

Development of Non-normalized Nitrocarburized High Strength Crankshaft

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ABSTRACT

A non heat-treated nitrocarburized crankshaft was developed by designing the material composition so as to maximize the effectiveness of the strength increase due to nitrocarburization. This crankshaft has a fatigue strength that is approximately 16% higher than that of a conventional crankshaft of the same material hardness, while possessing the same workability and straightening ability. Strengthening ferrite by adding a relatively small quantity of molybdenum (Mo) gave the developed material both high fatigue strength and excellent straightenability. The mechanism of strengthening by the addition of Mo is thought not to be the secondary hardening due to the precipitation of molybdenum carbonitride, but the formation of a Mo cluster consisting of several atoms during the nitrocarburizing process. This results in a greater strengthening effect compared to solid solution strengthening, thus contributing to higher yield strength. It was found that compared to the conventional high strength crankshaft, the elimination of the normalization process and so on reduced CO₂ emission during and after the hot forging process by approximately 22%, and costs by approximately 8%.

1. Introduction

There are diverse demands on modern automotive engines. In addition to environmental performances such as high fuel efficiency and low exhaust emissions, demands for more weight reduction, more power, and lower costs also exist. To respond to these demands, it is necessary to increase the strength, reduce the cost, and reduce the production energy of the crankshaft that is one of the structural components of the engine. Carbon steel is the base material used for the majority of crankshafts that are manufactured by hot forging. The characteristics of the component are enhanced by additional processing and heat treatment such as secondary heat treatment, surface rolling, induction hardening and nitrocarburization^{(1) - (5)}. When a material is strengthened by nitrocarburization, steels with relatively high carbon contents (0.45 mass% or more) are used, and quenching and tempering or normalizing are often used to increase the strength of the base material. The nitriding elements such as aluminum (Al), chromium (Cr), vanadium (V), which promote the formation of nitrides, are added to

increase the strength around the surface of the product after nitrocarburization⁽⁶⁾. However, these methods all involve increases in production energy, CO₂ emissions, and costs due to the secondary processing. In addition, the high hardness of the materials reduces machinability, and the high hardness of the surface layers following nitrocarburization reduces straightenability.

The research discussed in this paper attempted to develop a nitrocarburized crankshaft that would display no reduction in machinability or straightenability while strengthened without any requirement for heat treatment.

2. Development Goals

Honda engines have used two different types of crankshafts, produced from the normal-strength and high-strength materials. Both types of material are nitrocarburized to enhance their mechanical properties. While the high-carbon steel is used in the high-strength crankshafts with normalization after hot forging to increase its strength higher than that of the normal-strength material, the normal-strength material does not

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undergo normalization. Since the normal-strength material is based on lowering the hardness of the raw material and that of the surface layers after nitrocarburization compare to high-strength material, it displays better machinability and straightenability. The production cost of normal-strength crankshafts is therefore lower than that of high-strength crankshafts. The goal of this research was to develop a crankshaft material that would display an equivalent level of strength to the current high-strength material while maintaining production costs equivalent to those of the current normal-strength material, and a material which would satisfy the following criteria was studied.

- (1) To be produced without normalization (Equivalent to the current normal-strength material process)
- (2) To have high fatigue strength (Equivalent to the current high-strength material)
- (3) To have low raw material hardness (Equivalent to the current normal-strength material)

3. Concept of Material Alloy Design

3.1. Basic Composition Setting

As shown in Fig. 1 (a), when the conventional high-strength material is not normalized, its structure becomes coarse with a low ferrite area ratio, and straightenability declines. It is therefore necessary to increase the ferrite area ratio and the nucleation sites of the proeutectoid ferrite so that the material does not need to be normalized. For this matter, the same method used for the normal-strength material, which is not normalized either, should be used⁽⁷⁾. This involves refining the structure by increasing the ferrite area ratio through optimization of the amount of carbon (C) and manganese (Mn), and by means of promoting the nucleation of proeutectoid ferrite through the addition of nitrogen (N). And as shown in Fig. 2, reducing the amount of C content and increasing the amount of Mn is effective in enhancing the fatigue strength and straightenability of this type of non-normalized nitrocarburized steel. Straightenability was evaluated by the value of bending strain when cracking occurred (crack strain)⁽⁸⁾. If a material displays a high degree of plastic deformation, i.e., if the level of bending that can be straightened is high, the material is said to

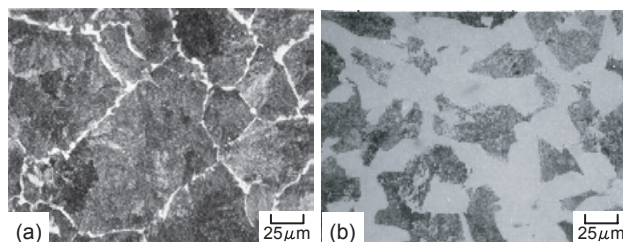


Fig. 1 Optical micrographs of as-forged state:
(a) Conventional high-strength steel
(b) Developed steel

possess a high degree of straightenability.

Crankshafts should also possess wear resistance at the points of contact with the oil seals, and the characteristics depend on the amount of C content as shown in Fig. 3.

Based on these considerations, the amount of C and Mn in the steel was adjusted according to the relationship shown in Fig. 4 as no less than 0.35 mass% for C and the ferrite ratio equivalent to that of the normal-strength

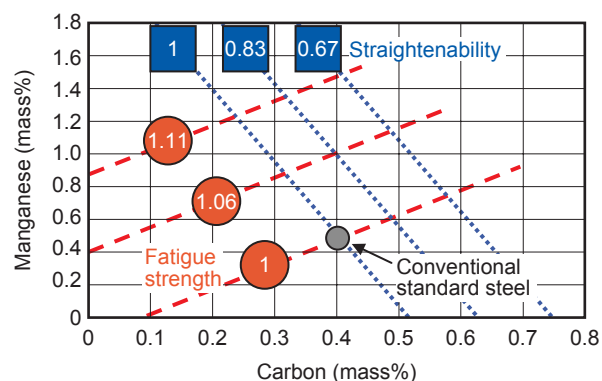


Fig. 2 Correlation diagram between content of alloying additions and properties of nitrocarburized specimen

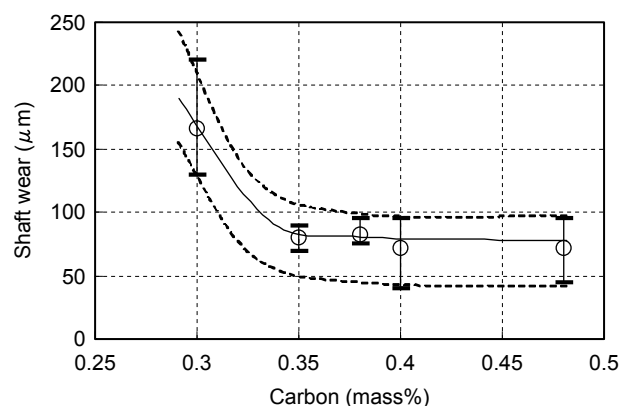


Fig. 3 Relationship between carbon content in steel and wear loss at oil seal section of crankshaft

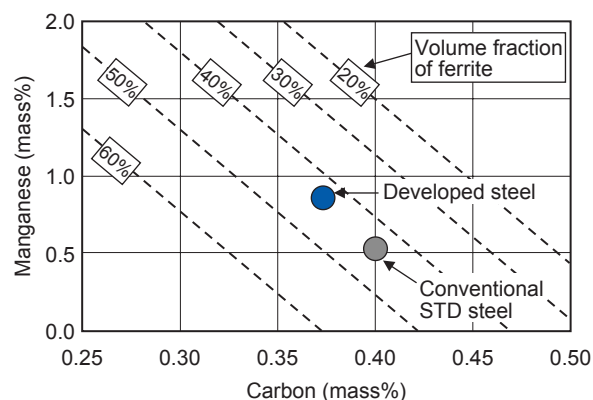


Fig. 4 Relationship between content of alloying additions and volume fraction of ferrite

material. This resulted in the achievement of a fine structure with a high ferrite area ratio after hot forging as shown in Fig. 1 (b).

3.2. Achievement of High-strength by Addition of Molybdenum (Mo)

Though a high ferrite area ratio was achieved, the achievement of the target fatigue strength would require strengthening of the ferrite structure and hardening of the surface layer after nitrocarburization. However, if the surface layers become excessively hard, ductility declines. The method used to strengthen the material, i.e., the selection of the additive elements, is therefore an important issue. Si, Ni, Mo, V, and Al are considered to be appropriate ferrite-strengthening agents in common structural steels^{(9), (10)}. However, Si and Ni make almost no contribution to increased strength after nitriding⁽¹¹⁾, and they are not expected to increase fatigue strength. On the other hand, Al, Cr, and V form hard nitrogen compounds,

hardening the surface layer^{(12), (13)}, and result in a significant decline in straightenability. For these reasons, none of these elements should be used.

Molybdenum (Mo), however, is effective in solid solution strengthening of ferrite and it also hardens the surface appropriately after nitriding. Test pieces were fabricated for the planar bending fatigue tests as shown in Fig. 5 to study the effect of Mo on fatigue strength. As Fig. 6 shows, even a small amount of the addition of Mo results in increased fatigue strength. According to this result, the amount of Mo to be added to increase strength was determined to 0.16 mass%. The next section will discuss the mechanism for the achievement of high strength by means of the addition of Mo.

4. Strengthening Mechanism by Addition of Mo

4.1. Increase in Yield Ratio during Nitrocarburization

Nitrocarburization is thought to have an effect on the mechanism of strength increase by the addition of Mo. The changes in mechanical properties after a thermal history corresponding to the nitrocarburization process (600 °C x 2h) were examined. To provide a comparison, tensile tests of test pieces that did not contain Mo were also conducted. Figure 7 shows the preparation procedure of the test pieces. Table 1 shows the chemical composition of the materials used for the tests, and Table 2 shows the test results. The material that did not contain Mo displayed no change in yield ratio (yield point/tensile strength) before and after the heat treatment, while the material containing Mo displayed an increase of approximately 6% in yield ratio. In general, the higher the

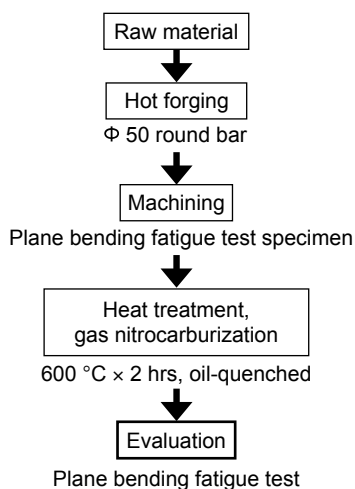


Fig. 5 Method of specimen preparation and property evaluation

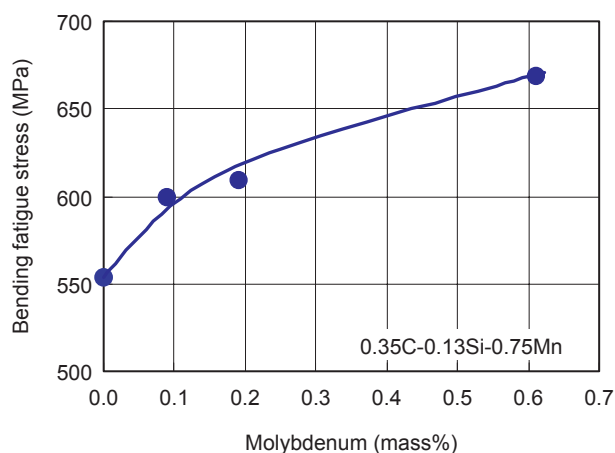


Fig. 6 Effect of Mo on plane bending fatigue strength in developed steel

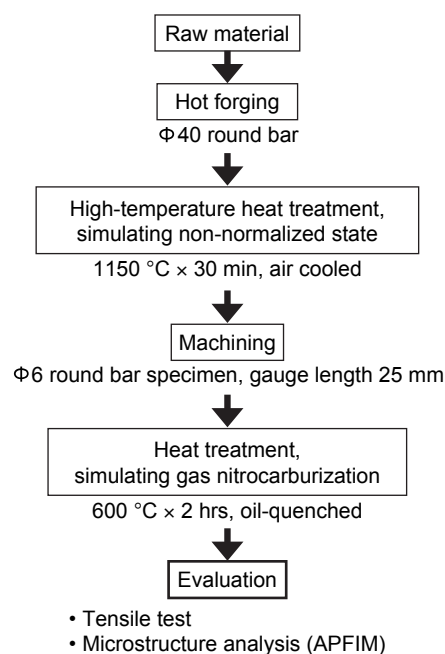


Fig. 7 Method of specimen preparation and property evaluation

Table 1 Chemical composition of Mo-added and Mo-free steel, in mass %

	C	Si	Mn	P	Cu	Ni	Cr	Mo	Ti	N
Mo-added steel	0.35	0.21	0.76	0.016	0.01	0.02	0.08	0.16	0.008	0.0180
Mo-free steel	0.41	0.19	0.58	0.014	0.01	0.02	0.06	0.01	0.009	0.0190

Table 2 Variation of mechanical properties of Mo-added and Mo-free steel, before and after heat treatment at 600°C for 2 hours

Material	Before 600 °C × 2h				After 600 °C × 2h			
	Tensile strength	Yield point	Elongation	Yield ratio (YP/TS)	Tensile strength	Yield point	Elongation	Yield ratio (YP/TS)
Mo-added steel	668 MPa	387 MPa	23.2%	0.579	658 MPa	402 MPa	23.2%	0.611
Mo-free steel	676 MPa	352 MPa	22.4%	0.521	653 MPa	340 MPa	22.8%	0.521

yield ratio of a material, the higher its fatigue strength⁽¹⁴⁾. This result therefore indicates that the fatigue strength of steel containing Mo increases merely by the temperature rise during the nitrocarburization treatment.

4.2. State Analysis of Mo

In order to clarify the strengthening mechanism by addition of Mo including the reason for the increase in the yield ratio from the perspective of the microstructure of the material, an atom probe field ion microscope (APFIM)⁽¹⁵⁾ was used to analyze the distribution of Mo at the atomistic level.

4.2.1. APFIM

The APFIM is a combination of a field ion microscope (FIM) and a time-of-flight mass spectrometer. By using the FIM, the arrangement of atoms on the surface of a material test piece can be observed as a collection of luminescent spots respectively corresponding to each atom. Figure 8 shows a schematic diagram of the APFIM, and the principle is as follows.

- (1) A strong electrical field, several V/Å, is generated at the tip of a needle-shaped test piece when high voltage is applied.

- (2) Atoms are successively stripped off the surface of the test piece, and are emitted into a vacuum as positive ions (field evaporation).
- (3) The mass of the ions, i.e., their atomic type, is identified by their time-of-flight to a detector and the applied voltage.

Ions reaching the detector are sorted out via a tiny hole called the “probe hole.” As a result, atoms are sampled from within a cylinder of a height (depth) of approximately 100 nm, the area of the bottom equivalent to the area of projection of the probe hole onto the surface of the test piece (diameter: approximately 2 nm). This volume is indicated by the dotted line in the figure. Two types of information regarding the individual atoms are obtained: the atomic type and the order in which the atom was detected (corresponding to its position in the direction of the depth). This enables the APFIM to detect fine precipitates at the early stage of precipitation and clusters of solute atoms, which are difficult to be detected with a transmission electron microscope (TEM)^{(16), (17)}. The APFIM analysis is usually conducted in an ultra-high vacuum. When extremely small amounts of neon or helium is introduced into the vacuum chamber, these inert gas atoms become ionized on the surface of the test piece

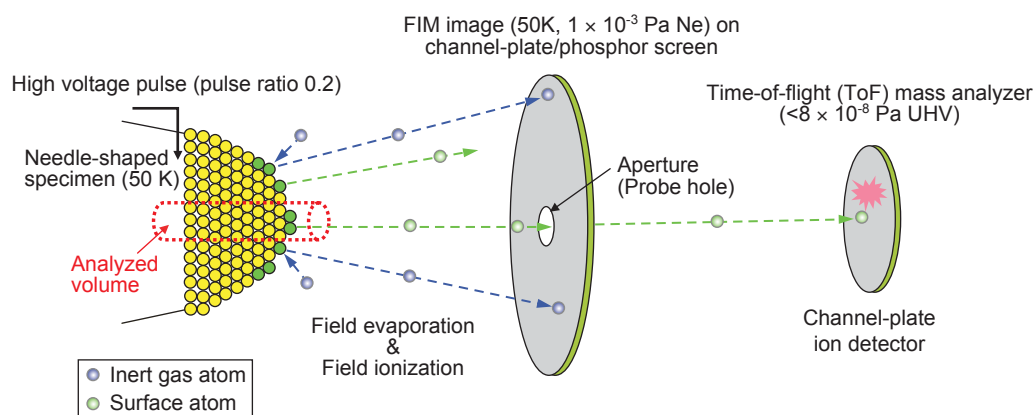


Fig. 8 Schematic diagram showing principles of atom-probe field ion microscopy (APFIM) and analyzing condition of present study

and produce light when they strike a facing fluorescent screen, and the atomic arrangement on the surface of the test piece can be observed as a collection of luminescent spots. These are called FIM images. As this ability to image individual atoms, the FIM provides several millions magnifications as a microscope.

4.2.2. Results of APFIM analysis

Figure 9 shows a FIM image of steel containing Mo that has been heated for 2 hours at 600 °C. The number of brighter spots that display a higher degree of luminescence than neighboring are looks increasing after heat treatment (marked by circles in the images). These spots are thought to be Mo clusters.

If atoms of alloying element with a higher evaporation

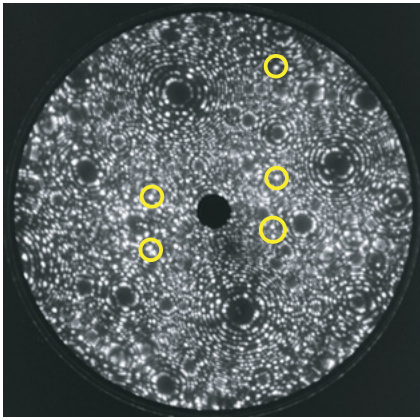
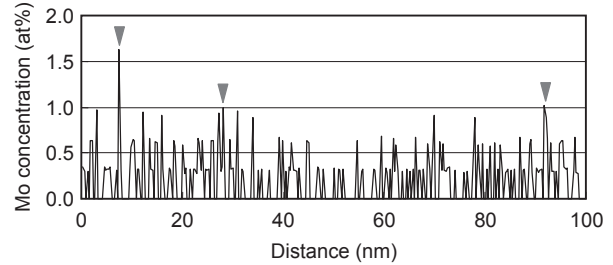
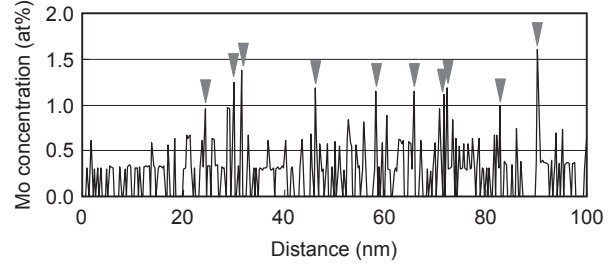


Fig. 9 FIM image of developed steel containing 0.2mass% Mo, after aged at 600 °C for 2 hours

field than the matrix aggregate and form precipitates in the material undergoing the FIM observation, the atoms in the surrounding matrix will evaporate preferentially first when the electrical field is applied. Precipitates therefore tend to remain on the surface. Due to the edge effect of these precipitates, atoms of the noble gases are more frequently field-ionized at the precipitates. Accordingly, these sections appear brighter than the surroundings. This also happens to the clusters of alloy elements that are much smaller than ordinary precipitates.



(a) As-forged (non heat-treated) specimen



(b) Aged specimen (aged at 600 °C for 2 hours)

Fig. 10 Concentration profiles of developed steel containing 0.2mass% Mo

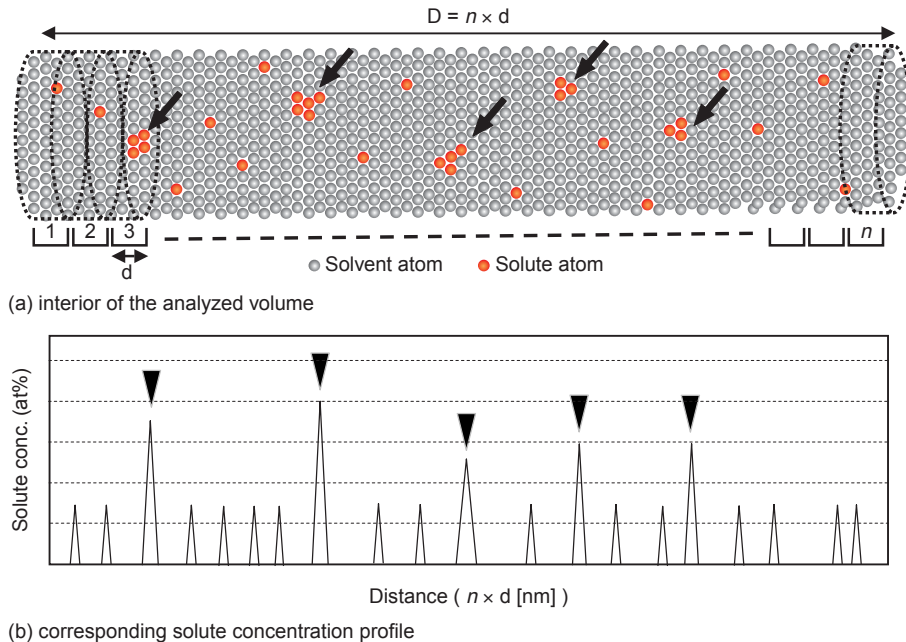


Fig. 11 Schematic diagram

Table 3 Chemical composition of developed and conventional steel, in mass %

	C	Si	Mn	P	S	Cr	Mo	N	Ti	Pb
Developed high-strength steel	0.37	0.20	0.82	0.015	0.07	-	0.16	0.015	0.01	-
Conventional standard steel	0.40	0.25	0.52	0.015	0.05	-	-	0.015	0.01	-
Conventional high-strength steel	0.48	0.30	1.42	0.015	0.05	-	-	-	-	-

To provide further verification of the existence of these Mo clusters, the APFIM was used to conduct a detailed examination of the distribution of Mo atoms. The results are shown in Fig. 10. The detected ions were sequentially divided into blocks of a depth of approximately 3Å, basically corresponding to the lattice constant of iron, and the concentration of Mo in each block was determined. The Mo concentration profile resulting from this procedure is shown in Fig. 10. Each block contains approximately 300 ions.

Figure 11 is a schematic for interpreting the data shown in Fig. 10. When the analyzed volume where atoms are counted (the area indicated by the dotted line in Fig. 8) is enlarged, it should be as shown in Fig. 11 (a). The arrows in the figure are supposed to indicate the presence of clusters of solute atoms. By dividing this column into discs (unit blocks) of the appropriate thickness, d , the concentration of solute atoms in the disc can be calculated from the number of solvent and solute atoms. Plotting the concentration values sequentially in the direction of depth gives the solute atom concentration profile as shown in Fig. 11(b). If clusters of solute atoms exist in the unit blocks, the concentration of solute will be higher than in the case of random or homogeneous solid solution. The existence of these clusters is demonstrated by spikes in the concentration profile as shown by the ▼ mark in the figure.

Comparison of the as-forged material and the material subjected to heat treatment (600 °C x 2h) after hot forging demonstrates three to four times the frequency of aggregates, which are thought to be Mo clusters, in the heat-treated material. The Mo concentration in the case of uniform solid solution was approximately 0.1 at%. Concentrations of 1.0 at% and higher were regarded as representing Mo clusters. These results indicate that the formation of Mo clusters is promoted by exposure to a thermal history corresponding to the thermal conditions of nitrocarburization. In addition to the Mo clusters that form at 600 °C for 2 hours, the diffusion layers close to the surface of the material that underwent nitrocarburization are also thought to contain Mo and N clusters as a result of the absorption of N into the Mo clusters. However, because the APFIM cannot distinguish between bivalent Si^{2+} ions and monovalent N^+ ions, which both possess a mass-valence ratio of 14, this was not verified in the developed steel, which contains approximately 0.2% Si.

Next, a test piece taken from the nitrogen diffusion

layer (approximately 50 μm below the surface) of the steel containing Mo that had undergone nitrocarburization was subjected to TEM analysis. Mo nitrides were not observed in this analysis. As Fig. 12 shows, the only nitrides observed in the analysis were rod-shaped γ' - Fe_4N and particulate α'' - Fe_{16}N_2 , both iron nitride precipitates. In addition, as Fig. 13 shows, the concentration of N in the diffusion layer of this Mo cluster-forming steel following nitrocarburization is higher than that of the normal-strength steel, which does not contain Mo.

4.3. Considerations Regarding Strengthening Mechanism

The results described above led to the following

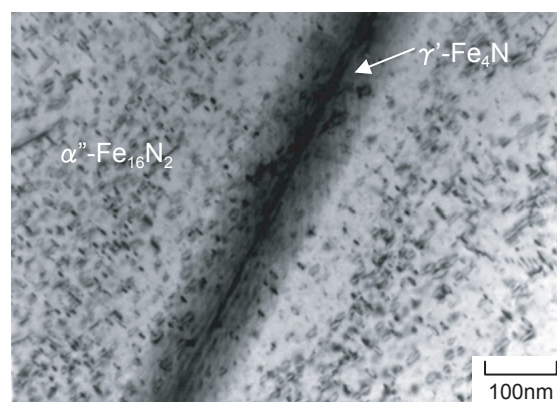


Fig. 12 Transmission electron micrograph taken from diffusion layer of developed steel containing 0.2mass% Mo, after nitrocarburization

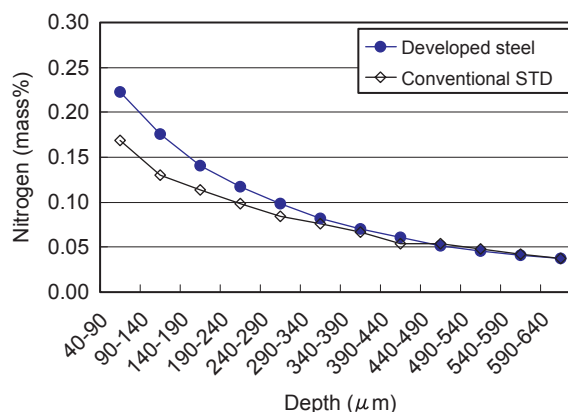


Fig. 13 Nitrogen content of steel after nitrocarburization

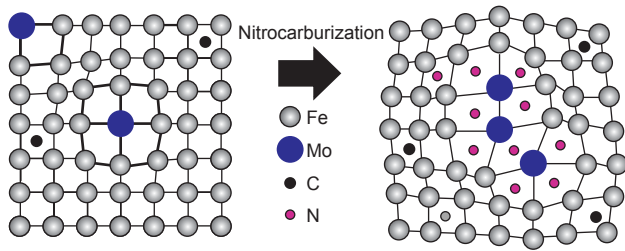


Fig. 14 Schematic illustration of Mo clustering process during nitrocarburization in developed steel

considerations regarding the mechanism that generates increased fatigue strength after nitrocarburization in steel containing 0.16 mass% Mo. As Fig. 14 shows, as the temperature during nitrocarburization rises, the Mo in solid solution in the ferrite forms clusters of several atoms, generating a higher level of lattice strain than single Mo atoms. During nitrocarburization, a higher amount of N than usual infiltrates the spaces between these distorted lattices and become trapped. These areas of high strain prevent dislocation motion, thus increasing yield stress and resulting in increased fatigue strength.

5. Crankshaft Characteristics

On the basis of the results discussed above, the chemical composition of the developed material was established as shown in Table 3. Table 3 also shows the composition of the current standard- and high-strength crankshaft materials. L4 crankshafts for 2.4L engines were manufactured using the developed materials and its performances were tested.

5.1. Mechanical Properties of Crankshaft

As shown in Fig. 15, the internal hardness of the newly developed crankshaft is lower than that of the current high-strength crankshaft, equivalent to that of the normal-strength crankshaft. However, the hardness around the surface layers after nitrocarburization is equivalent to

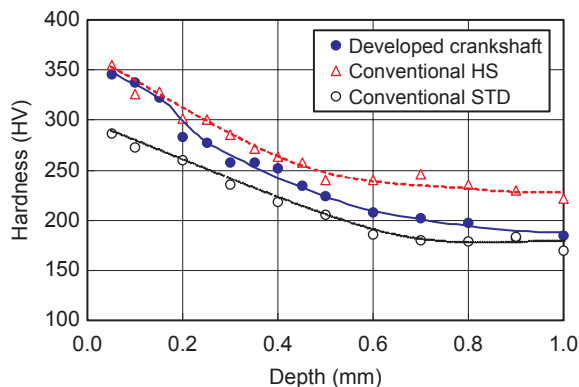


Fig. 15 Hardness distribution of crankshafts

Table 4 Bending fatigue strength and strain for cracking of crankshafts
(Conventional standard crankshaft = 100)

	Bending fatigue strength	Strain for cracking
Developed HS	116	90
Conventional STD	100	100
Conventional HS	113	73

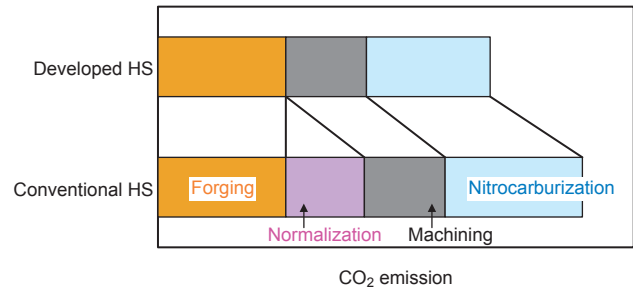


Fig. 16 Comparison of the total CO₂ emission and its constituents during production between developed and conventional high-strength crankshafts

that of the current high-strength crankshaft. As Table 4 shows, the bending fatigue strength of the developed crankshaft is equivalent to or higher than that of the current high-strength crankshaft, and 16% higher than that of the current normal-strength crankshaft. The crack strain of the new crankshaft is higher than that of the current high-strength crankshaft, but compares favorably with that in the current normal-strength crankshaft.

5.2. Merit by Application of Developed Material

As Fig. 16 shows, use of the new material has reduced CO₂ emissions in the procedures after hot forging by a maximum of approximately 22%, and has reduced costs by approximately 8%, compared to the current high-strength material.

6. Conclusion

A non-normalized high-strength crankshaft material was developed. The followings are the salient points of this development project:

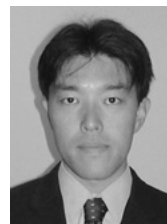
- (1) Addition of 0.16% mass% Mo to a crankshaft material increases fatigue strength by approximately 16% after nitrocarburization at 600 °C for 2 hours.
- (2) The yield ratio of steel containing Mo increases when the steel is only subjected to a thermal history corresponding to that of nitrocarburization (600 °C x 2h).
- (3) APFIM analysis showed that the formation of Mo clusters was promoted in the steel containing Mo that was subjected to a thermal history corresponding to that of nitrocarburization.

- (4) The N concentration in the diffusion layers of steel containing Mo after nitrocarburization was higher than that in steel that did not contain Mo.
- (5) The mechanism of the increase in fatigue strength after nitrocarburization in steel containing Mo is thought to be the high level of strain produced in the lattices due to the formation of Mo clusters and the consequent increase in the concentration of N.

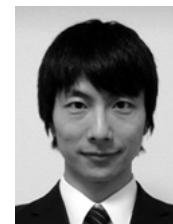
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