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Development of High-Strength Carburized Steel for Automobile Gears

Hideo Kanisawa*1 Tatsuro Ochi*1
Yoshiro Koyasu*2

Abstract:

Carburizing is widely applied to gears for automobiles and industrial machinery for the purpose of improving fatigue strength and wear resistance. In recent years, stronger and smaller gears have been in mounting demand to improve the fuel economy and reduce the vehicle weight as well as to increase the output of engines. Here is described the high-strength gear steel developed by Nippon Steel to meet the need for improved fatigue strength in gears used in automobile transmission and other applications.

1. Introduction

Gears are a major group of machinery parts used in automobiles and industrial machinery, and are usually made of carburized steel because they are required to have sufficient fatigue strength and wear resistance. In recent years, gears of higher strength and smaller size have been in strong demand in correspondence with the call for higher fuel economy and lower weight in automobiles as well as for a higher output of automobile engines.

Among the strength properties of gears are bending fatigue strength, pitting strength, wear resistance, and impact toughness. Gear life often depends on the bending fatigue strength and pitting strength of the tooth root. Various studies have been conducted on materials, heat treatment, and fabrication to produce gears with high bending fatigue strength and pitting strength.

This report describes the high-strength gear steel developed by Nippon Steel to answer the call for improved fatigue strength in gears used in automobile transmission and other applications.

2. Technology for Improving Bending Fatigue Strength

2.1 Considerations about improvement in bending fatigue strength

The fatigue strength of carburized gears may be generally divided into two types: tooth root strength (bending fatigue strength) and tooth surface strength (pitting strength). This section focuses on the bending fatigue strength that becomes a problem first when the gear strength is increased.

Photo 1 shows the fracture surface of a gear that was made of the conventional JIS SCM 420 steel, carburized, and tested to failure in the Ono rotating-bending fatigue test. It is evident that the fatigue crack originated in the grain-boundary oxidized layer formed during the carburization heat treatment, propagated along the grain boundaries, and resulted in the grain-boundary fracture.

Fatigue test specimens were similarly carburized and tested to an appropriate point of time. **Fig. 1** shows the fatigue crack propagation of the test specimens as determined by the oxidation method[1]. It is clear that fatigue cracks initiated very early relative to the overall fatigue life, and that the life to fatigue crack initiation (number of cycles to fatigue crack initiation) decreased

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*1 Technical Development Bureau

*2 Nagoya Sales Office

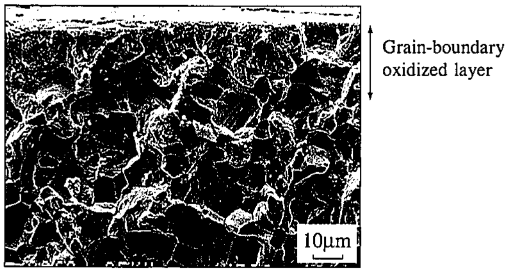

Photo 1 Bending fatigue crack initiation site in carburized specimen

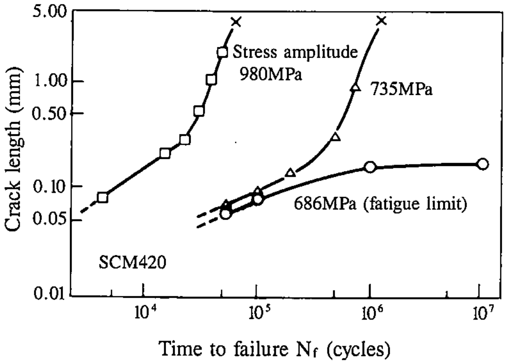

Fig. 1 Fatigue crack initiation and propagation behavior in carburized specimens

with increasing applied stress. These results show that the fatigue strength of carburized parts can be effectively enhanced by inhibiting the formation of the grain-boundary oxidized layer that serves as nucleus for fatigue crack initiation, and by imparting residual stress or increasing the surface layer hardness.

Fig. 1 shows the results of fatigue test made with the stress amplitude of 686 MPa, which is the fatigue limit. It is evident that 99% of the total life is accounted for by the propagation and arrest of the fatigue crack, suggesting that fatigue strength is heavily dependent on the fatigue crack arrest properties.

From the point of view of fracture mechanics, the fatigue crack arrest condition is given by the following equation[2]:

$$\Delta K_{eff} \leqq \Delta K_{eff.th} \ (\fallingdotseq \text{constant})$$

where

$$\Delta K_{eff} = \sigma_a (\pi a)^{1/2} + K_{res} + K_{clos}$$

where σ_a is fatigue stress amplitude; a is crack length; K_{res} is stress intensity factor for residual stress; K_{clos} is stress intensity factor for the crack tip closing phenomenon; and K_{op} is stress intensity factor for crack opening ($= -(K_{res} + K_{clos})$).

The threshold stress intensity factor $\Delta K_{eff.th}$ of 0.8%C steel (0.8%C being equal to the carbon content of the carburized layer) is almost constant. To improve fatigue strength, the effective stress intensify factor ΔK_{eff} at the crack tip must be reduced below $\Delta K_{eff.th}$ To this end, the effective tensile stress that acts at the crack tip must be reduced by decreasing the grain-boundary oxidized layer, which is the initial crack length, and by imparting compressive residual stress, which promotes the crack closing phenomenon.

The above discussion points to the importance of optimizing the gear steel chemistry and gear manufacturing conditions in improving the fatigue strength of carburized gears. As for the steel chemistry, it is effective to adopt an alloy design that minimizes grain-boundary oxidation during carburization and to minimize the reduction of surface hardness even if slight grain-boundary oxidation is inevitable. It is also effective to refine the grain size. As for gear fabrication, it is extremely effective to induce appropriate compressive residual stress in the surface by shot peening.

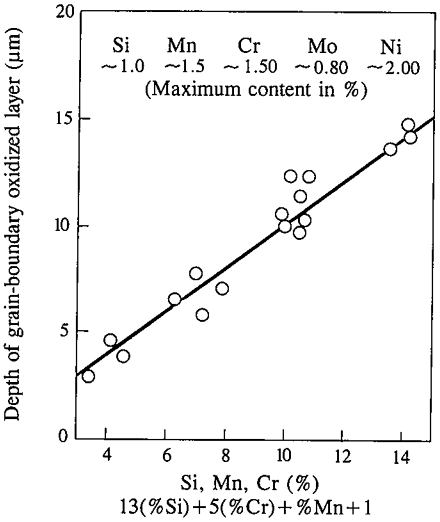

Fig. 2 Effects of alloying elements on depth of grain-boundary carburized layer (at 930℃ for 5 h and carbon potential of 0.8%)

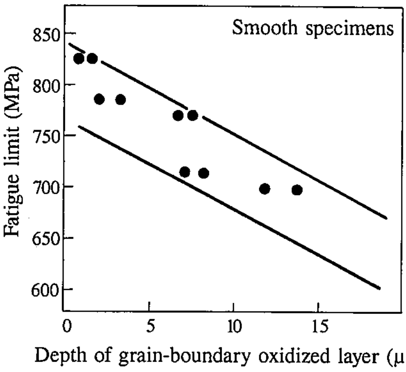

Fig. 3 Relationship between depth of grain-boundary oxidized layer and fatigue limit

2.2 Effects of metallurgical factors on bending fatigue strength

The grain-boundary oxidation phenomenon that occurs during the carburization heat treatment is strongly influenced by silicon, chromium, and manganese, the steel alloying elements having strong affinity for oxygen. The depth of the grain-boundary oxidized layer is expressed by the following equation. As shown also in **Fig. 2**, lowering the silicon content is particularly effective in preventing the grain-boundary oxidation of the steel[3]:

Depth of grain-boundary oxidized layer (μm)

$$= 13(\%Si) + 5(\%Cr) + \%Mn + 1$$

when the carburizing temperature and time are 930℃ and 5 h, respectively, and the carbon potential in the carburizing atmosphere is 0.8%.

The fatigue limit of the steel can be improved by reducing the depth of the grain-boundary oxidized layer as shown in **Fig. 3**[4]. Since the fatigue fracture originates in the grain-boundary oxi-

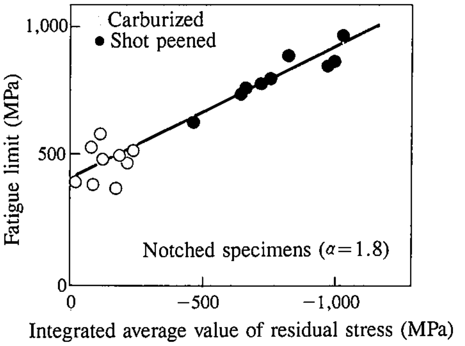

Fig. 4 Relationship between compressive residual stress (integrated average value from surface layer to depth of 300 μm) and fatigue limit

dized layer and propagates along the grain boundaries, it is clear that grain-boundary strengthening by grain refinement is also effective in improving the fatigue strength of the steel[5].

The factor that has the greatest impact on fatigue crack propagation and arrest properties is the residual stress present in the surface layer. **Fig. 4** shows the relationship between the integrated average value of the surface layer residual stress and the fatigue limit. The fatigue limit improves with increasing residual stress. In a normal case, carburization produces an incompletely hardened microstructure through grain-boundary oxidation in the surface layer, which often fails to induce a sufficient compressive residual stress in the surface layer. The compressive residual stress can be increased by inhibiting the grain-boundary oxidized layer or by shot peening the gear.

When evaluating the fatigue properties of gears by specimens, it is a common practice to take a specimen from the gear steel stock in a direction parallel to the rolling direction (longitudinal direction) and to test the specimen by the rotating-bending fatigue test method. On the specimen, the fatigue crack propagates at right angles to the rolling direction and eventually leads to the failure of the specimen. This differs from the tooth root fatigue of gears in which the fatigue crack often propagates parallel to the rolling direction of the gear steel stock before it results in the failure of the gear. The fatigue properties of gears may not be correctly evaluated by specimens unless the specimens are taken at right angles (transverse direction) to the rolling direction of the gear steel stock.

To further clarify the aforementioned points, **Fig. 5** shows the anisotropy of fatigue properties with the sampling direction of fatigue test specimens[6]. As evident from this figure, fatigue strength is much higher in the longitudinal direction than in the transverse direction and thus is notably anisotropic. In other words, the fatigue strength of actual gears is presumably lower than predicted by the conventional rotating-bending fatigue test. This phenomenon is attributable to the elongation of manganese sulfide (MnS) by forging and rolling and is subject to the influence of the reduction taken on the stock. The anisotropy of fatigue strength is an important consideration in improving the fatigue strength of gears.

3. Technology of Improving Pitting Strength

3.1 Considerations about improvement in pitting strength

In recent years, the practical application of hard shot peening has changed the principal mode of gear failure from tooth root fatigue to tooth surface pitting, and has created a very strong demand for higher pitting strength of gears.

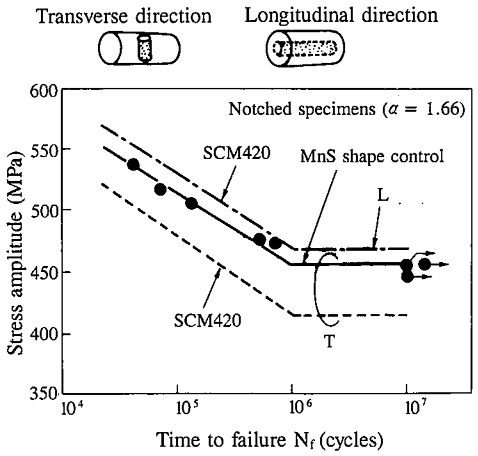

Fig. 5 Anisotropy of fatigue strength and effect of sulfide shape control

A two-cylindrical roller pitting test specimen (test roll diameter of 26 mm and load roll diameter of 130 mm) was prepared from the conventional JIS SCM 420 steel; carburized; pitting tested at the contact stress of 2,648 MPa, speed of 25 revolutions/s (1,500 rpm), slip ratio of 40% and oil temperature of 353 K; and examined for cross-sectional fatigue crack initiation. The results are shown in **Photo 2**. As in the bending fatigue test, the pitting fatigue crack originated in the grain-boundary oxidized layer formed during the carburization heat treatment.

Some specimens were pitting fatigue tested to an appropriate point of time and examined for cross-sectional fatigue crack propagation[7]. The results are shown in **Fig. 6**. The fatigue crack occurred significantly early for the overall fatigue life and propagated at a considerably slow rate until pitting occurred. These results indicate that preventing the formation of the grain-boundary oxidized layer that nucleates the fatigue crack is effective in raising the pitting strength of gears.

It is reasoned by the analogy of bending fatigue strength that developing compressive residual stress by shot peening is effective in improving the pitting strength of gears. The surface roughness created by shot peening, however, has undesirable effects on the overall gear quality. It is therefore important to use a steel free from such shot peening-caused surface roughness.

3.2 Effects of metallurgical factors on pitting strength

The steel factor that has the largest bearing on the pitting strength of gears is the grain-boundary oxidized layer. The pit-

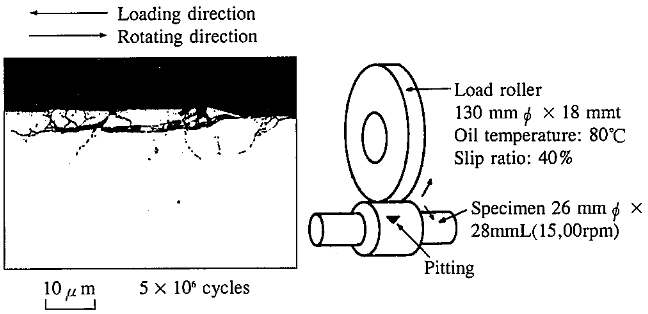

Photo 2 Crack initiation site in pitting

ting strength of gears can be improved by inhibiting the formation of the grain-boundary oxidized layer, as shown in **Fig. 7**. The reason is the proven effect of retarding the fatigue crack initiation.

On the gear fabrication side, factors that have the strongest impact on the fatigue crack initiation and propagation properties of gears are shot peening to induce compressive residual stress and surface cleaning to remove the grain-boundary oxidized layer and alleviate the surface roughness. These factors were investigated for their effects on the pitting strength of gears[8].

Fig. 8 shows the roller pitting test results of gears. As shown, the shot-peened gears and electropolished gears are superior in the fatigue limit compared with the carburized and tempered gears. The fatigue crack propagation in these gears was examined to investigate their fatigue crack initiation and propagation properties. The results are shown in **Fig. 9**. It can be seen from **Fig. 9** that the improvement in the pitting strength of both shot-peened gears and electropolished gears is ascribable to the extension of time until fatigue crack initiation.

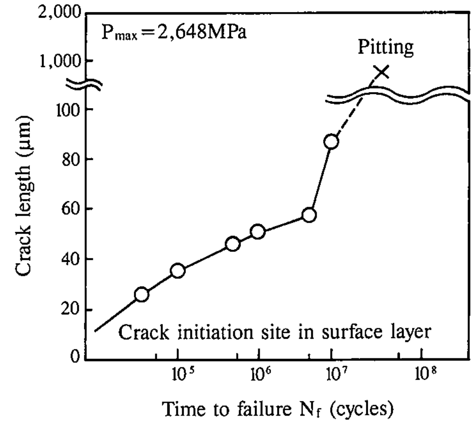

Fig. 6 Relationship between time to failure and crack length (P_{max} = 2,648 MPa)

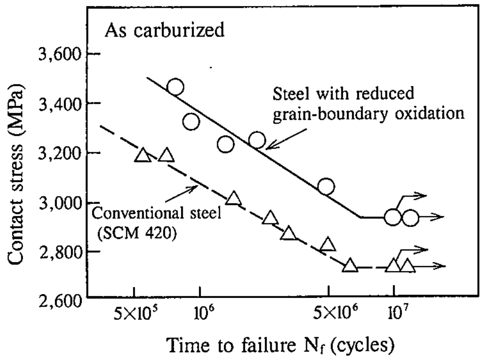

Fig. 7 mprovement in pitting strength by suppressing formation of grain-boundary oxidized layer

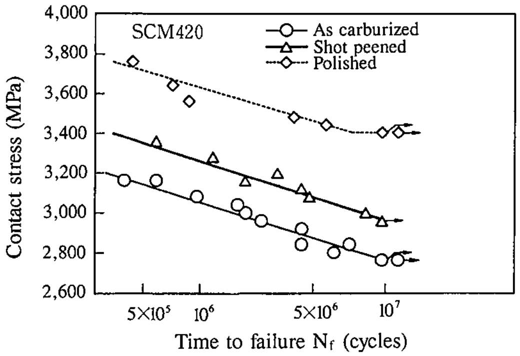

Fig. 8 Relationship between surface treatment and pitting strength

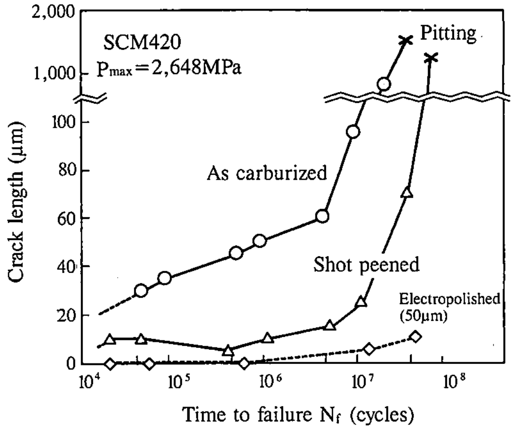

Fig. 9 Effect of surface treatment on crack initiation and propagation behavior

The above results indicate that the pitting strength of gears can be effectively improved by inhibiting the formation of the grain-boundary oxidized layer in the gear steel, shot peening the gear, and cleaning (or electropolishing) the gear surface.

4. High-Strength Gear Steel

Table 1 gives the typical chemical composition of a new high-strength gear steel developed in accordance with the results of the basic study discussed above. The silicon content that encourages the formation of the grain-boundary oxidized layer is reduced, hardenability is supplemented by adding molybdenum and vanadium, and the grain refinement effect is ensured by vanadium. To cope with the anisotropy of gear fatigue properties, calcium is added to modify MnS into (Ca, Mn)S, so that the excessive elongation of MnS is prevented, as shown in **Photo 3**.

Photo 4 compares the grain-boundary oxidation and carburized grain size of the new high-strength gear steel carburized at 930°C for 5 h with those of the conventional JIS SCM 420 gear steel. The new steel scarcely shows the formation of a grain-

Table 1 Typical chemical composition of new high-strength gear steel (wt%)

C	Si	Mn	S	Cr	Mo	V	Ca	O
0.20	Reduced	0.50/0.70	0.015	0.50/0.90	0.75	0.1	Added	Reduced

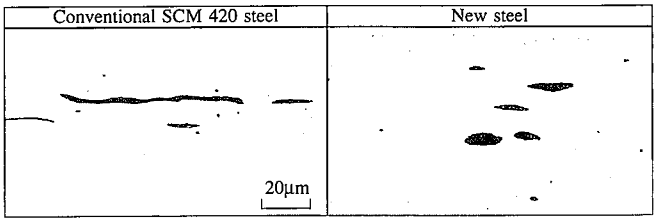

Photo 3 MnS shape control in high-strength gear steel

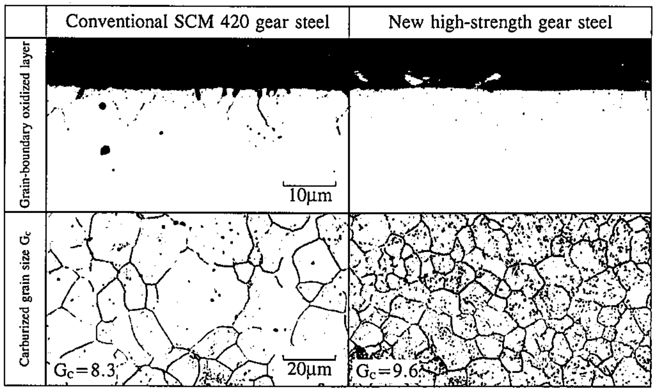

Photo 4 Microstructures of new high-strength gear steel after carburization

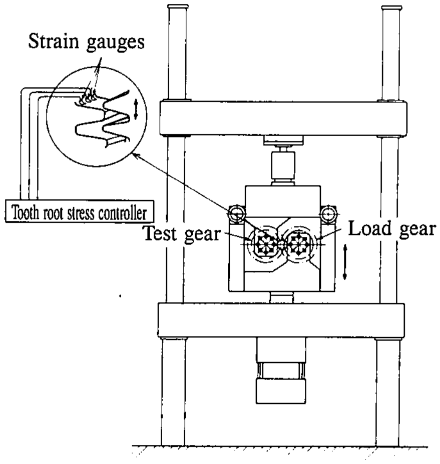

Fig. 10 Gear tooth bending fatigue testing machine

boundary oxidized layer, is thoroughly grain refined, and differs greatly from the conventional gear steel.

After carburization, the new gear steel was hard shot peened by the air nozzle method extensively used in recent years, and was tested by a Nippon Steel-developed tooth bending fatigue testing machine. The machine is schematically illustrated in **Fig. 10**. Conventional tooth bending fatigue testing machines have the problem of large test value variations. The new tester performs tooth bending fatigue tests with extremely small variability by 1) fixing the point of stress application by the meshing of gears and 2) controlling tooth root stress with strain gauges.

The conventional SCM 420 gear steel forms the grain-boundary oxidized layer that prevents the surface layer from being completely quenched and hardened. When hard shot peened as it is, the surface layer is severely roughened, nucleates a fatigue crack, and defeats the purpose of hard shot peening. The new gear steel has the surface layer fully hardened, makes full use of the hard shot peening effect, and reduces the anisotropy of fatigue properties.

As a result, as shorn in **Fig. 11**, much higher tooth bending fatigue strength can be obtained than when the conventional SCM 420 gear steel is normally shot peened.

The new gear steel is resistant also to pitting, the problem that comes next. The roller pitting fatigue test has confirmed that the fatigue life has more than doubled in gears made of the new steel.

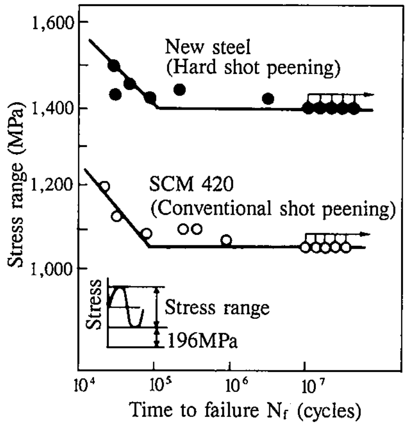

Fig. 11 Gear tooth bending fatigue strength of new high-strength gear steel

5. Conclusions

Reviewed in the foregoing is the development of new high-strength gear steels Nippon Steel has undertaken with the aim of reducing weight and enhancing fuel economy in automobiles.

When developing high-strength gears, it is important to combine designing, manufacturing and fabricating methods in a balanced manner as well as to develop appropriate high-strength gear steels. Advancing performance and improving fuel economy are everlasting challenges for automobile and auto parts manufactures. High-strength steels will assume increasing importance in meeting these challenges.

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