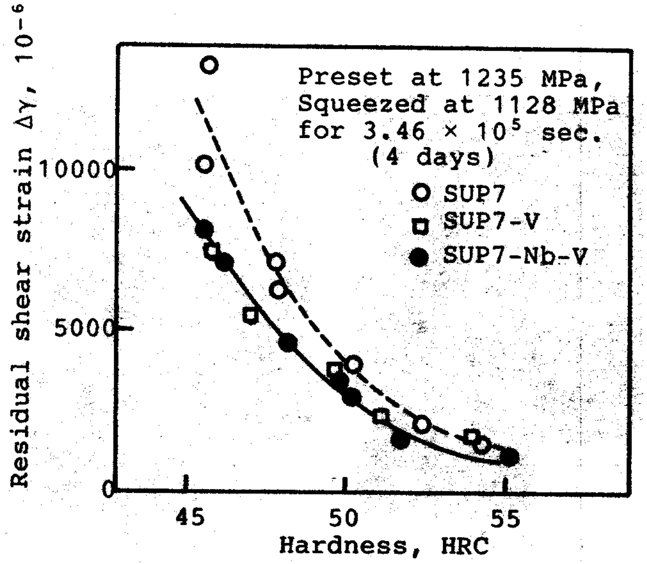


Fig. 10 - Residual shear strain by the coil spring squeezing test

The latter was to derive some features of sag, which will be discussed later.

The dimensions and characteristics of the coil springs used in the coil spring squeezing test were listed in Table 2. The springs were wound in a line for mass-production, quenched from 1173°K (1652°F) and tempered at various temperatures to give rise to hardnesses of HRC 45 to 55. After the tempering, they were subjected to shot peening operation in the line. Prior to the squeezing test, the springs were pre-set under the load that brought about the surface stress on the coils higher by 98 MPa (14.2 ksi) than the squeezing stress for relaxation. Then the coil springs were squeezed to yield a definite shear stress on the material surface and were left for 3.46×10^5 sec (4 days) at a constant environment temperature of 293°K (68°F); relaxation. The loads at a constant compressed height before and after the relaxation were measured and the load difference was converted into residual shear strain of the material surface by the following equation.

$$\Delta\gamma = \kappa\frac{8D\Delta P}{\pi d^3 G} \qquad (1)$$

where $\Delta\gamma$: residual shear strain,
κ : Wahl's coefficient, 1.176,
D : mean coil diameter, Ø100 mm (3.94 in),
ΔP : load difference,
π : 3.14,
d : bar diameter, Ø12.0 mm (0.472 in),
and G : shear modulus, 7.85×10^4 MPa (1.14×10^4 ksi).

In Fig. 10, the residual shear strain is plotted against the hardness of the specimen when the squeezing stress is 1128 MPa (164 ksi). SUP7-Nb-V has smaller residual shear strain than SUP7 at every hardness level from HRC 45 to 55.

TORSION CREEP TEST - Another test was devised to evaluate the sag-resistance using a small specimen shown in Fig. 11. The specimen was cramped at both ends; one end to a fixed vise and the other to a cantilever. A dead torque was applied by weights hanging from the other end of the cantilever. The shear strain development, γ_i, on the specimen surface was measured by a thin foil strain gauge at proper time, t_i, from 60 sec to 3.46×10^5 sec (4 days) after the torque application.

Overall shear strain development, $\Delta\gamma$, in 3.46×10^5sec (4days) is the most direct measure of the sag. Fig. 12 is the plot of $\Delta\gamma$ against hardness of the specimen. Apparently this figure is very similar to Fig. 10, which is the result of coil spring squeezing test, assuring the superiority of SUP7-Nb-V in sag-resistance to SUP7.

A different aspect of the data is rather interesting. Every shear strain developing rate,

$$v_i = \frac{\Delta\gamma_i}{\Delta t_i} = \frac{\gamma_{i+1} - \gamma_i}{t_{i+1} - t_i} \qquad (2)$$

is calculated and plotted bilogarithmically against the time, t_i. An example of the plot is shown in Fig. 13, where the data are fairly regressible to a straight line whose slope, m, represents the time dependency of the shear strain development. The regression line is expressed by

$$\log\frac{d\gamma}{dt} = a + m \cdot \log t, \qquad (3)$$

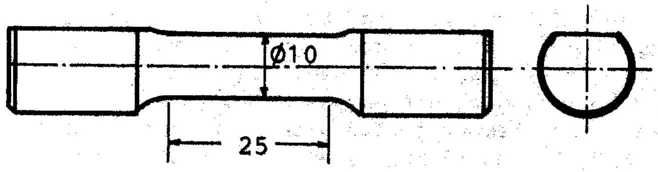


Fig. 11 - The specimen of the torsion creep test (dimensions in mm)

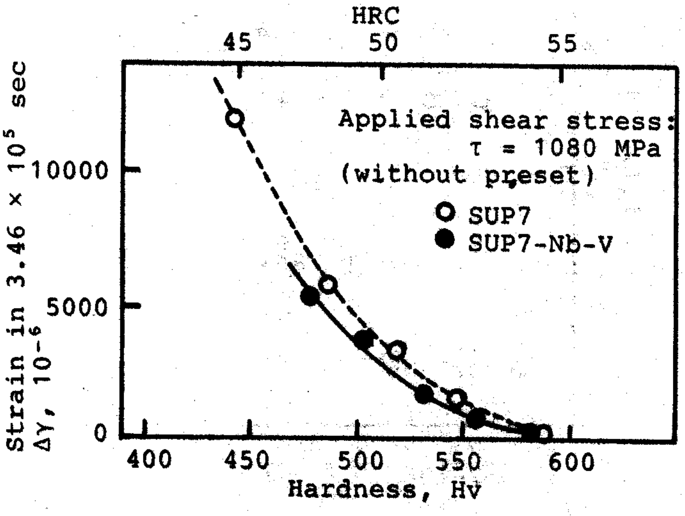


Fig. 12 - Shear strain development in 3.46×10^5 sec (4 days) by the torsion creep test

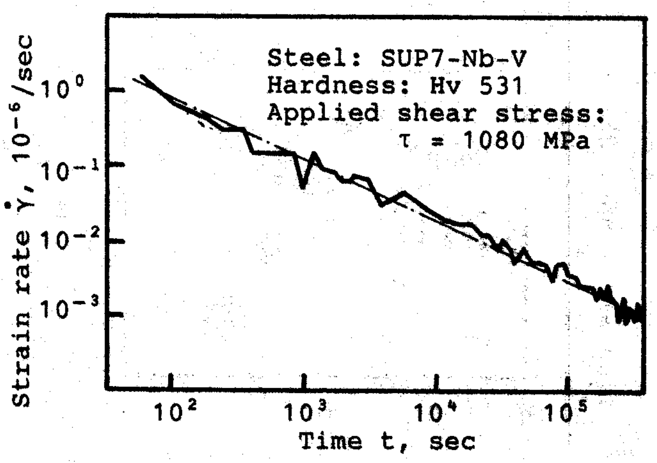


Fig. 13 - Change in shear strain development rate by the torsion creep test

so the strain rate is

$$\dot{\gamma} = \frac{d\gamma}{dt} = k \cdot t^{m} . \qquad (4)$$

The time dependency of the shear strain development is expressed, when $m \neq -1$, as

$$\gamma \propto t^{m+1} . \qquad (5)$$

In case $m = -1$,

$$\gamma \propto \log t. \qquad (6)$$

Fig. 14 is the plot of m-value vs. the hardness of the specimen. The m-value increases as the specimen becomes harder until around Hv 550 (HRC 52); beyond the hardness, it tends to decrease. Since m-value is connected to the strain rate, $\dot{\gamma}$, as shown in Eq. (4), it expresses the extent of dislocation mobility. The larger becomes the absolute value of m, the more easily move the dislocations, leaving a large amount of permanent strain. That is, in such a case, the dislocations move until they are entangled with each other or piled up along the grain boundaries. On the contrary, when the absolute value of m is small, it is showing that the dislocations are pinned at some obstacles such as precipitates from the early stages. Again, from this respect, SUP7-Nb-V is superior to SUP7.

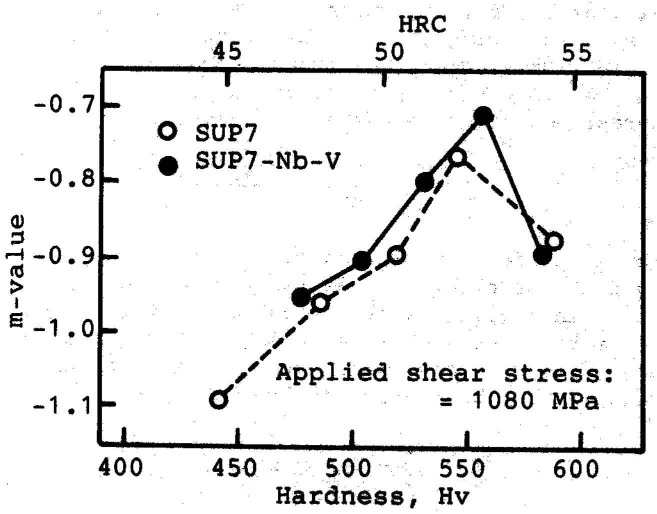


Fig. 14 - Change in m-value with respect to the hardness of the specimen by the torsion creep test

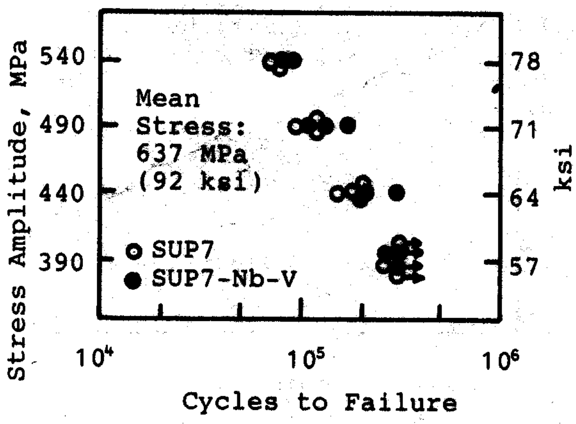


Fig. 15 - Fatigue life of the coil springs

FATIGUE PERFORMANCES - Various tests were performed to evaluate fatigue properties of SUP7 and SUP7-Nb-V.

Rotational bending fatigue test was performed on specimens which were quenched and tempered to have hardnesses of HRC 50 and HRC 54 followed by surface grinding. In both hardnesses, SUP7 and SUP7-Nb-V had about the same fatigue limit of about 750 MPa (109 ksi). This value is within the conventional data band compiled by Society of Spring Research of Japan(4).

Surface ground and shot-peened specimens of SUP7 and SUP7-Nb-V with the same hardnesses as above case were subjected to torsional fatigue test. In this case the mean stress was 637 MPa (92 ksi) and the stress amplitude was varied from 440 MPa (64 ksi) to 540 MPa (78 ksi). There wasn't any significant difference in the fatigue life between SUP7 and SUP7-Nb-V and the value was similar to that from the fatigue test on coil springs which is cited below.

Fatigue test on coil springs with the dimensions listed on Table 2 and the hardness of HRC 50 was performed to examin the feasibility of SUP7-Nb-V to the actual suspension coil springs. When the coil springs were free of corrosion, the result was as Fig. 15, in which SUP7-Nb-V has comparable fatigue life to that of SUP7 in any stress amplitude. When the coil springs were corroded, on the other hand, the result was rather different. The corroding condition was as follows: an exposure in a chamber filled with salt water mist for 1.08×10^4 sec (3 hours) and a keeping in the atmosphere for 7.56×10^4 sec (21 hours). After 10

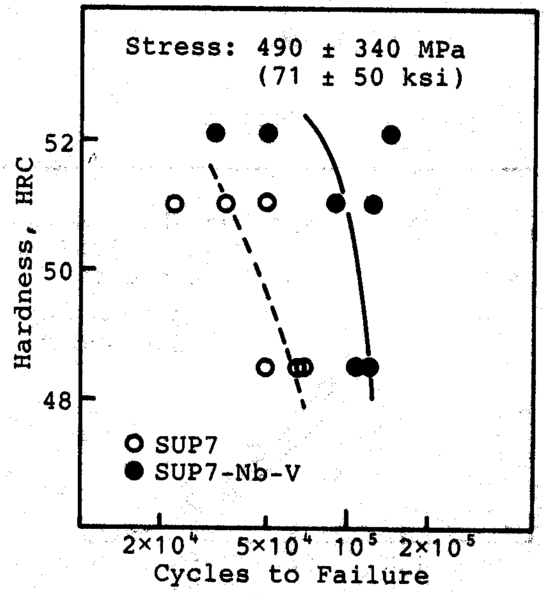


Fig. 16 - Fatigue life of the corroded coil springs

and 20 cycles of the corroding, the coil springs were loaded with the surface stress of 490 ± 340 MPa (71 ± 50 ksi). The fatigue life of the coil springs subjected to 20 cycles of the corroding were shown in Fig. 16. This time, different from the case in Fig. 15, there appears a remarkable difference between SUP7 and SUP7-Nb-V. Measurement of the surface corrosion depth of the two steels bore no difference. Now a detailed observation of the corrosion pit tip is under way to explain the difference.

OTHER RESULTS - Hardenability of the steels was evaluated by the Jominy test and niobium and vanadium were revealed to have little influence on the hardenability of SUP7. When one would apply SUP7-Nb-V to thick springs, some measures should be taken to enhance the hardenability; treating with boron is a recommended measures. Slack quenched structures due to poor hardenability will lead to an augmented sag despite the addition of niobium and vanadium.

Fracture toughness of the steels was evaluated by the bending method. This property, also, was not affected by the addition of the two elements.

SUMMARY

Making use of precipitation strengthening effect of niobium and vanadium on SUP7, which by itself have a good sag-resistance with its high silicon content, we have come up with a new sag-resistant spring steel. The difficulty presumed at the starting point was in the solubility of the carbides of niobium and vanadium into the austenite phase prior to the precipitation. The simultaneous addition of the two elements got rid of the difficulty; the resolution of the carbides was confirmed to take place at a rather low austenitizing temperature of 1173°K (1652°F) and for an austenitizing time of as short as 60 sec, which was no different condition than the conventional production line of springs for SUP7.

Other properties were almost unchanged by the addition of the two elements into SUP7. Among them, fatigue performance might be a problem; to achieve the weight reduction of springs, the springs must be used in a higher stress level. But in the actual spring designing, the increase in the stress amplitude was rather small in contrast with the increase in the mean stress. The fatigue life is affected more by the stress amplitude than the mean stress, so in actual situations SUP7-Nb-V can satisfy the fatigue life requirement necessary for the cars in the market.

Raising the working stress by about 100 MPa (14 ksi), the new spring steel lost the weight of conventional springs made of SUP7 by about 15%. The suspension springs made of the steel have been installed in some Japanese new models since last year and the application is increasing.

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