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Development of High-strength Nitriding Steel for Gear

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Abstract

Transmission gears require high fatigue strength and low heat-treatment distortion for high performance. We focused on the gas-nitriding process that was conducted at a transformation temperature lower than that of martensite and suppressed distortion and developed high-strength steel designated for nitrided gears. High surface hardness and deep case depth was achieved by optimizing the content of Cr and V in low carbon steel. The results of rotary bending and the roller pitting fatigue tests showed the fatigue strength of developed steel was equal to or higher than that of conventional carburized steel. Observation by transmission electron microscopy showed fine carbonitrides including both Cr and V precipitated at the nitride layer of developed steel. This suggests that fine precipitates contribute to optimal hardness distribution and excellent fatigue properties.

1. Introduction

Higher fuel efficiency and less CO_2 emission have become increasingly required of road vehicles recently in consideration of conservation of the global environment. Accordingly, the size and weight of transmission gears that compose the automotive power train have been significantly reduced through various measures.[1–4] Carburizing and quenching,[5] widely employed to strengthen gears, incurs large distortion during the treatment because the process involves structural phase transformation, and the gear surfaces have to be ground after the treatment to reduce gear noise, which incurs additional costs. For this reason, both high fatigue strength and low distortion must be realized at low cost. To this end, we focused on nitriding,[6–8] which is conducted at a comparatively low temperature and causes less distortion, and successfully developed a new high-strength nitriding steel for gears.

The present paper explains the design philosophy of the chemical composition of the developed steel, and explains the studies on its hardening mechanism, heat treatment distortion and fatigue properties.

2. Development Target

Automotive transmission gears are mostly made of carburized and quenched alloy steel for machine structural use in appreciation of high resistance to fatigue and wear and good machinability. The steel is cut into gears before hardening heat treatment, and then through carburizing and quenching processes, the gears are hardened by having carbon penetrate into the material from the surface and diffuse to inside. During the treatment, however, the steel is heated to the austenitic temperature or higher, incurring the problem of large distortion throughout the process. With the ring gears for planetary systems, especially, it is difficult to obtain the required dimensional accuracy by the carburizing and quenching process because of their large diameter and thin thickness. Moreover, because of the internal teeth, their re-machining after the treatment is problematic. Therefore, to reduce the heat treatment distortion, there have been many attempts to develop new steels for nitriding,[9–14] a surface hardening process at a lower temperature. It was difficult with nitriding steel, however, to obtain a fatigue strength equal to or higher than that of carburized and quenched steel and a material hardness adequate for gear machining at the same time.

In the present development, we aimed at obtaining high-strength nitriding steel for gears[15] having a hardness adequate for the machining before the treatment and the fatigue strength equivalent to that of carburized and quenched steel after it. At the same time, regarding the distortion due to nitriding, we focused on the volume expansion of the nitrided layer as a likely cause, and studied the influences of alloy elements over steel expansion.

3. Improvement of Steel Strength

In the present development study, the steel chemistry of JIS

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SCr420H, a popular alloy steel for machine structural use, was modified to obtain good machinability for gear cutting before nitriding as well as high fatigue strength after the treatment. **Table 1** shows the chemical compositions of related steels; here JIS S35C, a popular carbon steel for machine structural use, is referred to as a comparative steel.

First, regarding nitriding properties, we considered the addition of Cr and V, which form nitrides in the surface layer during nitriding to increase surface hardness. Next, to improve nitriding properties and lower the material hardness before the treatment, we aimed at lowering carbon content to increase the percentage fraction of ferrite. In addition, the contents of other alloy elements were set such that a ferrite-pearlite structure not containing bainite would be obtained for good machinability.

4. Tests

The developed steel and S35C were prepared using a converter, continuously cast into blooms, rolled into billets and then into bars. The bars were then machined into test pieces, and subjected to a turning test before nitriding. Then, they underwent gas nitriding at 600°C for 2 h, and their properties were examined. The sectional hardness distribution after nitriding was measured using a micro-Vickers hardness tester. The microstructure of the surface layer was observed through an optical microscope, and precipitations in the layer were observed through a scanning electron microscope (SEM) and a transmission electron microscope (TEM).

Distribution of nitrogen concentration was measured using turning chips cut out from the surface layer. Because the distortion (volume expansion) due to nitriding is very small, it was measured by the method given in **Fig. 1**, that is, depression marks were pressed at equal intervals of 200 μm using a micro-Vickers hardness tester on one surface of the test pieces of square bars, each $10\times10\times20$ mm in size, the change of the intervals before and after the nitriding was measured through the SEM, and the expansion was evaluated using the value of (1) below as the indicator. Note that, when the press marks were unclear after the treatment, the surface was lightly polished by buffing before the measurement.

$$[\{d(1)+d(2)+...+d(16)\}-16\times200]/16 \qquad (1)$$

Fatigue strength was evaluated by the Ono-type rotating bending fatigue test and roller pitting test using test pieces after nitriding. The former test was conducted at room temperature at a rotation of 3 000 rpm using V-notched test pieces with a stress concentration ratio of $\alpha=2.0$, and the fatigue strength was the maximum stress that the test piece could withstand for 10^7 cycles of bending. The latter test was conducted at a rotation of 1 500 rpm using an automatic lubricant oil with a slipping ratio of −40% at 90°C, and the fatigue strength was the maximum stress that the test piece could withstand for 2×10^7 cycles of pitting.

Table 1 Chemical compositions (mass%)

Material	C	Si	Mn	Cr	V
Developed high-strength steel	0.10	0.15	0.55	1.25	0.17
JIS SCr420H	0.20	0.20	0.80	1.00	–
JIS S35C (conventional steel)	0.35	0.20	0.75	–	–

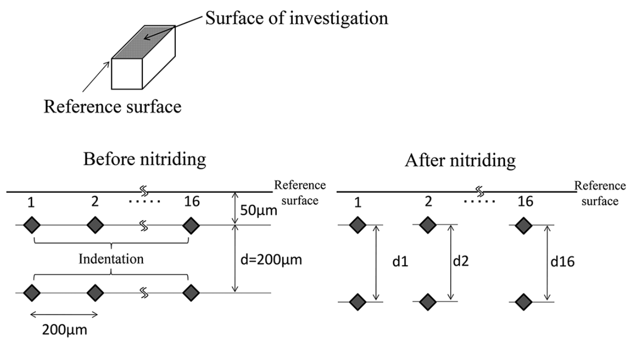


Fig. 1 Method of measuring distortion

5. Test Results

5.1 Machinability

Machinability was evaluated by a turning test. The specimens of substantially the same hardness were used: the developed steel HRB 86, and S35C HRB 85. As seen in **Fig. 2**, the turning force was nearly the same with both steels. The turning chips are shown in **Fig. 3**; the chips of both specimens were divided into short pieces, evidencing good machinability of the two steels.

5.2 Nitriding properties

Figure 4 compares the two steels in terms of sectional hardness distribution after nitriding. The developed steel, which contains Cr and V, had far higher hardness at the surface layer than that of S35C. Considering that the surface hardness of common carburized steel is mostly in the range of HV 700 to 800, the developed steel has the same surface layer hardness as that of carburized steel.

Figure 5 shows the measured nitrogen concentration distribution in the surface layer after nitriding. The points represent the analysis results of the turning chips taken at intervals of 50 μm from the surface. The nitrogen concentration in the surface layer of the developed steel was more than twice that of the comparative steel, S35C. This is presumably because the developed steel contains Cr and V, which have an affinity for N.

Figure 6 shows the microstructures in the surface layer of both the specimens after nitriding. While the structure of the two specimens was ferrite+pearlite, the developed steel, which contains less carbon, had a higher percentage fraction of ferrite than that of S35C. Note that both the specimens had a layer of compounds, roughly 5 μm in thickness, at the outermost layer.

(Turning condition)
Tool : Sumitomo Electric Industries DNMG150412-GU(AC520U)
Lubricant : Soluble
Speed : 250m/min, Feed : 0.4mm/rev, Depth of cut : 1.5mm

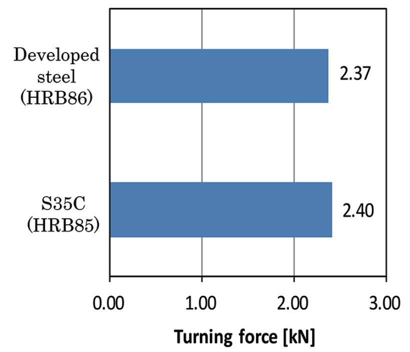


Fig. 2 Turning force

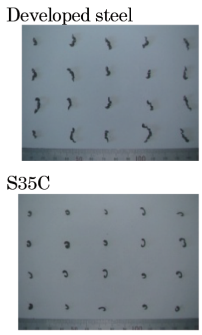


Fig. 3 Photos of chips

Figure 7 shows the microstructures of the specimens at 50 μm from the surface after nitriding observed through the SEM. Whereas there were many acicular crystals of iron nitride (marked with arrows) in the ferrite of the S35C specimen, few similar types were found in the developed steel.

Figure 8 shows TEM photomicrographs of the specimens at 50 μm from the surface after nitriding; fine precipitates were seen to have formed in the nitrided layers of the two steels. Considering their distribution, stretched grains, some tens of nanometers in length, were sparsely observed in S35C, and in the developed steel in contrast, finer grains, several nanometers in size, were seen more densely. The difference in the precipitate distribution corresponded well to that of the surface hardness, which indicates that the higher hardness of the nitrided layer of the developed steel than that of S35C is due to the difference in the distribution of the fine precipitates. From the selected-area diffraction pattern of a precipitate of the developed steel given in **Fig. 9**, it proved to be a FCC crystal in the Baker-Nutting orientation relationship with the parent phase. Either Cr or V is capable of forming FCC carbo-nitrides, but judging from the fact that all the precipitates in the developed steel are of the same shape and size, they are presumed to be complex carbo-nitrides of Cr and V, or (Cr, V) (C, N).

Next, **Fig. 10** shows the change in the hardness of surface layers after nitriding of specimens prepared based on the developed steel and changing the contents of the alloying elements (C, Mn, Cr and V) individually. Decreasing C and increasing Cr and V are especially effective at increasing the surface layer hardness.

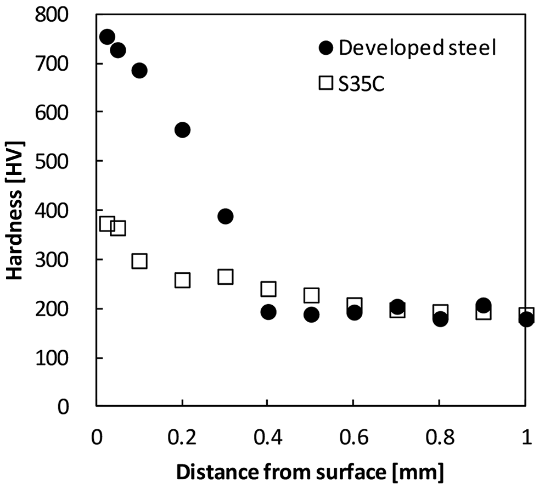


Fig. 4 Hardness profiles of nitrided layers of developed steel and S35C

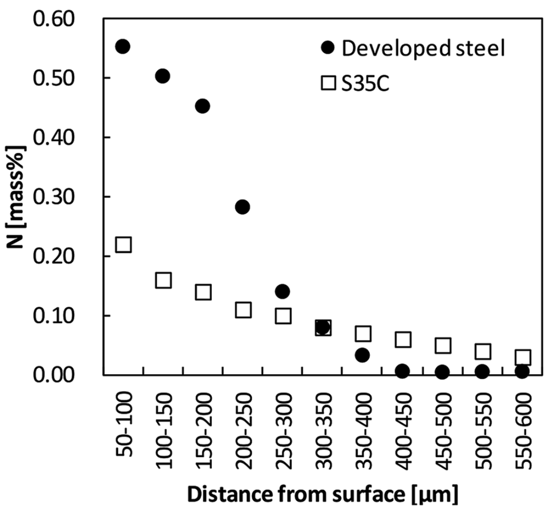
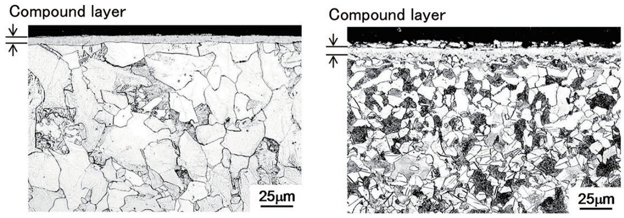
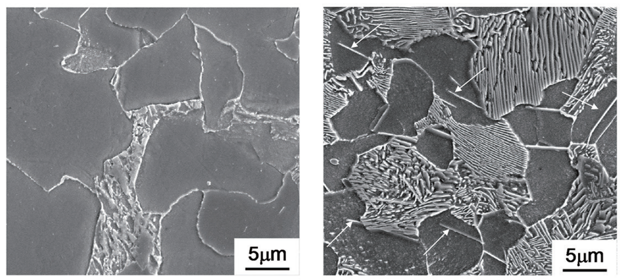


Fig. 5 Nitrogen concentration profiles at the nitrided layers of developed steel and S35C



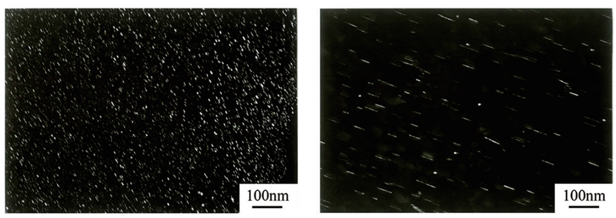
(a)Developed steel (b)S35C

Fig. 6 Microstructures of nitride layers near surface after nitriding (nital etching)



(a)Developed steel (b)S35C

Fig. 7 SEM images of nitride layers near the surface (nital etching)



(a)Developed steel (b)S35C

Fig. 8 TEM dark field images of precipitates taken at a depth of 50μm below the surface

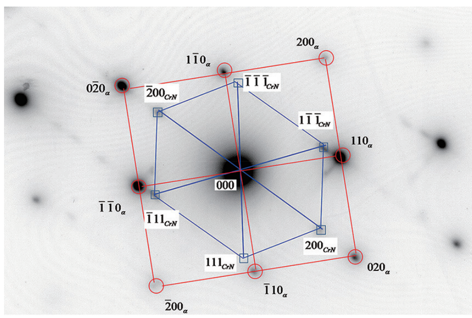


Fig. 9 Selected area diffraction pattern taken in nitrided developed steel and corresponding key diagram

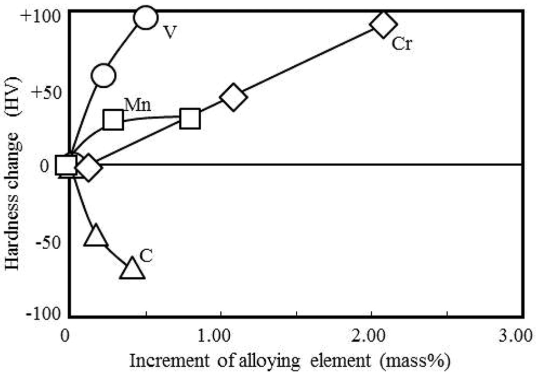


Fig. 10 Influence of alloying elements on surface hardness after nitriding

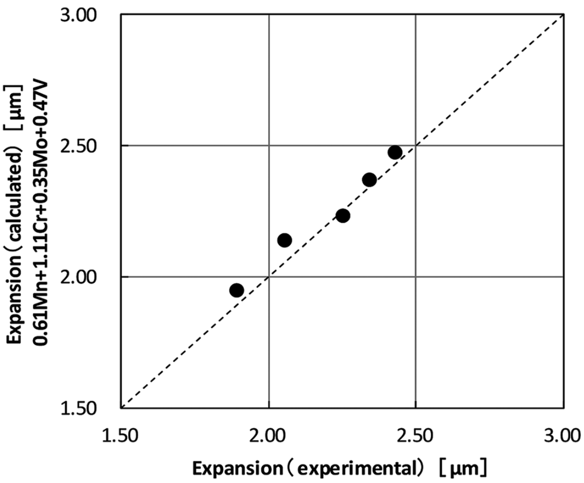


Fig. 11 Expansion due to nitriding

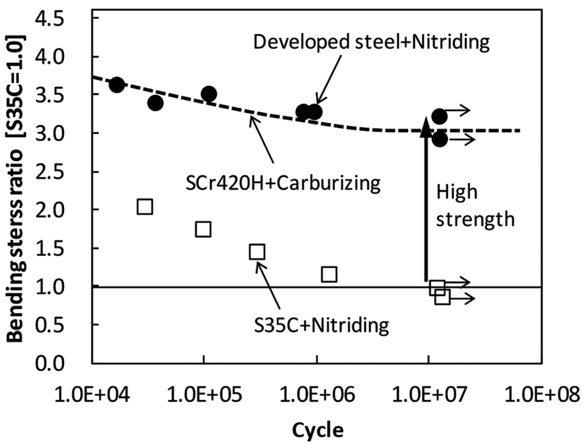


Fig. 12 Results of Ono-type bending fatigue test

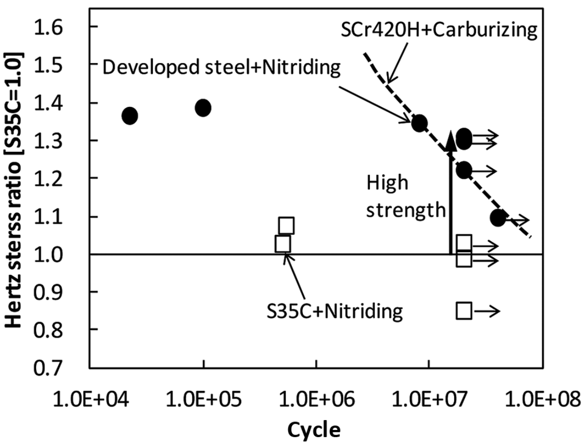


Fig. 13 Results of roller pitting fatigue test

5.3 Deformation due to nitriding treatment

Figure 11 shows the evaluation result of the distortion (volume expansion) due to gas nitriding of the steels prepared by changing the contents of the alloying elements (Mn, Cr, Mo and V) individually from those of the developed steel. Using multiple regression analysis, the volume expansion could be expressed as given in (2) below; the calculated figures agreed well with the measurements.

$$0.61\,Mn + 1.11\,Cr + 0.35\,Mo + 0.47\,V \qquad (2)$$

Here, Mn, Cr, Mo and V represent the contents of the respective elements. From the above, it is clarified that each of their contents has positive effects over the expansion, and the more a steel contains these elements, the more it expands through nitriding.

All the above results indicate that the developed steel has an original hardness suitable for gear machining and excellent nitriding properties when designed to contain appropriate amounts of Cr and V on the basis of low-C steel. In addition, minimizing the expansion due to gas nitriding has been enabled by making the value of (2) as small as possible within the content ranges of the alloy elements to satisfy the required properties.

5.4 Fatigue strength

Using nitrided specimens of the developed steel and S35C, an Ono-type rotating bending fatigue test simulating the fatigue at gear tooth roots and roller pitting test simulating that at tooth faces were conducted.

Figure 12 shows the result of the former test. Here, the points are in ratios to the fatigue strength of gas nitrided S35C after 10^7 cycles of bending, given as 1.0. The developed steel proved to have a bending fatigue strength 3.2 times larger than that of S35C, and substantially equal to that of gas carburized JIS SCr420H, as indicated by the dotted curve.

Figure 13 shows the result of the latter test. Here, as in Fig. 12, the points are in ratios to the fatigue strength of gas nitrided S35C after 2×10^7 cycles of bending, defined as 1.0. The developed steel had an anti-pitting strength higher than that of S35C by 28%, and substantially equal to that of SCr420H after gas carburizing, shown by the dotted curve.

6. Conclusion

A new low-distortion, high-strength nitriding steel for gears having significantly higher strength than conventional steels was developed. The development studies revealed the following findings:

(1) To improve the surface hardness after nitriding, it is effective to add appropriate amounts of Cr and V to low-C steel.
(2) Fine precipitates of the carbo-nitrides of the alloying elements, (Cr, V) (C, N), which form in quantities in the surface layer of the developed steel during nitriding, serve to increase surface hardness.
(3) The volume expansion due to nitriding, which can be expressed as a function of the contents of Mn, Cr, Mo and V, can

be minimized by decreasing the contents of these elements within the content ranges to satisfy the properties required for the steel.

(4) The developed steel has a bending fatigue strength 3.2 times that of S35C, and an anti-pitting strength higher than that of S35C by 28%. These figures are substantially the same as those of gas carburized SCr420H.

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