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Development of a New Light-Weight Suspension Coil Spring

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ABSTRACT

This newly developed helical spring can be used at a stress level up to 1300 MPa. The material is composed of Fe-C-Si-Mn-Ni-Cr-Mo-V alloy. Its strength-toughness balance was greatly superior to that of other spring steels.

To improve the fatigue strength at a higher stress level, decarburization at the surface upon austenitizing was severely controlled, applying induction heating. Then, a special shot peening process, introduced for the first time, was applied to obtain a surface residual stress at the surface of over 1000 MPa. The spring was first applied to a 1992 TOYOTA model car. Plans are to increase the use since the spring material achieves a weight reduction of at least 30 % and, possibly, 35 to 40 %.

1.INTRODUCTION

Automotive suspension springs which affect greatly the automobile's running performance have been changed for this fifteen years. In particular, the suspension spring of a passenger car changed from leaf springs to coil springs radically in the seventies. Also at the same time the suspension system was improved to optimize the running characteristics using computers, and various kinds of suspension systems with coil springs were developed and tried from multi-link suspension to Mc Pherson strut. While electronic controlled active suspension systems were developed, their applications are confined to a small usage.

A high silicon spring steel similar to SAE9260 has been in use in Japan for twenty years in order to maintain vehicle bumper height. At the same time considering the improvement of fuel economy, a lightweight and high sag resistance spring with vanadium and columbium was developed for use in the early eighties(1). Since the oil crisis in '73, the weight reduction of automotive parts has been one of the imperative agenda, and now the preservation of global environment requires us to reduce the exhaust carbon dioxide as well, leading to the conclusion that the automotive parts should be as light as possible.

2.TECHNOLOGICAL PROCEDURES

Weight reduction in coil spring implies the use of light weight materials or a thinner steel bar while maintaining adequate spring performance and characteristics. Light weight materials are not within the coopo of this paper.

Assuming a cylindrical coil spring with coil diameter, D and bar diameter, d, the spring mass, W is expressed as follows.

$$W=(2\rho GP^2/k)/\tau^2$$

(ρ:density,P:load,k:spring rate), where τ means the design stress.

Namely the spring weight is inversely proportional to the square of design stress as shown in the equation and in Fig.1, leading to that the weight reduction of a coil spring is accomplished by raising the design stress, in other words, by using a high strength steel .

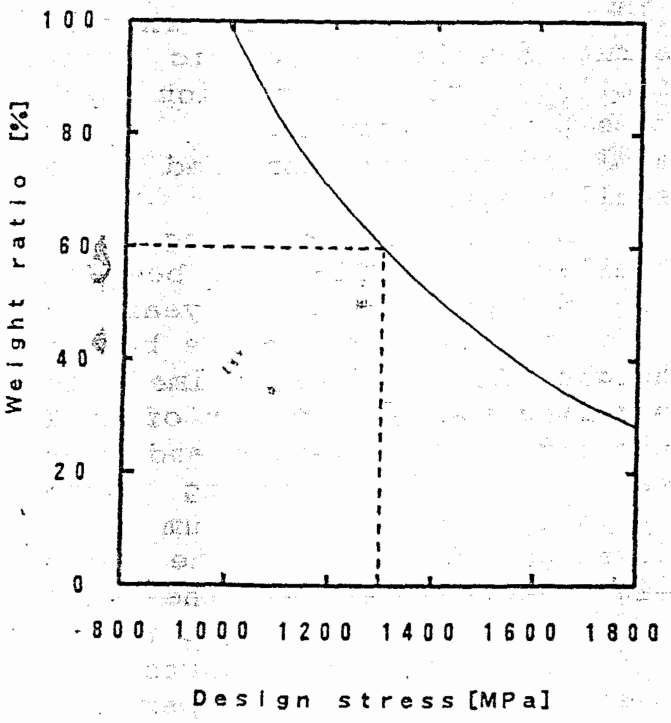

Fig.1 Relation between stress and spring weight

Generally automotive suspension coil springs are coiled after heating above austenitizing temperatures, followed by quenching and tempering. While the weight reduction of a coil spring corresponds to raising the maximum design stress with a spring steel bar of a smaller diameter, two things must be put into consideration, sagging (creep or stress relaxation) and fatigue, as listed in Fig.2.

One of the functional damages in suspension coil springs is permanent deformation to shorten the spring height. It causes lowering the bumper height and the headlight focus to deteriorate the riding performance and safety(2).

In the development of suspension coil springs, the main technology was placed upon sag resistance to keep the height of a car during service. Since then using a high silicon steel and applying warm setting have been most popular ways to improve the sag resistance.

Silicon is well known for its solution strengthening ability in steel and it is found that it is effective in improving of sag resistance as seen in Fig.3. Silicon does not form the original carbides and exists in the ferrite matrix as a substitutional solute atom. The atomic radius ratio of silicon is large and then contributes to solid solution strengthening(3). About ten years ago a high

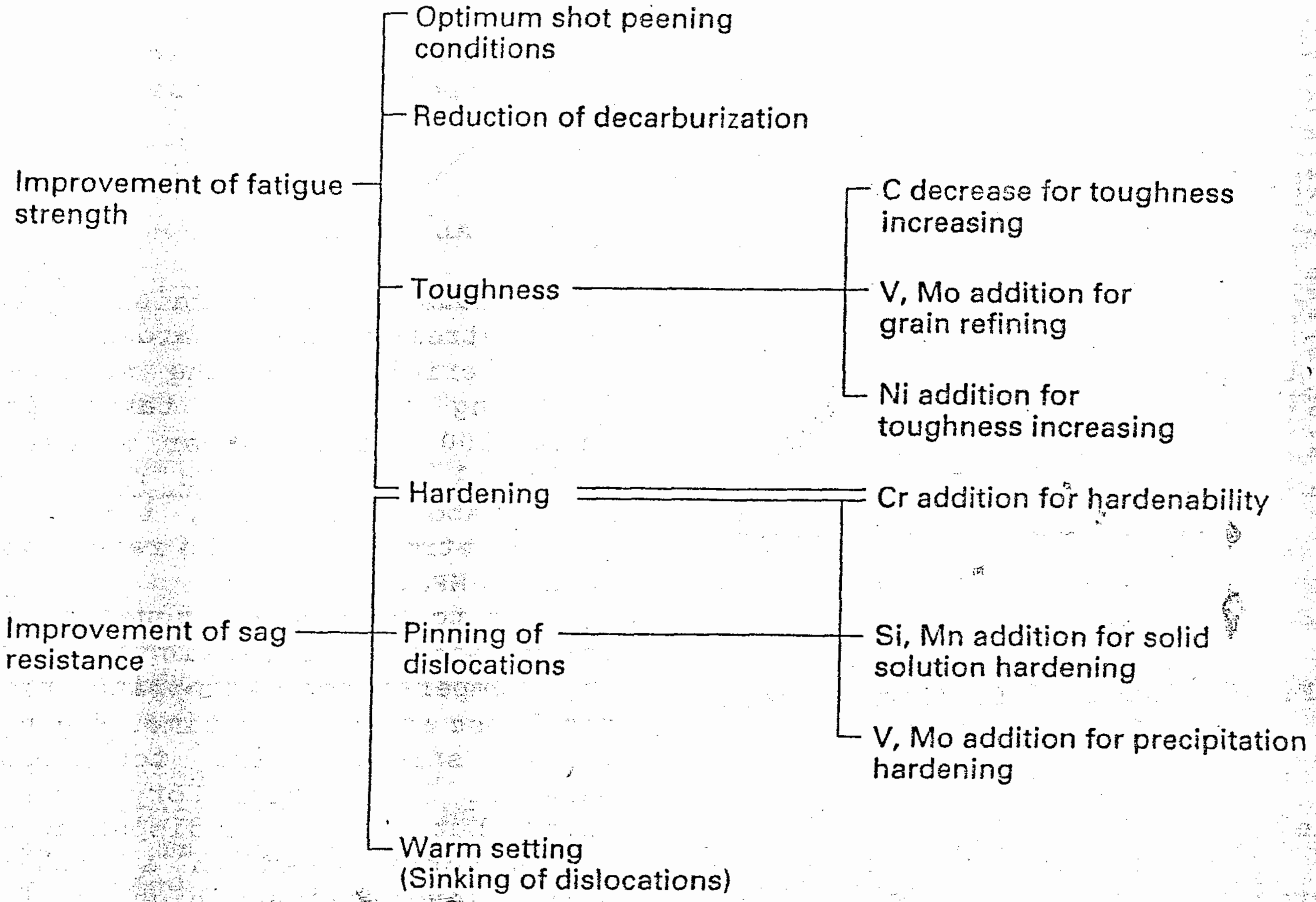

Fig.2 Procedures for making light weight springs

silicon steel such as SAE9260, with an addition of vanadium and columbium was developed in Japan. It is said that using three mechanisms i.e. solution strengthening, precipitation strengthening and grain refining can raise the sag resistance.

It is also said that the sag resistance will be controlled by constraining the dislocation movement, for which there are three ways. Firstly it is to raise the dislocation movement resistance by increasing the hardnes . Secondly, pinning effect of dislocation by precipitation of carbides is known to be effective. Thirdly grain refining is also effective in shortening of the average distance of dislocation movement.

On the other hand fatigue is another functional damage to be taken into account. But compared with sag resistance, fatigue of suspension coil springs has been thought negligible, for there has been no report on the fatigue fracture of the suspension coil springs in the market. At the first stage of our development, however, the springs made by conventional processes were found not to satisfy the specified fatigue endurance at a high stress

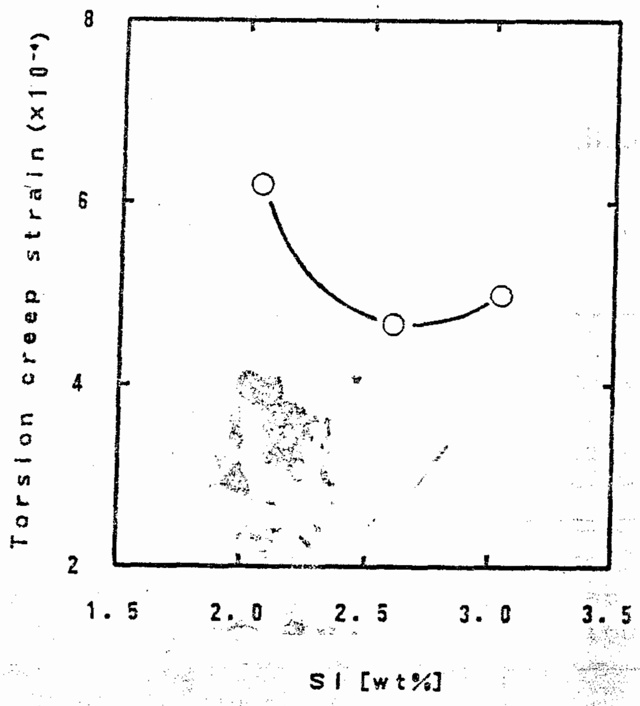

Fig.3 Effect of silicon content on sag resistance

level.

As the design stress increases, the pitch angle also increases to give the spring an additional bending stress. This additional bending stress does not come from Wahl's theory, but only finite element analysis can clearly show the effect corresponding to the result of stress measurement by strain gauges.

Generally speaking the fatigue starts from the surface of a spring, especially when it was fatigue tested at a higher stress level. This corresponds to the fatigue crack initiation on the surface, for which surface strengthening such as nitriding is known to be effective(4), but as long as a large suspension spring is concerned, nitriding process is not realistic from an economical point of view. Instead decarburization control and residual stress become very important for a suspension coil spring to satisfy the specified fatigue endurance.

3.MATERIAL DEVELOPMENT

As previously stated, raising the design stress requires hardening of the material. When the maximum designing stress is taken as τ max=1300 MPa in shear stress, torsional proof stress must be raised above 1300 MPa, i.e. the tensile strength must be raised up to 2100 MPa.

As to hardening, usually it can be done with decreasing tempering temperatures, dropping the toughness at the same time. Essentially strength and toughness were in a contradictory relation, but it is indispensable for a spring used in a higher stress level to have high toughness as well as high strength. It is well known that toughness is improved with decreasing carbon content,but in that case it is necessary to increase the strength by adding the alloying elements.

With a low carbon steel one of the technological ways to increase the strength is to increase the softening resistance upon tempering. This means retarding the decomposition of quenched martensite into ferrite and carbides during tempering. In this respect Si is mostly effective especially at a low temperatures tempering, for Si is known to delay the formation of cementite(θ :Fe_3C) during tempering (6,7). Another way to increase the strength of a low carbon steel is to exploit both solution hardening and

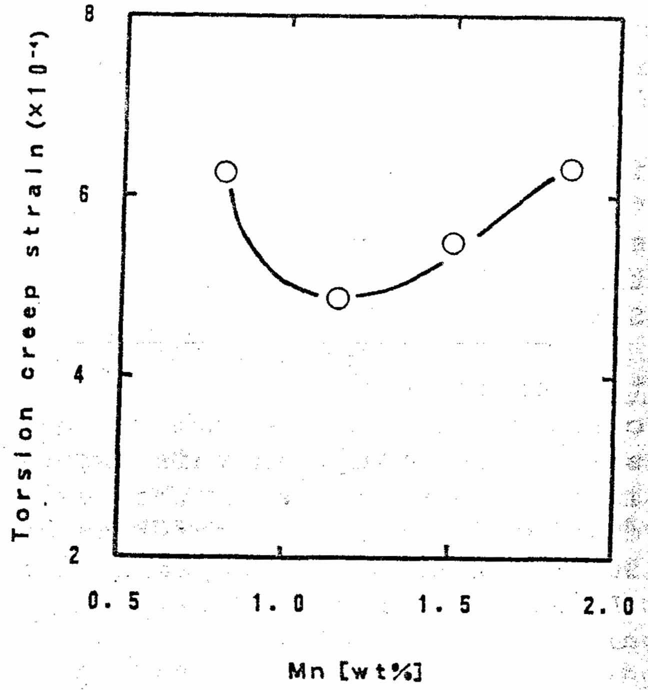

Fig.4 Effect of manganese on sag resistance

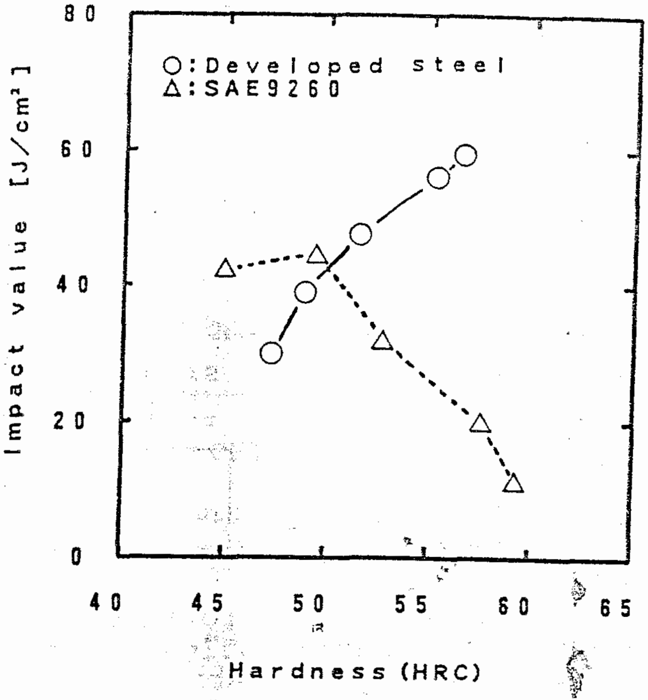

Fig.5 Notched toughness in relation to hardness

precipitation hardening. For this respect Si and Mn are effective in solution hardening as confirmed in Fig.4, and V and Mo are expected to contribute to precipitation hardening(8).

According to the presumption stated above, a L-16 matrix was laid down to optimize the content of alloying elements. In the process, Ni was added to enhance the toughness of the steel. As the result, the following chemical composition was determined based upon creep testing to see sag resistance, tensile strength and Charpy impact test to obtain a steel;0.45C-2.5Si-1.3Mn-0.2Mo-1.0Ni-0.4V.

Fig.5 shows notched toughness of the newly developed spring steel after quenching and tempering as a function of hardness in comparison with that of SAE9260, where toughness

Table 1 Chemical composition [wt%]

	C	Si	Mn	Cr	Mo	V	Ni	N (ppm)
Developed steel	0.45	2.5	1.3	0.2	0.2	0.4	1.0	150
SAE9260	0.6	2.0	0.8	–	–	–	–	–

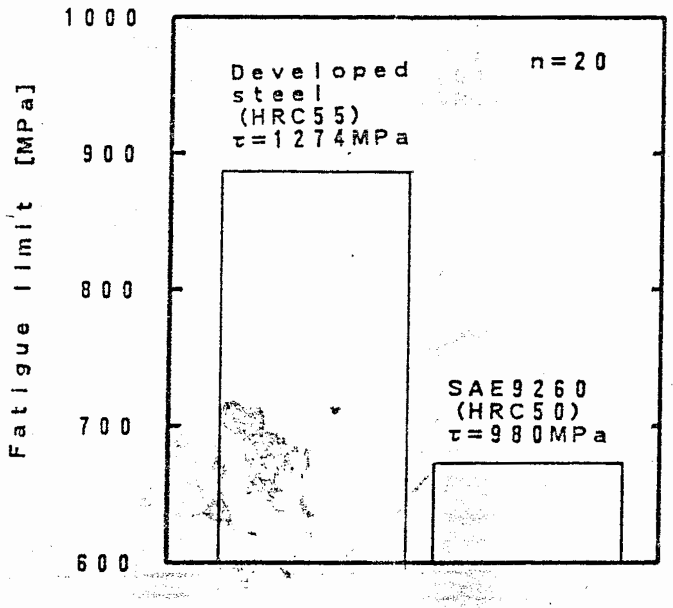

Fig.6 Result of rotational bending fatigue test

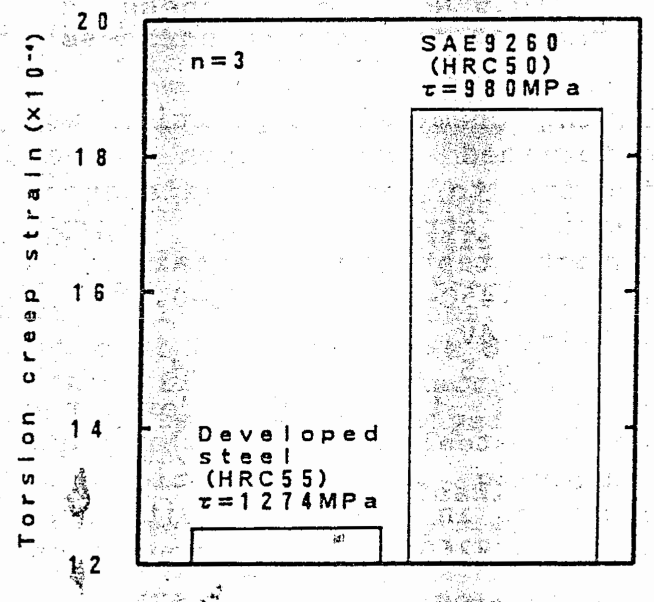

Fig.7 Result of torsion creep test

evaluated by Charpy impact test becomes low. On the other hand, toughness of the newly developed steel increases with hardness. This reverse dependence of toughness on hardness might be related to shifting of the temper brittleness to a higher temperature because of Si addition. And toughness improvement might be related to reducing of carbon from 0.6 wt% to 0.45 wt%.

The result of rotating-bending fatigue test is shown in Fig.6. The fatigue limit of the developed steel was found to be higher than that of conventional SAE9260 by 30 %.

Fig.7 shows the result of torsion creep test. The torsion creep strain corresponds to sag seen in a spring. In this experiment, creep stress on the newly developed steel was increased by 30 % , when it is compared with SAE9260 at normal stress level.

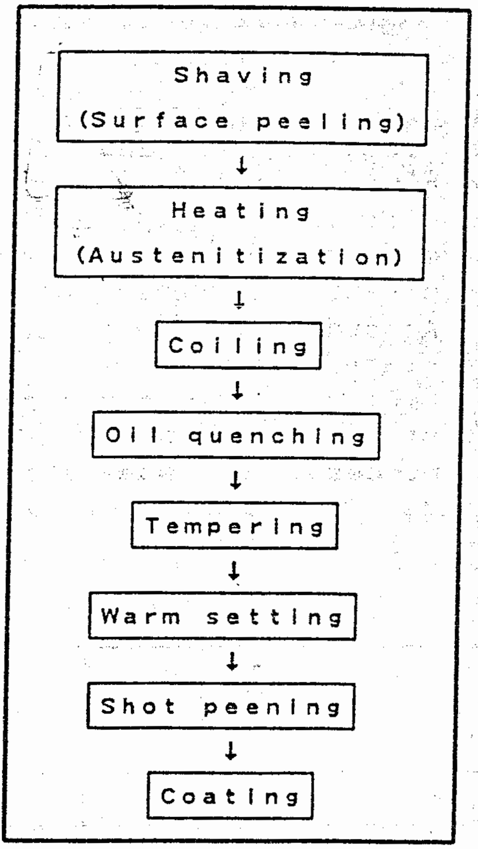

Fig.8 Manufacturing process

Table 2 Dimensions of the spring used for test

Wire diameter [mm]	Coil diameter [mm]	Number of total turns	Free height [mm]	Spring rate [N/mm]
ø 12.1	ø 104.6	5.4	263.4	47.0

The result was that even after the higher stress was exerted, the residual strain of the newly developed steel was much smaller than that of SAE9260 tested at a lower stress level, indicating that the newly developed spring steel can be used at a high stress level to reduce the spring weight.

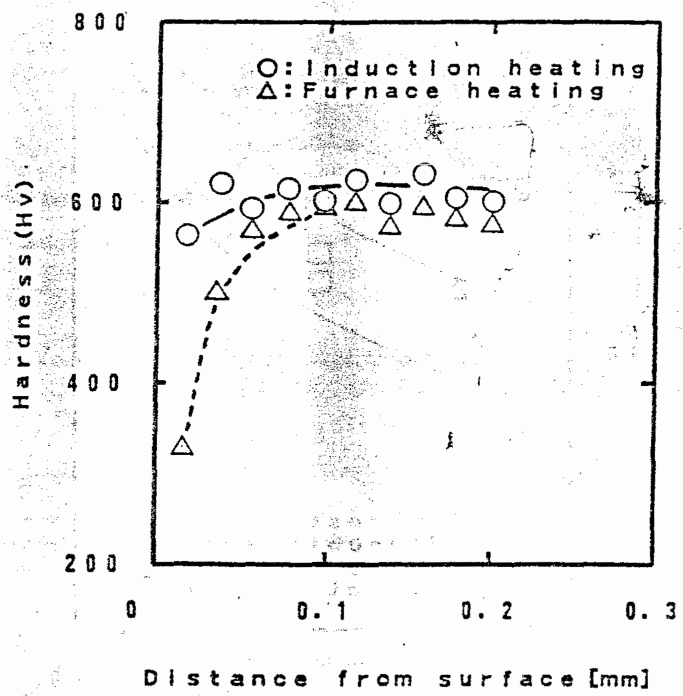

Fig.9 Reduction of decarburization by induction heating (after 663 K tempering)

4.SPRING CHARACTERISTICS

To see the spring characteristics, coil springs were coiled for evaluation according to the process shown below in Fig.8. The spring specifications are also shown in Table 2.

The austenitizing furnace for the heating of steel bars over A_3 point (about 1130 K) is an induction heating especially developed for this purpose. The objective of utilizing the induction heating is to suppress the decarburization usually seen on the surface of springs. The effect of the induction heating is seen in Fig.9.

Just after the heating, the steel bar is to be coiled around a mandrel, then quickly quenched into oil to make the phase hard martensite, and spring is picked up from the oil, passed into a tempering furnace for about an hour. In the tempering process, the phase changes from martensite to sorbite to give the steel both toughness and strength necessary for a spring.

The spring is then warm set and shot peened to create a large amount of residual stress distribution on the surface. As previously mentioned, in this case, the spring is tempered as hard as HRC55, about five point harder than that of

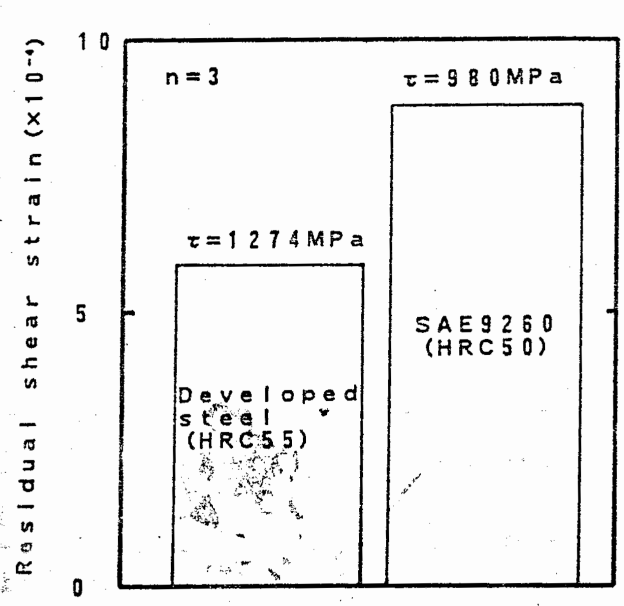

Fig.10 Comparison of sag resistance between SAE9260 and developed steel

the conventional springs. So the shot peening process must be fitted to such a hardened spring. Since the springs processed through this line exhibit no decarburization, the hardness at the surface after tempering is about HRC53, so the shot used in this process must be hard as well.

As well known, since the sag resistace is proportional to hardness, this hardened spring exhibits a superior sag resistance in combination with solution hardening even at a higher stress level, as shown in Fig.10.

In the development of the spring, the main problem existed in fatigue. In order to satisfy the specified fatigue endurance, two measures were taken into account. One is eliminate the surface defects such as decarburization as well as non-metallic inclusions. The induction heating we introduced to sup-

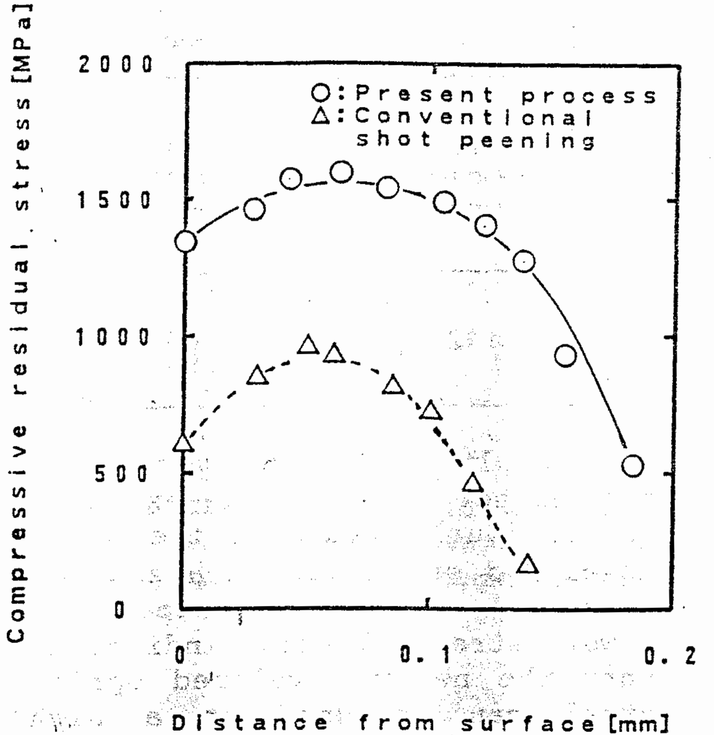

Fig.11 Comparison of residual stress

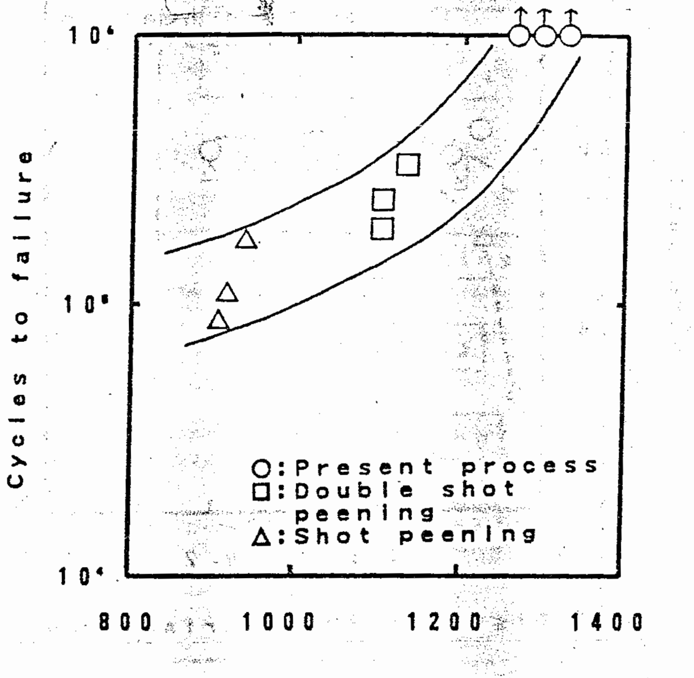

Fig.12 Relation between residual stress and endurance (τ=686±588 MPa)

press the decarburization on the peeled steel bars were so successful that basic fatigue characteristics were enormously improved. The other is to create a deep and large compressive residual stress distribution compared with the conventional process, as shown in Fig.11. As the result, fatigue was put up to a level over the generally specified limit even under a higher stress amplitude. The comparison of the fatigue endurance is shown in Fig.12.

Finally, as to the corrosion, corrosion resistance was investigated in a salt spray chamber without coating, for corrosion of suspension springs has been a problem especially in the salt sprayed regions in winter. As shown in Fig.13, the depth of corrosion pits after salt spray for 20 days, during which drying process was introduced every 21 hours, is clearly shallower than that of SAE9260, probably due to the effect of Ni added to the steel. Then the springs were put into fatigue test to see the corrosion fatigue. The result showed that the fatigue endurance was equal to that of the conventional springs even tested at a higher stress level.

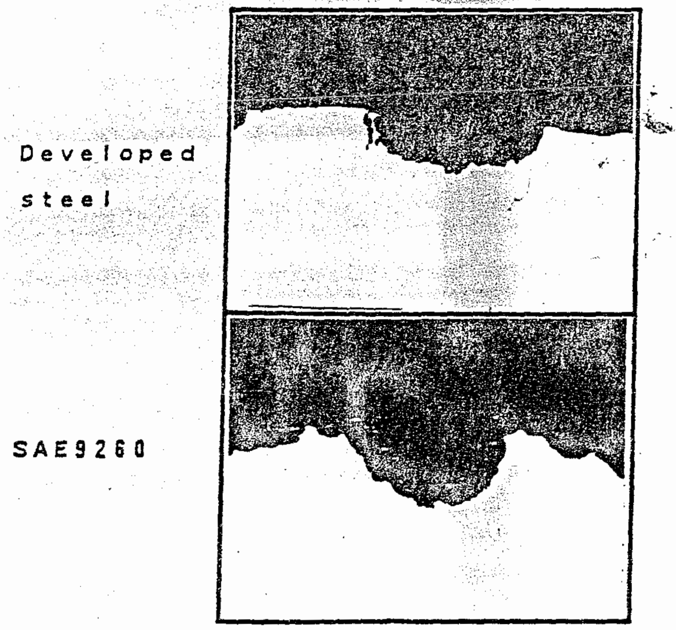

Fig.13 Micrographs of corrosion pits ((3 hrs. Salt spray +21 hrs. atmospheric exposure)x20 cycles) (X 70)

5.SUMMARY

Through this development of a light weight steel spring, we applied almost all of the advanced technologies we could try, but difficulties existed in its realization in the process. For almost three years in close collaboration with an auto maker, a steel maker and a spring maker, we designed and constructed from the basic to realize the weight reduction of a suspension coil spring by over 30 %.

(1) The spring was found to be designed and used with the maximum shear stress of 1300 MPa, reducing the spring weight by over 30 %, presumably 40 % in comparison with a SAE9260 spring.

(2) To meet the specified fatigue endurance, decarburization must be completely eliminated to increase the effect of shot peening. It is estimated that the residual stress after shot peening should be as high as 1000 MPa.

(3) To increase the toughness, carbon content was lowered from 0.6 % to 0.45 % and 1 % Ni was added. Si, Mo and V played an important role in increasing the strength, enabling a low temperature temper-

ing.

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