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Technical Report

Low-alloyed High-strength Suspension Spring Steel

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Abstract

To meet environmental regulations, weight reduction of automobiles for fuel efficiency improvement is strongly demanded. Suspension springs for automobiles are also required to reduce weight by strengthening the spring steel. In recent years, conventional spring steel SAE9254 has been used under increasingly higher strength conditions than ever before, supported by the improvement of spring manufacturing technologies. However, some properties required for suspension spring steel, such as toughness and resistance for hydrogen embrittlement, are found to be lacking under such high strength conditions. To further strengthen suspension springs, stronger spring steel is indispensable. Therefore, we developed "low-alloyed high-strength suspension spring steel" focusing on the toughness and resistance required for hydrogen embrittlement, using fewer alloying elements those used in former developed alloyed spring steels. In this paper, we introduce the chemical composition of the low-alloyed high-strength suspension spring steel, and present the mechanical properties of spring steel wire for cold coiling springs.

1. Introduction

1.1 Outline of automotive suspension springs

Suspension springs for automotive use are installed in the automotive suspension system to perform the function of absorbing and relieving the shock that acts on wheels from the road surface as well as supporting the car body weight. In the general passenger car suspension system wherein the down-sizing and the weight reduction are oriented, a compact coil spring made of spring steel wire is mainly used as the suspension spring. The size of the suspension spring coil, although differing in size depending on the car weight, is 8–18 mm in wire diameter, 100–200 mm in coil diameter and 400–500 mm in coil height, with each coil weighing 1–2 kg.

Suspension spring properties are as follows: fatigue endurance to withstand the vibrational load during travelling, resistance for height reduction of the coil spring that resists the permanent disfiguring of the coil even after prolonged operation in supporting the car weight, sufficient toughness to withstand the shock caused by the irregularities of the road surface, and so forth. In order to satisfy these mechanical properties, for the automotive suspension spring steel, middle carbon-high silicon steels with a carbon content of about 0.5%, such as SAE9260 (JIS SUP7) and SAE9254 (JIS SUP12), are used in many cases. The steel is quenched and tempered to form a tempered martensitic microstructure having a high strength and a high yielding point for use.

The manufacturing process of the suspension springs is basically divided into two types of the "hot coiling process" and "cold coiling process", depending on the quenching and tempering method. In the hot coiling process, a spring steel wire rod is coiled at a high temperature and then quenching and tempering-treated. In the cold coiling process, a straightened spring steel wire rod undergoes the quenching and tempering treatment to form a high strength spring steel wire, and is then coiled at room temperature. Furthermore, in the cold coiling process, the coiled spring is annealed to relieve the residual stress that is produced during the coiling work. Both the hot coiled and the cold coiled springs are applied with the setting treatment that imparts a large deformation to enhance the yielding point and the shot-peening treatment that imparts residual stress to the subsurface layer to improve the fatigue characteristic, and then processed to the final suspension coil products after the coating treatment to protect the surface.

The cold coiling process has the advantage of being able to manufacture a suspension spring of sophisticated function with high

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freedom of spring configuration design and high accuracy. However, in order for the high strength spring steel wire to coil in the cold coiling process, high ductility as well as high strength are required for the high strength spring steel wire being discussed herein. Furthermore, since the wire undergoes two heat treatments of quenching and tempering in the straightened state, and the stress-relieving annealing after the coiling work, optimization of the heat treatment conditions in the respective process is also required.

Nippon Steel Corporation is promoting extensively the development of the high strength suspension spring steel based on the cold coiling by utilizing its expertise in the steel chemical composition design and the optimization of heat treatment conditions.

1.2 Properties required for automotive suspension spring steel

Regarding automotive use, suspension springs having a maximum shearing load (τ_{max}) higher than 980 MPa are mainly used, and the tensile strength (TS) required for the steel material is 1 800 MPa or above. In addition, the ductility is required for cold coiling work, and high toughness is also required. As the steel material that satisfies such required properties, SAE9254 (JIS SUP12) has been widely used in recent years. SAE9254, or silicon-chromium spring steel, has the typical chemical compositions of 0.54C-1.4Si-0.7Mn-0.7Cr. As the carbon content is high, a high tensile strength martensitic microstructure is obtained by the quenching and tempering treatment. Furthermore, by adding Si and Cr to enhance the resistance to temper softening, the tensile strength of 1 800 MPa is realized by the higher tempering temperature. By tempering at a high temperature, the yield point and the elasticity limit can be enhanced, and the steel becomes excellent in the fatigue property, the resistance for height reduction of the coil spring, and the toughness also increases. Presently, the SAE9254 is the global standard for automotive suspension spring steel.

In addition, as the automotive suspension springs are used for the under carriage suspension of a vehicle, the issue of corrosion is problematic. As a means of surface treatment to secure the corrosion resistance, only a resin coating is applied to the suspension springs because the high strength of the automotive suspension springs is achieved by the quenching and tempering treatment, and the hot-dip zinc coating treatment that heats the springs up to a temperature that exceeds that required for tempering is not applied. Accordingly, during a long period of operation, the resin coating of the suspension springs is partly damaged by the striking shock of airborne pebbles and/or by the frictional sliding between the coil spring edges caused by the repetitive coil spring deformation, therefore, corrosion may develop in the damaged coating region and propagates, and the life span of the suspension springs may thus deteriorate. This deterioration is attributed to the following two factors: the delayed fracture, a type of hydrogen-embrittlement, caused by the hydrogen that diffuses to the steel material through the corrosion, and the deterioration of the fatigue resistance property attributed to the formation of the corrosion pit.

The hydrogen-embrittlement phenomenon (delayed fracture) by corrosion is well-known. As far as the steel material of tempered martensitic microstructure is concerned, the higher the strength, the higher the susceptibility to the hydrogen-embrittlement is assumed to be. Since the suspension spring steel is of the high strength tempered martensitic microstructure, and since the suspension springs are subjected to the load exerted by the weight of a car body even in their resting state, the risk of the delayed fracture increases when hydrogen diffuses in the steel material via the corrosion. Particularly, when the strength of the spring steel is enhanced for the weight saving of the suspension springs, measures to suppress the delayed fracture are required.

Furthermore, along with the development of the corrosion, corrosion pits are formed on the surface of the suspension springs. As the corrosion pit becomes the stress-concentrating site whenever the suspension springs are subjected to the repetitive deformation, the fatigue limit is deteriorated thereby. In addition, in the compression deformation of the suspension springs, the coil spring element wire is subjected to distortion. To suppress the deterioration of the fatigue limit, suppression of the formation of the corrosion pit and rendering the corrosion pit harmless are conducted. For the former, improvement of the corrosion resistance property of the steel material is important, and for the latter, the suppression of the influence of the stress concentration at the corrosion pit is important. Kubota et al.[1] suggest that by imparting compressive residual stress by shot peening, the corrosion pit having the same depth as that of the compressive residual stress layer is rendered harmless. They also suggest additionally that although the hydrogen diffused at the corrosion exerts a harmful effect on the corrosion fatigue, if the pit is rendered harmless by the compressive residual stress, the influence of hydrogen on fatigue is not revealed. Thus, concerning the corrosion fatigue property, the improvement thereof is expected not only from aspect of the steel material, but also from that of the spring processing.

1.3 Trend of automotive suspension springs

Similarly to the general automotive use steel, enhancement of the strength of the spring wire of the suspension springs for automotive use is pursued, aiming at improving the fuel consumption. Realizing the trend of the suspension spring requirements, Nippon Steel has developed an alloyed suspension spring steel applicable to the springs with the maximum shearing load τ_{max}: 1 200–1 250 MPa.

However, in recent years, owing to the improvements of spring processing techniques such as the wire heat treatment method, spring design, shot peening treatment, coating, and so forth, application of the standardized suspension spring steel SAE9254 to the higher strength springs is increasing. As a result, the cost-performance of the alloyed suspension spring steel is declining, and therefore, low-cost, high performance alloyed suspension spring steel is being demanded. In addition, amid the trend of the increase in the numbers of HV and EV cars, car weight is on an increasing trend, and to support this increased car weight, further enhancement of the strength of automotive use suspension spring steel is demanded.

To deal with this situation and the alloyed suspension spring steel, "low-alloyed high-strength suspension spring steel" has been developed to enhance the cost competitiveness by improving the performance through enhancing the strength and reducing alloying elements.

2. Design Guideline for "Low-alloyed High-strength Suspension Spring Steel"

The low-alloyed high-strength suspension spring steel has been developed based on the cold coiling process, and with the focus on the cold coiling workability, toughness and improvement of the delayed fracture resistance properties, all of which are problems in enhancing the strength in the assumed cold coiling process. In order to enhance the cost competitiveness, the use of costly alloying elements such as Mo and V that are used conventionally in the alloyed suspension spring steel was eliminated. Instead, in order for the respective property to compatibly coexist at a high level, the addition of an appropriate amount of the alloying metals pursuant to the respective inducement mechanism was implemented, and the microstructure was optimized by the wire heat treatment condition.

2.1 Guideline to develop high strength, high ductility

The automotive suspension spring steel is required to be equipped at the same time with high strength and ductility, toughness and the hydrogen embrittlement resistance property (delayed fracture resistance property). In the tempered martensitic microstructure, relative to the decrease of the tempering temperature, strength is increased; however, the ductility and the toughness are deteriorated in general. As factors affecting the hydrogen embrittlement resistance property, Nagumo cites: 1) hydrogen content, 2) temperature, 3) material strength, 4) material compositions and microstructure, and suggests that to further enhance the high strength alone deteriorates the hydrogen embrittlement resistance property, and the increase of the tempering temperature improves it.[2)]

From this, it is considered that the increase of the strength by decreasing the tempering temperature deteriorates the delayed fracture resistance property. Accordingly, to enhance the strength of the automotive suspension spring steel, the steel material compositional design that realizes high strength without decreasing the tempering temperature is important. Conventionally, elements such as Mo and V that enhance the temper softening resistance were added. However, since these alloying elements are relatively costly, in this development, the alloy elements that substitute these elements were studied. As a result, Si and Cr that exhibit high temper softening resistance in the tempering temperature range for the automotive suspension spring steel (350–450°C) were utilized.

2.2 Guideline to develop high toughness

Regarding enhancement of the toughness of the spring steel, Kawasaki et al. conducted the experiments of heating SAE9254 by furnace and induction heating. They reported that the austenitic grain size is refined by the short-time heating and quenching by the induction heating, and the toughness is improved thereby,[3)] and that the behavior of the carbide precipitation changes due to the tempering of short-time induction heating, thereby improving the toughness.[4, 5)] Pursuant to the report, for the quenching and tempering treatment of the high strength spring steel wire to develop higher toughness, the induction heating treatment was employed instead of furnace heating. Furthermore, in order to refine the austenitic grain size, by adding a micro alloying of Ti, the titanium carbonitride having a pinning effect on the growth of the austenite grain was utilized.

2.3 Guideline to improve hydrogen embrittlement resistance property (delayed fracture resistance property)

The hydrogen embrittlement (delayed fracture) is a phenomenon wherein hydrogen is diffused in the steel material via corrosion or the like, and the hydrogen is accumulated at the prior-austenite grain boundaries and induces the intergranular fracture. Therefore, the suppression of the hydrogen diffusion and the strengthening of the prior-austenite grain boundary are considered to be effective for the improvement of the hydrogen embrittlement resistance property (delayed fracture resistance property).

To suppress the diffusion of the hydrogen, it is important to suppress the corrosion, the source of hydrogen. Ni or Cu having electrochemical nobility higher than that of Fe is effective for the improvement of corrosion resistance, and these alloys are utilized. Additionally, the reduction of the lattice defect such as dislocation that acts as the trap site of the hydrogen is considered effective for the suppression of the hydrogen diffusion.[6)] To reduce the dislocation density, the high temperature tempering is effective. For example, regarding the PC bar steel having a tempered martensitic microstructure, Matsumoto et al. evaluated the hydrogen embrittlement resistance properties of the low Si steel tempered at a low temperature and the high Si steel tempered at a high temperature, wherein the test pieces used were tempered to be the same strength (about 1 450 MPa). Based on the result, they suggest that the high Si steel tempered at a high temperature exhibits superior delayed fracture resistance properties.[7)]

The segregation of the embrittling element P and the precipitation of the intergranular carbide occur at the grain boundaries of the prior-austenite, and weaken the prior-austenite grain boundaries. To improve the hydrogen embrittlement resistance property of high strength bolt steel, Yamasaki et al. suggest the effectiveness of vanadium carbide working as the hydrogen trap site. They also suggest that the suppression of the P segregation at the prior-austenite grain boundaries by reducing the P content and the shape control of the carbide at the prior-austenite grain boundaries by the high temperature tempering are also effective in improving the delayed fracture resistance property and in suppressing the intergranular fracture.[8)]

To suppress the P segregation, in addition to reducing the P content, the utilization of B (Boron) that segregates at the prior-austenite grain boundaries in a competitive manner with P is cited.[9)] As B has a higher diffusion rate and segregates at the boundary earlier than P, B is an element that suppresses the segregation of P and the precipitation of the intergranular carbide, and suppresses the intergranular embrittlement thereby. Therefore, we considered that the addition of B as well as the reduction of P content is effective for the improvement of the delayed fracture resistance property.

3. Performance of Low-alloyed High-strength Suspension Spring Steel

3.1 Steel chemical compositions and temper softening resistance

The influence of Si and Cr on the tempered hardness was investigated in a laboratory test. The steel material of the chemical compositions shown in **Table 1** was prepared by a laboratory 150 kg-vacuum induction melting furnace (VIM), and a round bar 16 mm in diameter was prepared by hot forging and machining. After heating for 15 min at 950°C in an electric furnace, the bar was oil-quenched at 60°C and was tempered for 30 min in an electric furnace at various temperatures. The tempered round bar was cut in the longitudinal direction on the center axis (L section), embedded in resin and polished. Vickers hardness (HV_{10}: Measuring load 10 kgf) was measured at a position situated one quarter of the diameter away from the center.

Figure 1 shows the relationship between the tempering temperature and the hardness of the respective steel material. Different from the steel material of 1.5Si-0.7Cr (equivalent to the SAE9254), in the Si-increased steel of 2.0Si-0.7Cr, the tempered hardness increased, and the tempered temperature to develop HV = 550–600 increased by 10–15°C. In the 2.0Si steel, when Cr content is decreased, the tempering hardness decreases, and it was confirmed that the tempered temperature of 2.0Si-0.3Cr steel to develop HV = 550–600 is

Table 1 Chemical compositions of the sample for evaluation of hardness after tempering

(mass%)

	C	Si	Mn	P	S	Cr
A	0.55	1.51	0.70	0.001	0.001	0.70
B	0.54	2.00	0.71	0.001	0.001	0.00
C	0.55	2.00	0.70	0.001	0.001	0.30
D	0.56	1.99	0.71	0.001	0.001	0.71

almost the same as that of the 1.5Si-0.7Cr steel (SAE9254).

3.2 Procedure of preparing test sample to evaluate mechanical properties

Based on the abovementioned preliminary study, two types of trial steel for development (hereinafter referred to as developed steel) of R1 (1900 MPa grade) and R2 (2000 MPa grade) each having a different temper softening resistance were prepared. **Table 2** shows the chemical compositions of the developed steel and the conventional steel SAE9254 for comparison. The ingots of both of the developed steels were prepared by a 2t-VIM furnace, rolled to actual size billets and rolled to an actual product at the Wire Rod Mill of the Muroran Works. R1 was rolled to a wire rod of 14.0 mm in diameter, and then drawn to a wire of 12.7 mm in diameter. Then the wire underwent the induction heating quenching and tempering treatment, and was tempered to achieve the targeted tensile strength of = 1900 MPa. R2 was rolled to a wire rod of 16.0 mm in diameter, and then drawn to a wire of 15.0 mm in diameter. Then the wire underwent the induction heating quenching and tempering treatment, and was tempered to achieve the targeted tensile strengths of = 2000 MPa and 2100 MPa. SAE9254 steel for comparison purposes, manufactured by the actual production furnace, was rolled to a wire rod of 13.5 mm in diameter, and then drawn to a wire of 12.0 mm in diameter. Then the wire underwent the induction heating quenching and tempering treatment, and was tempered to the targeted tensile strengths of = 1900, 2000 and 2100 MPa.

From the induction heating-quenched and tempered wires, the following test pieces were prepared by machining, and provided for the tests: tensile test piece (JIS No. 14, parallel and round portion is 6 mm in diameter: **Fig. 2**), Charpy impact test piece (5 × 10 mm sub size, 2 mm-U notch: **Fig. 3**), delayed fracture test piece (parallel and round portion is 8 mm in diameter, 1 mm depth annular notch: **Fig. 4**).

3.3 Test procedure

The tensile test was conducted under the condition of a constant cross head speed of 5.0 mm/min so that the strain rate becomes 0.002 + 0.0004 (s^{-1}). For the measurement of strain, a strain gauge 30 mm in length was used. For the Charpy impact test, a Charpy test machine of 300 J capacity was used, and the test was conducted at room temperature. In the delayed fracture test, a constant load was applied by a constant loading tester while charging cathodic hydrogen under a fixed condition, and the maximum load (σ) that endures 720000 s (200 h) testing was measured. The ratio of the load σ vs. the tensile strength (TS) was defined as the delayed fracture strength ratio and was evaluated. The cathodic hydrogen charging condition was: charging current density 1 mA/cm^2, 30°C-pH3.0 sulfuric acid aqueous solution.

3.4 Tensile test result

Figure 5 shows the tensile strength and the 0.2% yield strength of the respective material of the specifically targeted strength. The developed steels of the tensile strengths of 1900, 2000 and 2100 MPa were specifically prepared. The 0.2% yield stress of the developed steel is equal to or higher than that of the SAE9254 when they are compared on the basis of the same tensile strength.

Figure 6 shows the fracture elongation of the respective material of the specifically targeted strength. The fracture elongation of the developed steel is superior to that of the SAE9254 in the entire strength range of 1900–2100 MPa when they are compared on the basis of the same tensile strength, among which in particular, the developed steel R1 exhibits the best result.

Figure 7 shows the reduction of the area of the respective material of the specifically targeted strength. Reduction of the area of the

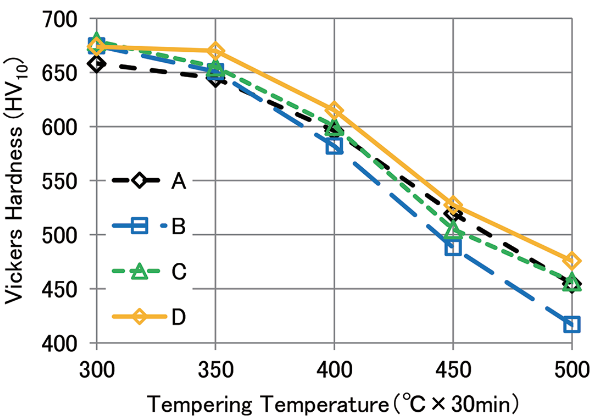

Fig. 1 Effect of Si and Cr on hardness after tempering

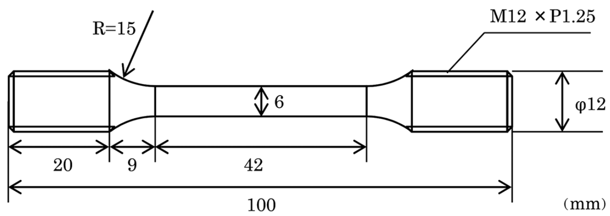

Fig. 2 Test piece for tensile test

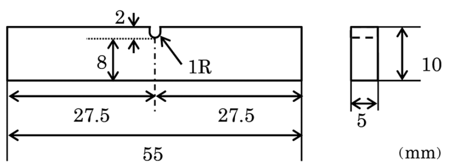

Fig. 3 Test piece for Charpy impact test

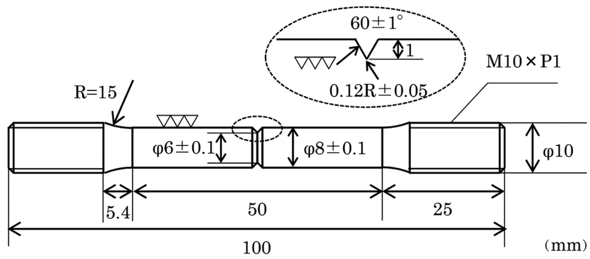

Fig. 4 Test piece for delayed fracture test

Table 2 Chemical compositions of the sample for evaluation of mechanical properties

(mass%)

		C	Si	Mn	P	S	Cu	Ni	Cr	Ti	B
Developed steel	R1	0.50	2.02	0.50	0.005	0.005	0.25	0.25	0.29	0.069	0.0026
	R2	0.50	2.00	0.52	0.005	0.005	0.24	0.24	0.75	0.065	0.0021
Conventional steel	SAE9254	0.55	1.35	0.70	0.013	0.003	–	–	0.70	–	–

developed steel is better than that of the SAE9254 in the entire strength range of 1900–2100 MPa when they are compared on the basis of the same tensile strength, and up to the high strength of 2100 MPa, the deterioration of the reduction of area is negligible.

From the above, even when the developed steels R1 and R2 are quenched and tempered to reach the high strength exceeding 1900 MPa, they exhibit good fracture elongation and good reduction of area, which are considered to render a good cold workability in coil spring forming. In addition, 0.2% yield strength and the yield ratio are also considered to be equal to or greater than those of the SAE9254.

3.5 Charpy impact test result

Figure 8 shows the Charpy impact value of the respective material of the specifically targeted strength. The Charpy impact values of the SAE9254 having the tensile strength grades of 1900 MPa and 2000 MPa are about 60 J/cm^2. However, in the case of the 2100 MPa tensile strength, the impact value drops to about 30 J/cm^2. On the other hand, the developed steel R1 having a tensile strength of 1900 MPa exhibits the very high toughness value of 90 J/cm^2. The high Cr developed steel R2 also exhibits higher toughness than that of the SAE9254 having equivalent tensile strength, and furthermore, the impact value of the steel having a tensile strength of 2100 MPa shows almost no reduction. This indicates that the developed steels R1 and R2 are considered to be excellent in the strength-toughness balance as compared with that of the SAE9254.

In order to clarify the toughness-improving mechanism of the developed steel, the fracture surface of the Charpy impact test piece was observed by a scanning electron microscope (SEM). **Figure 9** shows the result of the SEM observation (at the point 1.0 mm below the notch bottom) of the Charpy impact fracture surfaces of the 2000 MPa and 2100 MPa tensile strength material. Both images of the 2000 MPa and 2100 MPa tensile strength developed steel R2

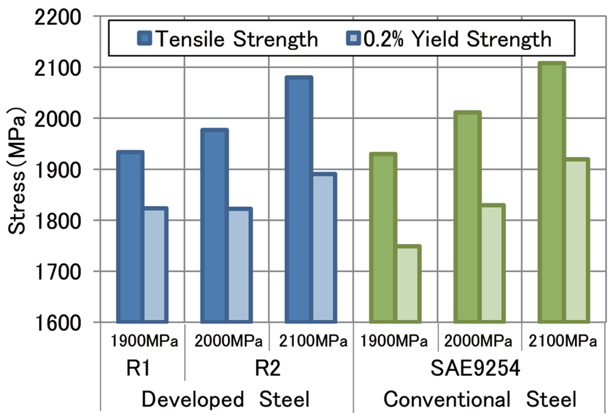

Fig. 5 Tensile strength and 0.2% yield strength of test pieces

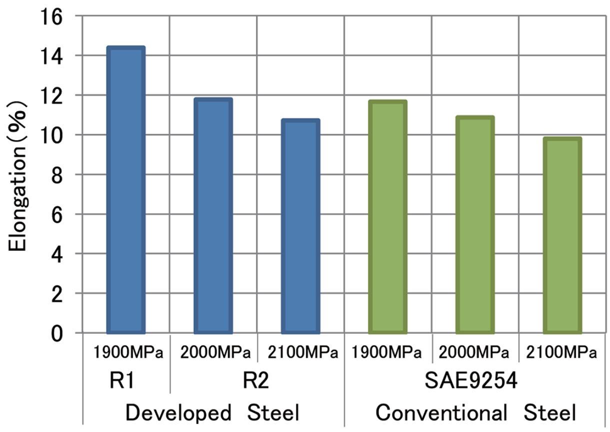

Fig. 6 Elongation of test pieces

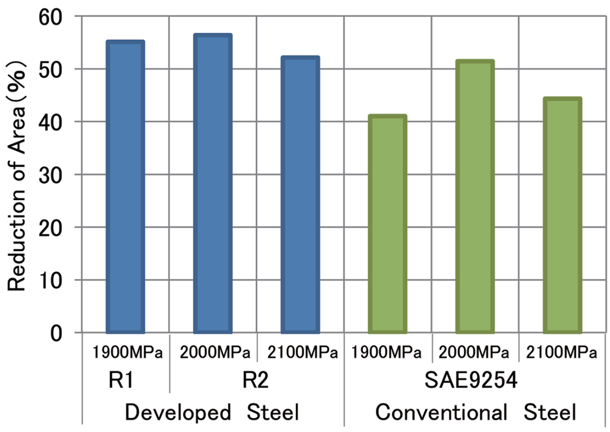

Fig. 7 Reduction of area of test pieces

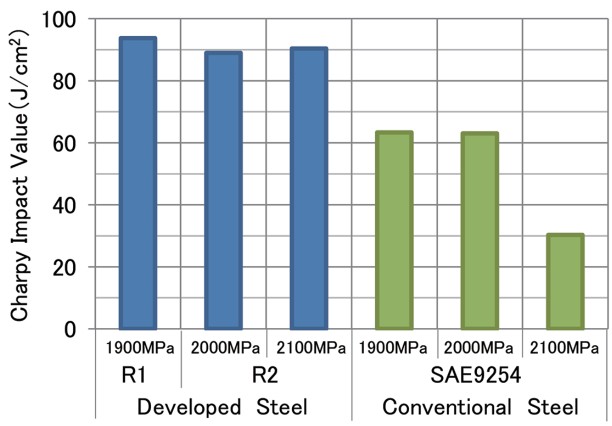

Fig. 8 Charpy impact value of test pieces

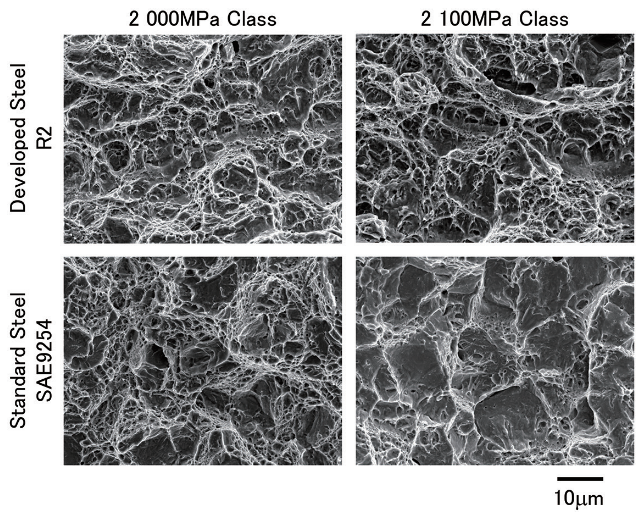

Fig. 9 SEM images of fractures after Charpy impact test

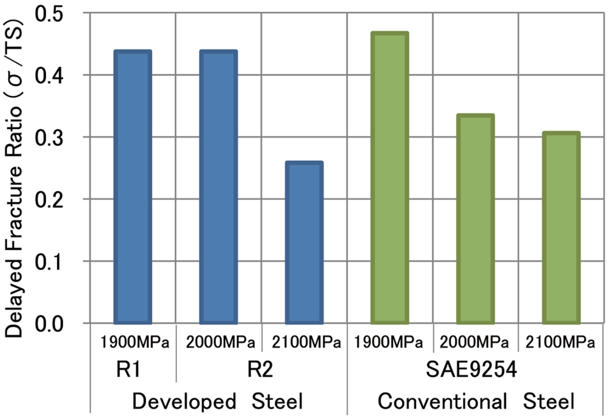

Fig. 10 Delayed fracture ratio of test pieces

show that the surface is ductile-fractured, consisting of fine dimples. However, although the images of the standardized steel SAE9254 of 2000 MPa show the ductile fracture surface with dimples, in the 2100 MPa grade, mainly, a coarse intergranular fracture surface is shown, and the emergence of the intergranular fracture is considered to cause the deterioration of the toughness. In the developed steel, as a result of intergranular strengthening by the addition of B and the reduction of P to improve the delayed fracture resistance property, the intergranular fracture is suppressed even when the strength is increased up to 2100 MPa.

3.6 Hydrogen embrittlement (delayed fracture) test result

Figure 10 shows the result of the hydrogen embrittlement (delayed fracture) test. In the SAE9254, when the tensile strength increases from 1900 MPa to 2000 MPa, the delayed fracture strength ratio deteriorates sharply. On the other hand, in the developed steel of 1900 MPa and 2000 MPa, the delayed fracture strength ratio is equal, and even when the strength is increased up to 2000 MPa, the resistance to the delayed fracture was confirmed as not deteriorated.

The reason for the improvement of the delayed fracture resistance property of the developed steel is that, in addition to the suppression of the intergranular fracture by intergranular strengthening similar to the case of the Charpy impact values, in the developed steel R2, owing to the improvement of the resistance to temper softening, the tempering temperature is sufficiently high even in 2000 MPa steel, and the influence of the dislocation density acting as the hydrogen trap site is reduced thereby.

Under the low alloy metal condition, as the further increase of the tempering temperature is considered difficult, in order to further improve the delayed fracture resistance property, utilization of more alloying elements is required.

4. Conclusion

In order to respond to the needs of further enhancing the strength of suspension springs, low-alloyed high-strength suspension spring steel excellent in ductility, toughness and the hydrogen embrittlement (delayed fracture) resistance property, all of which are problems when enhancing strength, has been developed. The R&D has revealed the strength limit of the standard steel SAE9254 and the problems of the low-alloyed spring steel, and at the same time has also confirmed the merit of using alloying metals. In conjunction with the change of the automobile structure, the needs of weight reduction and higher strength are intensifying and, based on the knowledge obtained in this R&D, we are determined to continue these activities, aiming at further higher strength of the suspension spring steel.

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