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Development of Gear Steel MSB20 for the Hybrid Process of Vacuum Carburizing with Induction Hardening

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Abstract

To address the issue of global warming, improvement in the fuel efficiency of automobiles has become of critical importance. To improve the fuel efficiency of automobiles, it's necessary to reduce the weight and the size of automobile parts by achieving high strength. Furthermore, against concerns of a steep price rise and drain on resources of alloying elements in the future, the development of steel for gears including the reduction of alloying elements in the steel materials of automobile parts is strongly required. Gears are used for power transmission and gear shifting of automobiles wherein high strength and alloy-reduction are highly required. Therefore, we undertook chemical composition design of steel capable of maximizing the advantage of the features of the new surface hardening process, "the hybrid process of vacuum carburizing with induction hardening" that is a substitute for the conventional carburizing process, and developed MSB20 that can achieve both high gear strength and reduction of alloying elements of steel.

1. Introduction

Recently, measures for the protection of the global environment and energy resources by reducing CO_2 emissions have become strongly demanded and in the automobile industry, improvement in fuel consumption has become of critical importance. To realize the improvement in fuel consumption, it is necessary to reduce the weight of automobile parts by down-sizing with enhanced strength. Gears are used for the power transmission and the speed change shift of automobiles. In most cases, they are produced by surface carburizing and quenching of the steel added with Cr and Mo as represented by JIS SCM420. Conventionally, to enhance the strength of gears, the addition of high alloying materials has been oriented on the basis of surface carburizing and quenching, and for example, the steel with increased Cr and/or Mo has been developed for gears, and practically used[1, 2].

However, the rapid price increase, unstable supply status and further, concerns regarding the drain on resources of alloying elements in the future have become acutely apparent of late. Accordingly, design of alloy-reduction type steel material that is less dependent on price fluctuations with less unreliability in supply has emerged as a new need and is being strongly pursued. To realize high strength of gears using alloy-reduction type steel, developments of a new production process different from the conventional carburizing and quenching method and steel appropriate for the process have been promote[3, 4]. As an example of the new production process, a mild carburizing process (hereafter referred to as mild carburization) that realizes the compatibility of reducing alloying metals in steel compositions and improvement in the fatigue strength of gear parts by combining the advantages of vacuum carburizing treatment and induction hardening has been developed[5].

We studied the optimization of the compositions of steel material to maximize the advantage of the new process of mild carburization and developed MSB20 as the steel appropriate for mild carburization that enables the enhancement of gear strength and reduction of alloying metals in the compositions of steel. This article introduces the development and the characteristics of MSB20.

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2. Development of MSB20 for Mild Carburization

2.1 Characteristics of mild carburization

Figure 1 shows the representative surface hardening treatment processes of gears. Figures 1 (a), (b) and (c) show the processes of the gas carburizing and quenching, induction hardening and mild carburization. In the case of applying the conventional surface hardening treatment processes of gas carburizing and quenching (Fig. 1 (a)) and/or induction hardening (Fig. 1 (b)), the following subjects had to be considered.

For instance, as materials are heat-treated for gas carburizing and quenching under the carburizing gas atmosphere that contains oxidizing gas such as CO_2, H_2O and O_2, grain boundary oxidization is generated during heating, and therefore, there is a deficiency of hardenability-increasing elements such as Mn and Cr and the incompletely-hardened layer is produced in oil quenching. Consequently, the gear subsurface hardness deteriorates. Furthermore, in the case of a high Si concentration, an oxidized film is formed on the material surface and the carburizing effect deteriorates[6]. Therefore, it is difficult to increase the Si concentration of the material. Furthermore, when the gas carburizing treatment condition becomes severe with a high temperature over a prolonged period of time, the crystal grains grow coarse and the gear strength deteriorates in some cases.

In the induction hardening, as only the subsurface is heated by high-frequency induction heating and then water-quenching is applied immediately after, the surface hardness after quenching is determined primarily by the carbon concentration of the material. To secure the required hardness of gears by induction hardening, a minimum of about 0.5% of carbon concentration of the material is required. Therefore, the carbon concentration of the steel for induction hardening is higher than that of the steel for gas carburizing and quenching. Therefore, deterioration in machinability due to an increase in material hardness is inevitable.

Contrary to the above, the mild carburization (Fig. 1 (c)) reported in this article consists of vacuum carburizing equipment and induction hardening equipment, and is a process that performs carburizing treatment after heating under a reduced pressure and surface hardening by water-quenching after heating by high-frequency induction heating. By combining the respective advantage of the vacuum carburizing and induction hardening, problems of the conventional process of surface hardening are solved.

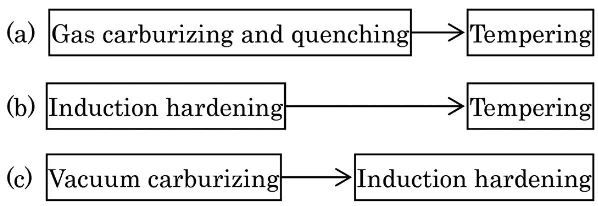


Fig. 1 Comparison of representative surface hardening processes

Vacuum carburizing has the advantage of suppressing grain boundary oxidation and prohibiting the formation of an incompletely-hardened layer by supplying hydrocarbon gas like C_2H_2 as the material gas, unlike the gas carburizing wherein the oxidizing gas component like CO_2 is continuously fed[7]. Furthermore, oxidization film is not formed during the vacuum carburizing. Accordingly, the Si concentration of the material does not need to be limited, and therefore, greater freedom in composition design with respect to Si concentration is enabled.

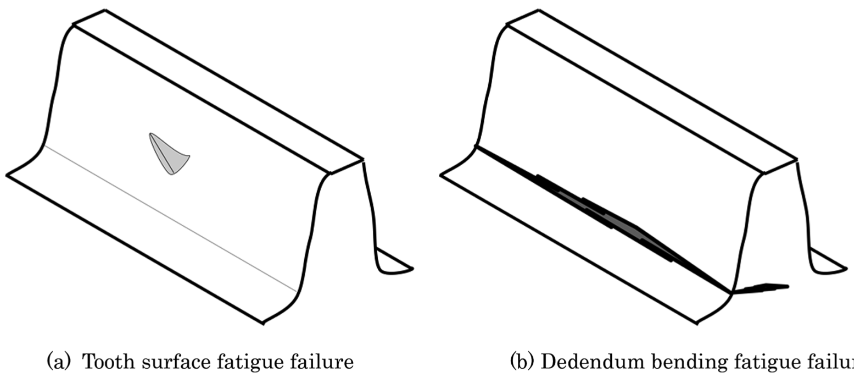
The advantage of the induction hardening is the ability to refine the crystal grain by heating for a short time and quenching. Therefore, for instance, measures for suppressing the coarsening of the crystal grain by adding micro-alloying elements like Nb and Ti[8] as practiced in the gas carburizing are not necessary. In addition, in the induction hardening, water can be used as the coolant. Therefore, the cooling rate higher than that of oil quenching that is conventionally employed in gas carburizing is obtained and can minimize the hardening requirements on the part of the steel material. Namely, the amount of elements added to enhance hardenability can be reduced.

Furthermore, as Fig. 1 (c) shows, the mild carburization is performed in the order of vacuum carburizing and induction hardening. Therefore, the subsurface carbon concentration before the induction hardening may be adjusted in the vacuum carburizing. Namely, the carbon concentration of the material can be controlled to the level of that of case-hardened steel used in the conventional gas carburizing, and the problem of the deterioration in machinability of the material can be eliminated.

Thus, the mild carburization is a new process that can eliminate the problems of the conventional surface-hardening process. Also, by utilizing the mild carburization, the composition design of steel materials not restrained by the conventional composition concept is possible.

2.2 Strength characteristics required for gear and viewpoint of steel material compositions

The major strength characteristics required for gears are the tooth surface fatigue strength and the dedendum bending fatigue strength. **Figure 2** shows the schematic illustrations of the tooth surface fatigue failure and the dedendum bending fatigue failure. The



(a) Tooth surface fatigue failure (b) Dedendum bending fatigue failure

Fig. 2 Schematic illustrations of (a) Tooth surface fatigue failure and (b) Dedendum bending fatigue failure

tooth surface fatigue failure is the phenomenon of surface spalling developed by the contact of teeth surfaces that takes place under a high surface pressure accompanied by slip. The dedendum bending fatigue failure is the fatigue failure phenomenon of a tooth caused by the bending stress, and tends to take place in the vicinity of the dedendum where stress is concentrated. Then, we studied the compositions of the steel that enables the enhancement of the tooth surface fatigue strength and the dedendum bending fatigue strength compatibly by taking advantage of the features of the abovementioned mild carburization.

2.2.1 Design of compositions to enhance tooth surface fatigue strength

As friction heat is generated on the gear tooth surface due to the contact of the tooth surfaces during driving and the tooth surface temperature rises to approximately 250–300°C, the tooth surface is tempered and the hardness deteriorates. The tooth surface fatigue strength deteriorates along with the deterioration of the hardness, and a high correlation is established between the tooth surface fatigue strength and the hardness of steel tempered at 300°C[9]. Then a study was performed to design compositions capable of suppressing the softening of the tooth surface caused by tempering due to the frictional heat.

The hardness of steel tempered at 300°C is determined by the initial hardness immediately after quenching and the resistance to softening caused by tempering. The initial hardness is determined primarily by the carbon concentration when martensite is obtained by quenching. Furthermore, the resistance to softening caused by tempering is an index that denotes the extent of suppression of softening caused by tempering. To improve the resistance to softening caused by tempering in the vicinity of 300°C, Si is effctive[10, 11].

In the mild carburization, as water-quenching is applied immediately after the high frequency induction heating, the carbon concentration required for obtaining the desired initial hardness after quenching can be reduced as compared to the gas carburizing and quenching[12]. Furthermore, since quenching is applied at a cooling rate much higher than that of the gas carburizing and quenching, the hardenability of the steel material required for obtaining martensite microstructure can be reduced as compared to the gas carburizing and quenching. Accordingly, the amounts of the addition of hardenability-enhancing elements such as Mn, Cr, Mo and so forth were those minimally-required in the design. Additionally, as the mild carburization is performed in a similar way to vacuum carburization and as the carburizing effect does not deteriorate due to the formation of oxidization film, the Si concentration higher than that of conventional case-hardened steel was employed in the design.

2.2.2 Design of compositions to enhance dedendum bending fatigue strength

The dedendum bending fatigue strength is governed by the subsurface hardness, the grain boundary strength and the compressive residual stress[13, 14]. The subsurface hardness at the dedendum is primarily determined by the carbon concentration when martensite microstructure is obtained by quenching. The carbon concentration is controllable in the carburizing process. Accordingly, compositions have to be designed, taking into consideration the hardenability required for obtaining martensite microstructure.

The grain boundary strength deteriorates depending on the precipitation of coarse cementite (θ) and the segregation of the embrittling elements like P and S at the grain boundary. Therefore, compositions need to be designed so as to suppress the θ precipitation and the segregation of the embrittling elements at the grain boundary. In the mild carburization in particular, as the vacuum carburizing is performed, in certain steel compositions, suppression of the precipitation of θ at the grain boundary becomes difficult, and the high degree of deterioration of the bending fatigue strength is of great concern[14].

Table 1 Representative chemical compositions of MSB20 and SCM420

(mass%)

Steel grade	C	Si	Mn	Cr	Mo	B
MSB20	0.20	0.80	0.80	0.10	-	0.0020
SCM420	0.20	0.25	0.80	1.10	0.20	-

Morita et al.[15], for instance, studied the precipitating condition of θ at the grain boundary in vacuum carburization by utilizing the thermodynamics and report that the subsurface carbon concentration of the material during the carburizing process in the vacuum carburizing agrees with the calculation result of thermodynamics wherein the equilibrium with graphite is assumed (carbon concentration balancing with graphite), and that θ precipitates at the grain boundary when the two phases of γ and θ balance with graphite. Furthermore, the carbon concentration in equilibrium with graphite lowers along with the lowering of Cr concentration and or the rise in Si concentration, and the region where the θ phase exists is reduced in the iron-carbon equilibrium phase diagram[16].

Based upon these findings, focus was placed on Si and Cr to suppress the precipitation of θ at the grain boundary, and the composition balance that does not allow the coexistence of two phases of γ and θ thermodynamically was studied. Using the representative values of the chemical compositions of the developed steel MSB20 and SCM420 shown in **Table 1**, a thermodynamic equilibrium calculation was performed. The iron-carbon equilibrium phase diagram thus obtained is shown in **Fig. 3**. The concept of the chemical compositions of MSB20 is explained in the following section.

In SCM420, as the coexistence phase of γ and θ exists on the lower carbon concentration side of the coexistence phase of γ, θ and graphite, θ may possibly precipitate at the grain boundary during the vacuum carburizing. However, in the developed steel of MSB20, as the coexistence phase of γ and θ does not exist, the precipitation of θ at the grain boundary is suppressed. Thus, in the development, the balance between Si and Cr that enables the suppression of the precipitation of θ at the grain boundary was studied and the Cr content was reduced to less than 0.1% and the Si content was set at 0.8%. As countermeasures for the segregation of embrittling element P at the grain boundary, B was employed. B in steel is expected when strengthening the grain boundary owing to the reduction in P concentration at the grain boundary realized by the site competition effect, and the effect of B alone that strengthens the grain boundary and delays the propagation of fatigue cracks[17].

Furthermore, in the mild carburization, as gears are locally heated and quenched by high frequency induction heating and quenching, the compressive residual stress in the vicinity of the dedendum becomes higher as compared to the conventional carburizing and quenching wherein the entire gear is oil-quenched. Namely, the effect of enhancing the bending fatigue strength by the mild carburization process independently is also expected.

2.3 Chemical compositions of MSB20

Based on the abovementioned concept, the steel chemical compositions were studied from the viewpoint of minimizing the rare-metal contents to the extent possible that still secures the fatigue strengths and machinability based on economic rationality. The de-

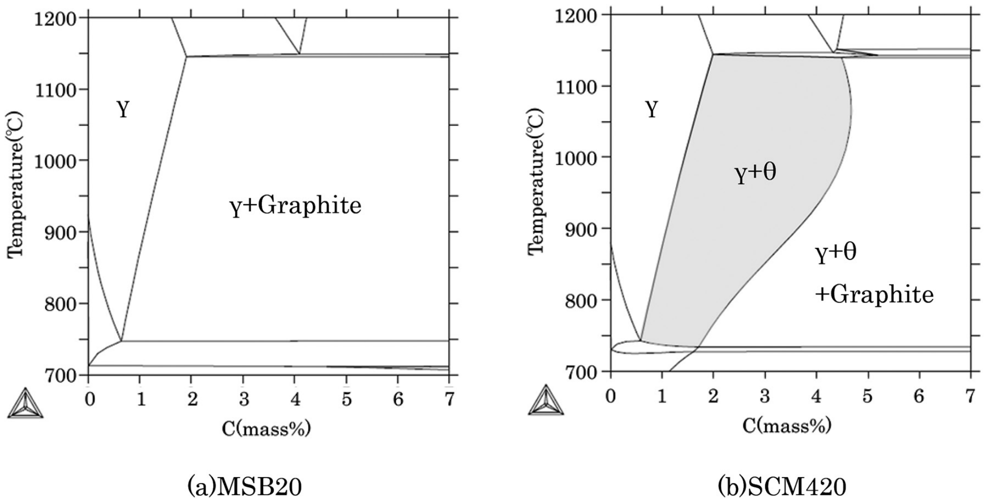


Fig. 3 Equilibrium phase diagrams of Fe-C system in (a) MSB20 and (b) SCM420

veloped steel is characterized by Si, Cr and B. High Si content was aimed at and set at 0.8% from the viewpoint of enhancing the resistance to softening in tempering. The Cr content was set at below 0.1 % from the viewpoint of suppressing the precipitation of θ at the grain boundary during the vacuum carburizing. Furthermore, to suppress the segregation of the embrittling element P at the grain boundary, the concentration of P was reduced to the minimum extent possible and furthermore, the grain boundary was strengthened with the addition of a very small amount of B.

3. Performance of Steel of Mild Carburization

3.1 Method of experiment

The tooth surface fatigue strength, the dedendum bending fatigue strength and the machinability of the developed MSB20 were evaluated by comparing them with those of SCM420 that is generally applied with gas carburizing and quenching. The chemical compositions of the test steel are shown in **Table 2**. A 150 kg ingot of test steel processed in a vacuum melting furnace was hot-forged to a round bar of 80 mm in diameter. Then the bar was held for 60 min. at 1 250°C for soaking and diffusion treatment, and for 10 min at 1 050°C for normalizing treatment. The roller pitting fatigue test specimen, the notched Ono-type rotating bending fatigue test specimen and the drill test specimen were prepared from the round bar by machining. The mild carburization was applied to the developed steel of MSB20, and the gas carburizing and quenching was applied to the SCM420 steel for comparison purposes. **Figure 4** shows the configuration of each test specimen.

Table 2 Chemical compositions of test samples

(mass%)

Steel grade	C	Si	Mn	Cr	Mo	B
MSB20	0.20	0.80	0.83	0.10	-	0.0015
SCM420	0.20	0.26	0.74	1.04	0.22	-

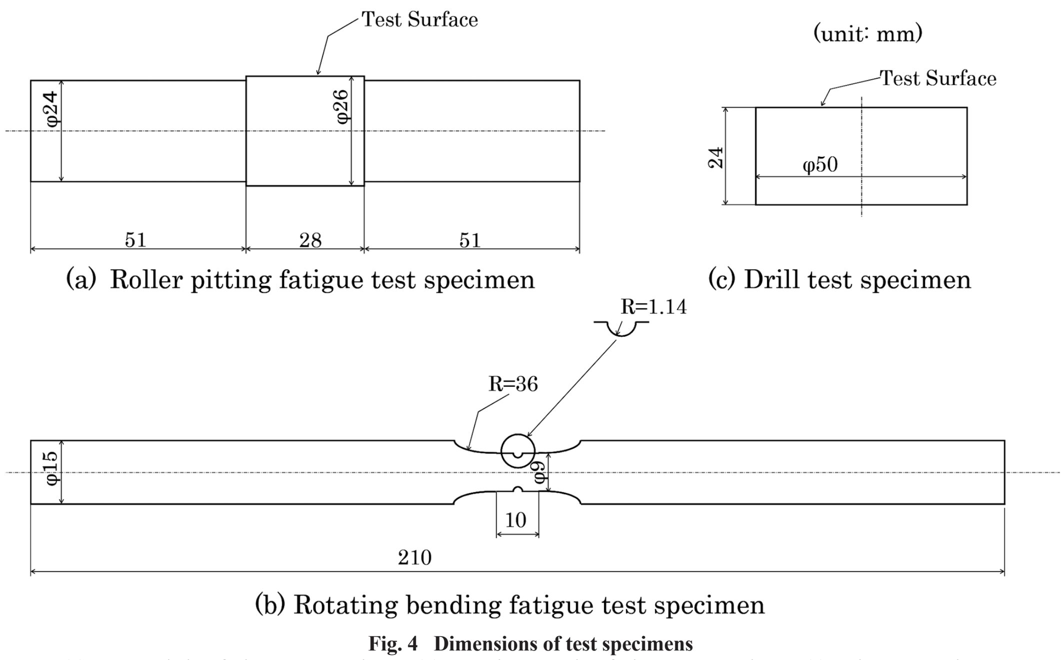


Fig. 4 Dimensions of test specimens
(a) Roller-pitting fatigue test specimen, (b) Rotating bending fatigue test specimen, (c) Drill test specimen

Microstructures, residual stress and the Vickers hardness after the mild carburizing and the gas carburizing and quenching were evaluated using the roller pitting fatigue test specimen prepared for evaluating the tooth surface fatigue strength. Further, the residual stress was measured by an X-ray diffraction analysis apparatus and the hardness was measured by a Vickers hardness test. Part of the roller pitting fatigue test specimen was cut out to examine the hardness after tempering at 300°C.

The tooth surface fatigue strength and the dedendum bending fatigue strength were evaluated by the roller pitting fatigue test and the rotating bending fatigue test, respectively. **Table 3** shows the roller-pitting fatigue test conditions. In the tooth surface fatigue test and the dedendum bending fatigue test, the stress enduring the number of loading cycles of 10^7 (hereafter referred to as 10^7 cycles enduring surface pressure or 10^7 cycles enduring strength) was used as the evaluation index for comparison for evaluation.

The machinability was evaluated by the drill test. **Table 4** shows the drill test conditions. As the index for evaluating machinability, the maximum peripheral speed VL1 000 (m/min)[18] to achieve the accumulated hole depth of 1 000 mm was employed.

3.2 Microstructure and subsurface hardness

Microstructures and the result of the measurement of the hardness of the developed steel MSB20 and SCM420 are shown in **Fig. 5** and **Fig. 6**, respectively. Both the mild-carburized MSB20 and the gas-carburized and quenched SCM420 exhibit the tempered martensite microstructure. However, when the subsurface microstructures are observed, in the gas-carburized and quenched SCM420, an incompletely hardened layer of about 20 μm at maximum is observed in the subsurface. On the other hand, in the mild-carburized MSB20, incompletely hardened layers are not observed in the subsurface.

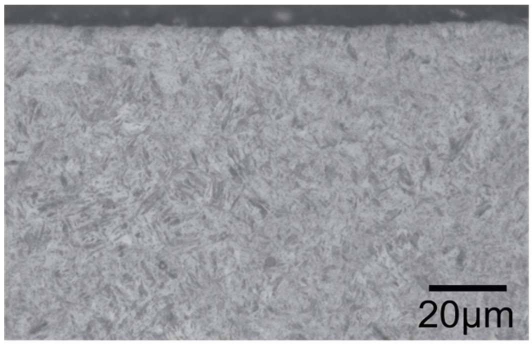
The difference appears in the result of the hardness measurement. The hardness of the mild-carburized MSB20 and the gas-car-

Table 3 Roller-pitting fatigue test conditions

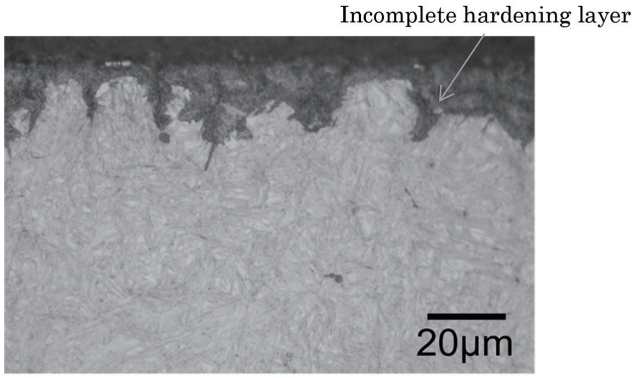
Rotational speed	2 000 min^{-1}
Lubricating oil	ATF (80°C)
Slip ratio	−40%
Crowning (opponent roller of the test roller specimen)	R150
Material (opponent roller of the test roller specimen)	SCM420 (gas carburizing)

Table 4 Drill test conditions

Coolant	Water-soluble oil
Tool material	High speed steel
Tip angle	118°C
Feed	0.25 mm/rev.
Hole depth	9 mm

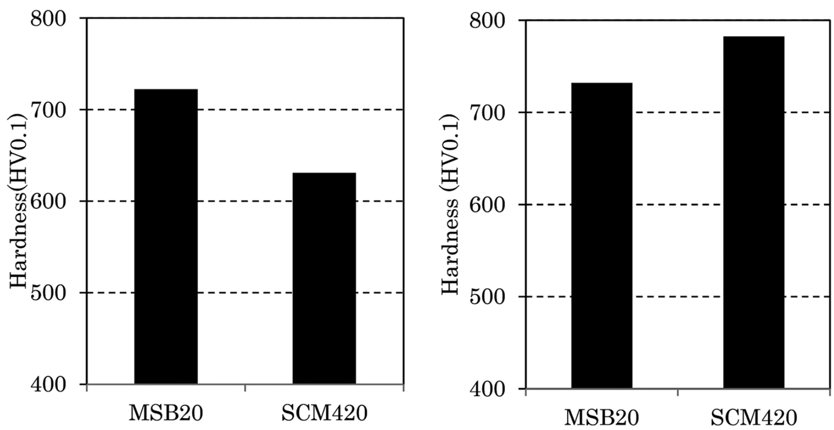


(a) MSB20



(b) SCM420

Fig. 5 Sectional surface microstructure of (a) MSB20 and (b) SCM420



(a) 20μm depth (b) 50μm depth

Fig. 6 Comparison of surface hardness at (a) 20 μm depth and (b) 50 μm depth

Table 5 Comparison of surface characteristics

Steel grade	Maximum depth of incomplete hardening layer	Hardness (20μm depth)	Austenite grain size number	Residual stress
MSB20	0μm	HV722	#10	−600 MPa
SCM420	20μm	HV631	#8	−300 MPa
Cause	Vacuum carburizing	Incomplete hardening layer	Induction hardening (short time heating)	Induction hardening (partial quenching)

burized and quenched SCM420 is 732 HV and 782 HV respectively at the depth of 50μm of the tempered martensite microstructures, and does not exhibit remarkable difference. However, when compared at the depth of 20μm that is nearer to the surface, different from the hardness of 722 HV of the mild-carburized MSB20, the hardness of the gas-carburized and quenched SCM420 drops greatly to 631 HV due to the formation of the soft incompletely hardened layer.

Table 5 shows collectively the result of the investigation of the materials of the mild-carburized MSB20 and the gas-carburized and quenched SCM420. The mild-carburized MSB20 exhibits excellent characteristics of subsurface microstructure, crystal grain size, residual stress and subsurface hardness.

3.3 Tooth surface fatigue strength

Figure 7 shows the result of the roller pitting fatigue test. All of the damages generated in the roller pitting fatigue test were of the pitting damage type that represent the tooth surface fatigue fracture. When compared, the 10^7 cycles enduring surface pressure of the mild-carburized MSB20 is 3 500 MPa, while that of the gas-carburized and quenched SCM420 is 2 800 MPa. Therefore, the tooth surface fatigue strength of the mild-carburized MSB20 became higher by 25% than that of the gas-carburized and quenched SCM420.

As the tooth surface fatigue strength and the hardness of steel tempered at 300°C maintain an appropriate relationship, the hardness of steel tempered at 300°C is evaluated for comparison purposes. As **Fig. 8** shows, the hardness of steel tempered at 300°C at the depth of 50μm of the mild-carburized MSB20 and the gas-carburized and quenched SCM420 is 656 HV and 643 HV respectively and equal. However, when the values at the depth of 25μm closer to the surface are compared, as opposed to 639 HV of the mild-carburized MSB20, the hardness of the gas-carburized and quenched SCM420 is 507 HV and the mild-carburized MSB20 is higher by 100 points than the gas-carburized and quenched SCM420 in terms of Vickers hardness. Generally, the pitting damage is the initiating-at-surface type fatigue[19], the improvement in the 10^7 cycles enduring surface pressure of the mild-carburized MSB20 is due to the superimposed effects of the suppression of the incompletely hardened layer and the increase in resistance to softening in tempering by increasing Si concentration.

3.4 Dedendum bending fatigue strength

Figure 9 shows the result of the rotating bending fatigue test. The 10^7 cycles enduring strength of the mild-carburized MSB20 is 600 MPa, improved by 13% as compared to that of the gas-carburized and quenched SCM420. Improvement in the bending fatigue strength is due mainly to the higher hardness near the surface developed by the suppression of the formation of the incompletely hardened layer and the higher residual compressive stress at the surface.

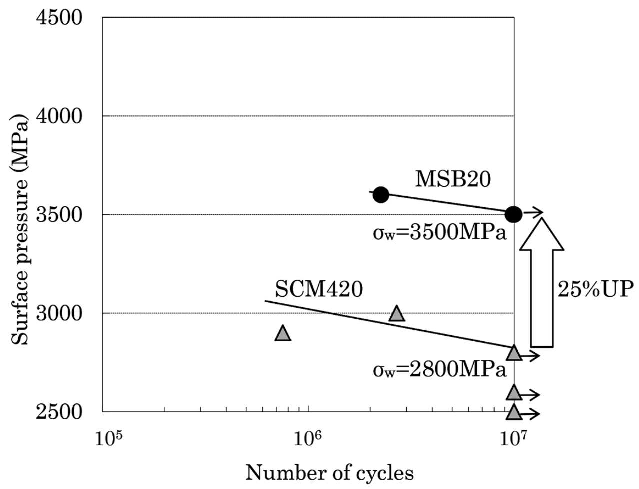


Fig. 7 Roller-pitting fatigue strength of MSB20 and SCM420

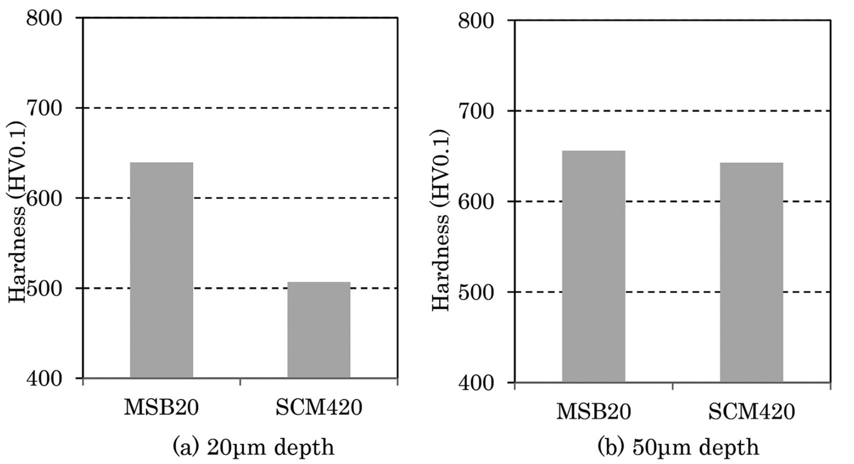


Fig. 8 Comparison of surface hardness at (a) 20μm depth and (b) 50μm depth after tempering at 300°C

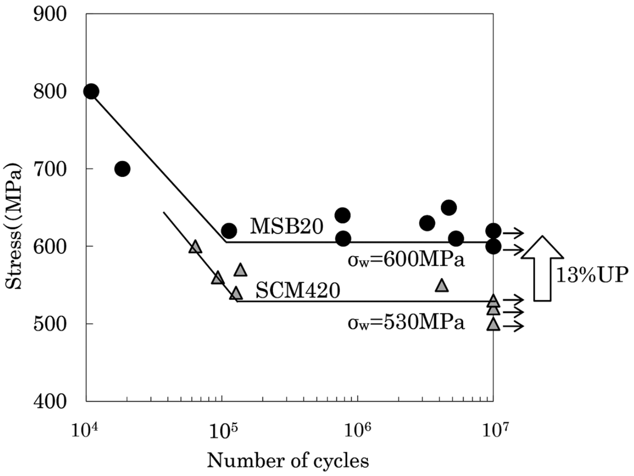


Fig. 9 Rotating bending fatigue strength of MSB20 and SCM420

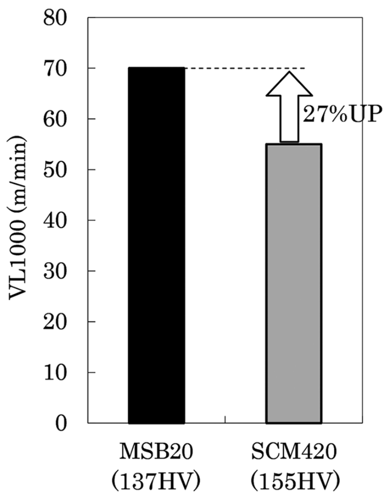


Fig. 10 Result of drill test in MSB20 and SCM420

There is also a view that the refined crystal grain contributes to the improvement in the bending fatigue strength through the improvement in yielding strength[20]. As shown in Table 5, when compared in terms of austenite grain size number, as different from #8 of the gas-carburized material, the mild-carburized material is refined to #10. Therefore, the refinement of the crystal grain is considered to contribute to the improvement in the fatigue strength.

3.5 Machinability

Figure 10 shows the result of the drill test. The parenthesized values in the figure indicate the Vickers hardness of the surface of the test specimen. For the evaluation of the machinability, VL1 000 (m/min), the maximum peripheral speed that attains the accumulated drilled hole depth of 1 000 mm, was used. Generally, the cutting speed and the accumulated hole depth are in a trade-off relationship (the larger the peripheral speed, the shorter the accumulated drilled hole depth); therefore, the higher the value of VL1 000, the better the machinability (tool life). VL1 000 of MSB20 is 70 m/min and the drill cutting ability is improved by 27% as compared to SCM 420. This is due to the material hardness of 137HV of MSB20 that is lower than that of 155 HV of SCM420.

4. Application of Steel MSB20 in Mild Carburization

MSB20 is the steel material jointly developed by Nippon Steel & Sumitomo Metal Corporation, Messrs. AISIN AW Co., Ltd. and Messrs. Aichi Steel Corporation. The commercial production of gears applied with this technology was started by Messrs. AISIN AW in January, 2013.

5. Conclusion

The concept of the development, machinability and fatigue strength of the mild-carburized steel MSB20 were introduced. As compared to the gas-carburized SCM420, the MSB20 of mild-carburization was improved by 25% in the tooth surface fatigue strength and 13% in the dedendum bending fatigue strength. Furthermore, the machinability of MSB20 was improved by 27% as compared to that of SCM420.

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