NIPPON STEEL TECHNICAL REPORT No. 122 NOVEMBER 2019

Technical Report

UDC 621 . 824 . 3 : 621 . 532

Development of Steel for Nitrocarburized High-strength Crankshafts that is Quenched and Tempered before Nitrocarburizing

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Abstract

We developed steel for nitrocarburized crankshafts that has high bending fatigue strength and bending ability for straightening. Adjusting the amount of chemical compositions and heat treatment conditions led to an optimum hardness profile and a fine microstructure. The fatigue strength of the developed steel was measured using a rotary bending fatigue test. The fatigue strength of the developed steel was larger than that of a conventional high-strength steel by around 10%. The bending property was measured using a four-point bending test. It showed that the bending property of the developed steel was comparable to that of a conventional high-strength steel. Consistent quality is expected because the hardness of the nitrocarburized layer in the developed steel is constant regardless of the rate of cooling from the nitrocarburizing temperature. It is assumed that robustness against the cooling rate arises by the mechanism of hardening, which was precipitation hardening with Mn and Cr complex nitrides.

1. Introduction

To reduce the fuel consumption and size of engines, the weight and size of engine parts need to be reduced. The crankshaft that converts reciprocating motions of pistons to rotary motions in an engine is the heaviest member in the engine. Downsizing crankshafts greatly contributes to downsizing and weight reduction of entire engines. To downsize crankshafts, raw materials used for crankshafts need to have superior fatigue properties to those before.

Crankshafts are sometimes nitrided to enhance their fatigue strength.[1–3] Nitriding is surface hardening heat treatment where a part is retained in an atmosphere including ammonia so that nitrogen enters the part from the surface to strengthen it. Treatment where carbon enters a part along with nitrogen is called nitrocarburizing. Nitrocarburizing has been used as surface hardening treatment of steel for various types of machine structure including crankshafts.

The processing temperature in nitrocarburizing is lower than those of other types of surface hardening heat treatment (e.g., carburizing/quenching and induction quenching), so deformation of parts as a result of heat treatment is very small. However, crankshafts need to be precisely straight as their structure, and the small deformation induced by nitrocarburizing needs to be straightened. The deformation is usually straightened by bending the crankshafts.[4]

Straightening crankshafts may cause cracks detrimental to the fatigue strength on the outer layers. Therefore, crankshafts that require straightening should have a property that allows them to be bent back without forming detrimental cracks. This property has various names. In this paper, it is referred to as the straightening property.

As the nitrided layer of a crankshaft is made harder to enhance the fatigue strength, the straightening property deteriorates further. Therefore, to enhance the fatigue strength of nitrocarburized crankshafts, it is important to improve both the fatigue strength and straightening property in a well-balanced way.

2. Relationship between Nitrocarburized Structure and Nitriding Properties

Nitrocarburized steel has a characteristic layer structure that mainly consists of iron nitrides with a thickness of a few micrometers to approximately 30 μm formed on the outermost surface. This layer is called a compound layer. A compound layer consists of compounds, as its name indicates, therefore its ductility and tough-

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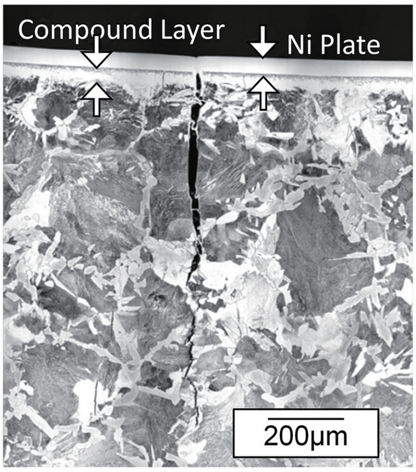

Fig. 1 Image of a crack introduced by bending at the surface of nitrocarburized steel

ness are low and thereby fractures and cracks are easily made by bending.

The area hardened by nitrocarburizing immediately under the compound layer is called a diffusion layer. The microstructure of the diffusion layer is same as that of the matrix before nitrocarburizing. The diffusion layer has been strengthened by dissolved nitrogen and fine nitrides, and its toughness is lower than that of non-nitrided layers. On steel whose diffusion layer was excessively hardened, a crack formed on the compound layer easily propagates to the diffusion layer during straightening. **Figure 1** shows an optical microscope image of the surface layer when a bending stroke in straightening over the limit was applied to nitrocarburized S40C. Such a large crack significantly deteriorates the fatigue properties.

3. Satisfying Both Fatigue Strength and Straightening Property

One means to satisfy both high fatigue strength and straightening property is to set the hardness of the diffusion layer within a proper range by avoiding enhancing it too much. However, it is difficult to significantly enhance the fatigue strength only by adjusting the hardness of the diffusion layer. The authors focused on optimization of the microstructure by pretreatment. **Figure 2** shows the effect of quenching and tempering on the relationship between the fatigue strength and straightening properties that are measured with nitrocarburized S40C and S50C. When looking at the same steel, the figure shows that quenching and tempering improves both fatigue strength and straightening property.

In recent years, to reduce costs and energy consumption, heat treatment is omitted on an increasing number of materials to be subject to nitrocarburizing. In our study, aiming to satisfy both fatigue strength and straightening property at higher levels than before, we worked on the development of materials assuming they would be subjected to quenching and tempering.

4. Design of the Composition of the Developed Steel

As described above, controlling the hardness of the diffusion layers appropriately is an essential requirement to satisfy both fatigue strength and straightening property at high levels. Both alloy contents and microstructure can contribute to the hardness of the diffusion layers. This section describes the design of the chemical composition of the developed steel.

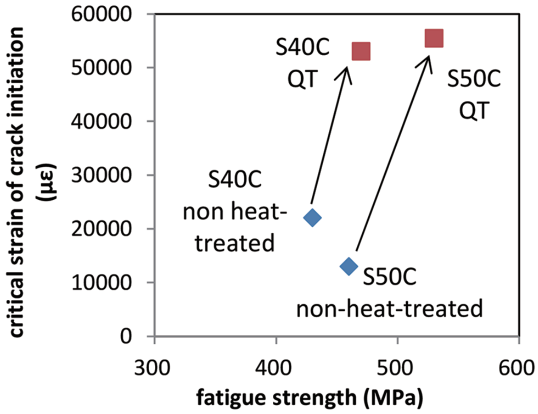

Fig. 2 Effect of quench-and-tempering on fatigue strength and critical strain of crack initiation in the nitrocarburized carbon steel

Table 1 Chemical compositions of the developed steel (mass%)

	C	Si	Mn	Cr
Developed steel	0.40–0.45	0.15–0.35	1.5–2.5	0.3–0.5
S40C (JIS)	0.37–0.43	0.15–0.35	0.6–0.9	≦ 0.20
S50C (JIS)	0.47–0.53	0.15–0.35	0.6–0.9	≦ 0.20

Table 1 lists the chemical composition of the developed steel. For normal-strength nitrocarburized crankshafts, carbon steel based on the chemical composition of S30C to S55C is often used. Meanwhile, the contents of Mn and Cr in the developed steel are higher than those of the carbon steel. These elements form alloying nitrides in the diffusion layers during nitrocarburizing.[2, 5, 6] The higher their contents are, the harder the diffusion layer becomes due to their effects. The contents of those elements have been optimized for the developed steel to balance fatigue strength and straightening property and to reduce variation of quality.

5. Developed Steel's Nitriding Properties

5.1 Developed steel's hardness profile

To compare the nitriding properties between the developed steel and conventional steel, four steels were used to evaluate various properties: the developed steel, conventional normal-strength steel, conventional high-strength steel, and SCr440. Although SCr440 is a steel used for nitride parts subject to higher stress than crankshafts, it was included in the evaluation for comparison. Ingots were made of these steels by vacuum melting and they were hot forged to round bars with a diameter of 60 mm. Specimens for rotary bending fatigue and four-point bending tests shown in **Fig. 3** were made from the round bars. They were nitrocarburized at 570°C for three hours and then quenched in oil. **Figure 4** shows the hardness profiles of the surface layers on the four steels. The hardness of the developed steel's surface layer is slightly higher than that of the conventional high-strength steel and lower than that of the SCr440.

5.2 Developed steel's fatigue properties

An Ono-type rotary bending fatigue test was conducted to evaluate the fatigue properties. The maximum stress when the steel did not rupture even when stress was loaded 10^7 times was regarded as the fatigue strength. **Figure 5** compares the fatigue strength of the four steels. The fatigue strength of each steel was normalized using that of S50C (conventional normal-strength steel). The figure clearly shows that the fatigue strength of the developed steel is higher than

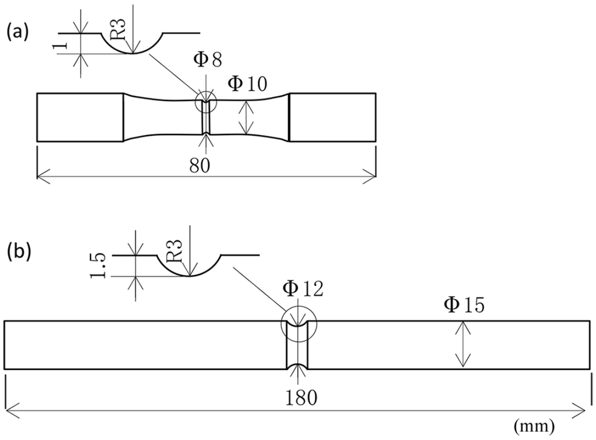

Fig. 3 Shapes of specimens for (a) Rotary bending fatigue test and (b) Four-point bending test

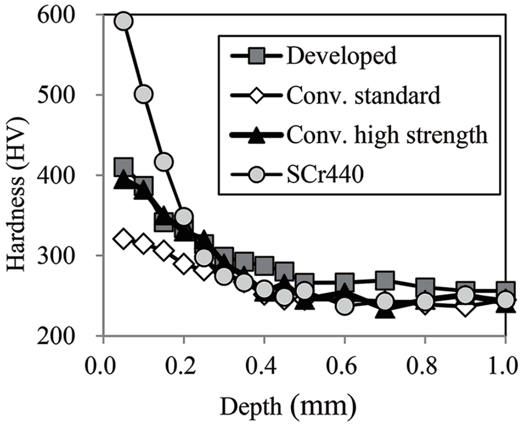

Fig. 4 Hardness profiles of nitrocarburized layers of various steels

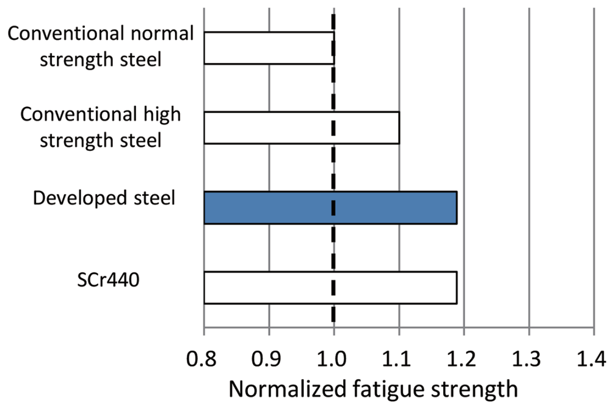

Fig. 5 Normalized fatigue strength of developed steel and conventional steels (Fatigue strength of conventional normal strength steel is taken as 1.0)

that of the conventional normal-strength steel and higher than that of the high-strength steel by approximately 10%. This strength is at the same level as that of the SCr440 with a harder surface layer. These results may arise because, for the SCr440, only the topmost surface has strongly hardened and the hardened depth is shallow, while the developed steel has a deeper hardened layer.

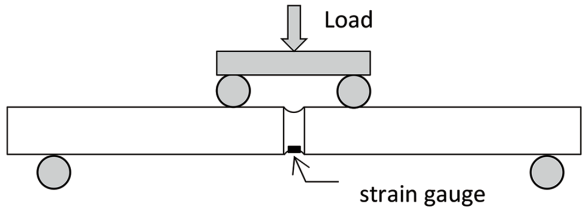

Fig. 6 Schematic of four-point bending test

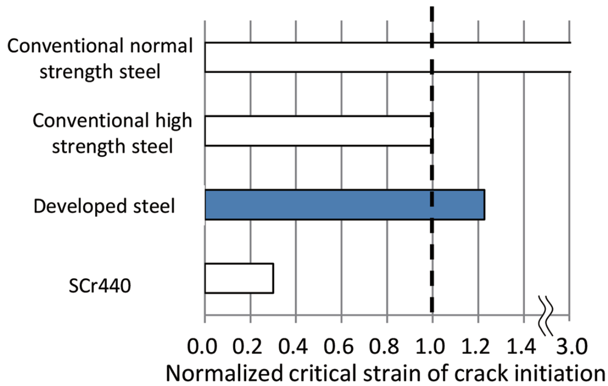

Fig. 7 Normalized critical crack initiating strain of developed steel and conventional steels (Critical strain of conventional high strength steel is taken as 1.0)

5.3 Developed steel's straightening property

The straightening property of the nitrocarburized specimens was evaluated in a four-point bending test. A strain gauge was attached to each specimen's section to which stress concentrated and that was bent at four points. The strain immediately before a crack formed was regarded as strain causing a crack (hereinafter critical crack initiation strain) and evaluated. **Figure 6** outlines the four-point bending test.

Figure 7 compares the critical crack initiation strain obtained in the four-point bending test between the developed steel and the conventional steel. The critical crack initiation strain of each steel was normalized by being divided by the critical crack initiation strain of the conventional high-strength steel. The critical crack initiation strain of the developed steel is smaller than that of the normal-strength steel, but larger than that of the high-strength steel. The strain of developed steel is equal to or higher than that of the high-strength steel that has been used for mass production. Therefore, the straightening property of the developed steel is at a practical level. Meanwhile, the critical crack initiation strain of the SCr440, whose fatigue strength is very similar to that of the developed steel, is very small. Such a material cannot be used for crankshafts that require straightening.

6. Developed Steel's Microstructure

To satisfy both fatigue strength and straightening property at high levels, the microstructure of the developed steel was made by optimizing the steel components and quenching conditions. **Figure 8** shows the microstructure of the surface layers of the developed steel and conventional normal-strength steel. Usually, even when large parts like crankshafts are quenched with water or oil, the cooling rate is slow. Therefore, when normal carbon steel crankshafts are quenched, the microstructure mainly consists of pearlite.[7] The

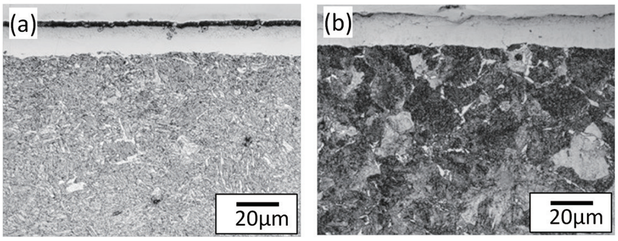

Fig. 8 Images of the cross sections of the nitrocarburized layers in (a) Developed steel and (b) S50C

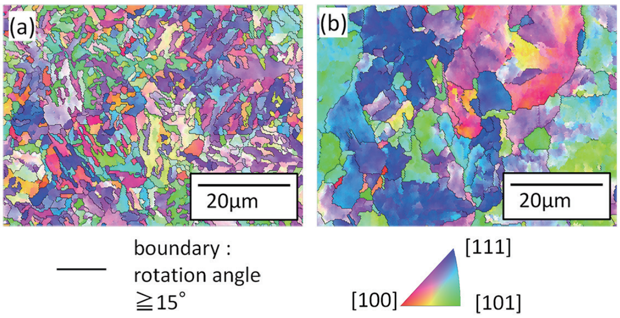

Fig. 9 Inverse pole figures of ferrite phase of (a) Developed steel, and (b) S50C analyzed with EBSD

contents of Mn and Cr, which are elements improving hardenability, were increased for the developed steel. It involves the microstructure of the surface layer becoming a mixture of martensite and bainite.

The microstructure of martensite and bainite has units of size such as lath scale and block scale. Their shapes are anisotropic, having concepts of width and length. There are various theories about which unit among these controls the mechanical properties.[8–10] We regarded regions enclosed with boundaries whose difference in crystal orientation was 15° or more as a factor that controls mechanical properties[11] and compared the microstructure of the developed steel and S50C after quenching and tempering.

Figure 9 shows the analysis results of crystal orientations in the ferrite phases of the developed steel and S50C by the electron backscattered diffraction (EBSD) pattern method. The solid lines in the figure are boundaries whose difference in orientation is 15° or more. Regions enclosed by such boundaries were virtually regarded as crystal grains and the grain diameter was calculated. It was found that the diameter is 16.4 μm for the S50C, while it is 3.7 μm for the developed steel, being smaller by approximately one-fifth. The reason that the developed steel satisfies both fatigue strength and straightening property at high levels may be because of such microstructure.

7. Mechanism for Strengthening in the Developed Steel's Nitrided Layers

When steel is nitrided, various interactions occur between the intruded nitrogen and the matrix and these interactions harden the steel. This hardening is caused by multiple mechanisms.[12, 13]

In carbon steel that does not contain many alloying elements, most nitrogen exists in a dissolved state in the diffusion layer during nitrocarburizing. When steel in this state is quenched to room temperature, nitrogen becomes supersaturated. The supersaturated nitrogen has large solid-solution-strengthening ability. If the cooling rate

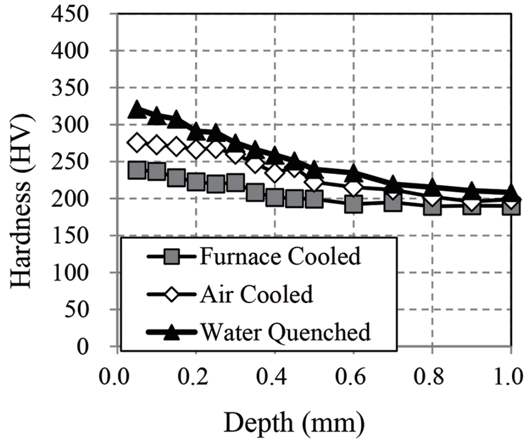

Fig. 10 Effect of the cooling rate at the cooling following re-heating on the hardness profiles of nitrocarburized S40C

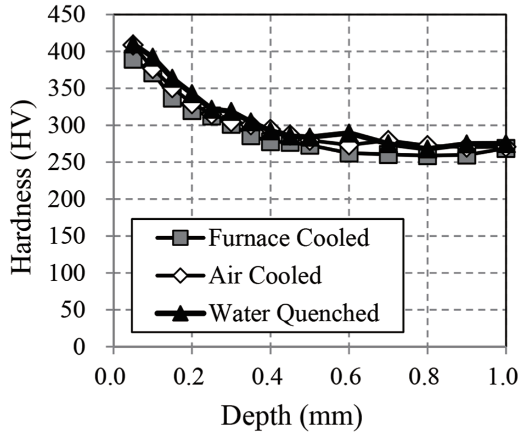

Fig. 11 Effect of the cooling rate at the cooling following re-heating on the hardness profiles of the nitrocarburized developed steel

during quenching is not sufficient, part of the dissolved nitrogen precipitates as iron nitrides during quenching. Iron nitrides precipitating at high temperatures tend to be coarser, and they significantly decrease the hardness.[14]

For large parts like crankshafts, the cooling rate after nitrocarburizing is not fast enough. In addition, for a part in a complicated shape, the cooling rate may vary section by section. Therefore, when carbon steel that does not contain many alloying elements is nitrocarburized, the diffusion layer's hardness may vary between sections for a large part in a complicated shape. To evaluate the degree of variation in nitriding properties while varying the cooling rate, the effect of the cooling rate on the hardness profiles of nitrocarburized steel was investigated using the developed steel and S40C.

Specimens nitrocarburized at 580°C were heated to 580°C again. Then, they were cooled to room temperature by water quenching, air cooling, or furnace cooling. **Figure 10** shows the hardness profiles of cross sections of the S40C cooled using the three methods. **Figure 11** shows those of the developed steel. For the S40C, the hardness profiles significantly change according to the cooling method. On the other hand, the developed steel's hardness profiles are almost constant, showing that the property is stable.

The reason that the developed steel's hardness profiles are not affected by the cooling rate may be because the main factors that have strengthened the developed steel's diffusion layers are nitrides of Mn and Cr and thereby the dissolved nitrogen does not greatly contribute. Therefore, to examine whether alloying nitrides precipitated, the developed steel's diffusion layer was observed using transmission electron microscopy (TEM).

Figure 12 shows a dark-field TEM image at a location 75 μm deep from the surface. When Mn alone is combined with nitrogen, the nitrides are η-Mn_3N_2 [3, 15, 16] and when Cr alone is combined with nitrogen, the nitrides are CrN.[6] These nitrides have a B1 crystal structure and their orientation relationship with the matrix is similar. Some researchers have reported that, when different alloying elements that can form nitrides having a B1 or similar crystal structure in steel are added to steel at the same time, those alloying elements can form complex nitrides.[17–19] In addition, when focusing on the size distribution of the precipitates, the length of the precipitates in the field is approximately 20 nm for all of them and thereby it does not seem that multiple types of precipitates coexist. From these facts, the precipitates observed in the diffusion layer may be complex nitrides of Mn and Cr.

The shape and size of alloying nitrides do not change during cooling after nitrocarburizing, and the diffusion layer of the developed steel was strengthened by these nitrides. Therefore, the hardness of the layer is constant regardless of the cooling rate after nitrocarburizing.

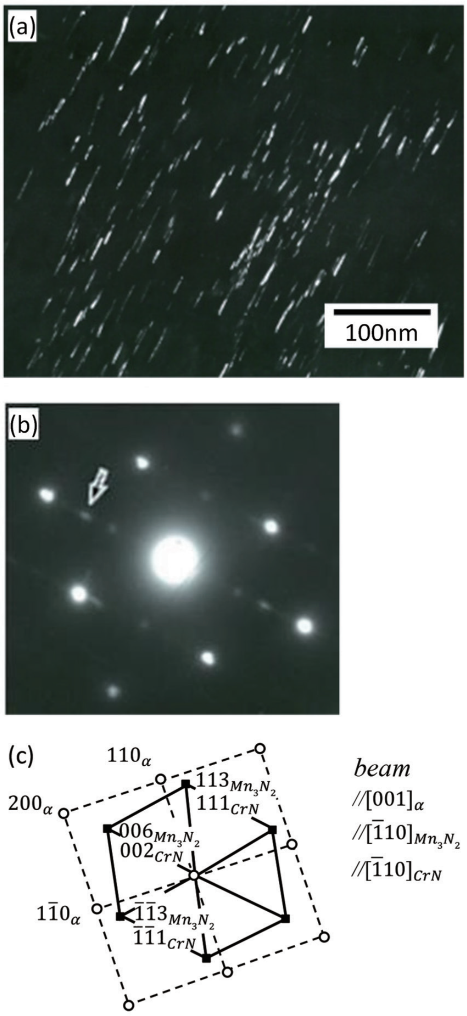

Fig. 12 TEM image taken at a depth of 75 μm below the surface of the diffusion layer in the developed steel
(a) Dark field image, (b) Selected area diffraction pattern, and (c) Corresponding key diagram to (b).

8. Conclusions

For nitrocarburized crankshafts that are to be straightened after nitrocarburizing, improving the fatigue strength was difficult because improving the fatigue strength causes decrease of the straightening property. The steel for nitrocarburized crankshafts introduced in this paper satisfies both the fatigue strength and straightening property at high levels by optimizing the alloy contents and pretreatment.

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