

Development of Nitrocarburized High-strength Crankshaft with No Rare Metals Added

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ABSTRACT

Conventional nitrocarburized high-strength crankshafts secure high fatigue strength through a strengthening mechanism using the rare metal molybdenum (Mo). In contrast, a crankshaft with high fatigue strength equal to that of the conventional material was developed without the addition of rare metals by using copper (Cu) and chromium (Cr) and optimizing the material design.

Cr increases the hardness near the surface layers during nitrocarburization, which effectively increases the strength. However, in this case cracking easily occurs when plastic deformation is applied to straighten crankshaft bending that occurs in the nitrocarburization process, which has made it a challenge to actively use Cr. The developed material combines hardening by Cr with ferrite solid solution strengthening by Cu, and enhances straightenability by suppressing the Cr content required for strengthening. This simultaneously achieved both high fatigue strength and good straightenability without the addition of rare metals.

1. Introduction

Recently the conflicting characteristics of higher output power and environmental performance are being simultaneously demanded of automobile engines. In particular, growing environmental needs are increasing demands for enhanced fuel economy. As a result, crankshafts, which are engine components, are tending to become lighter in weight and shaft diameters are also decreasing in order to reduce the sliding resistance between the crankshaft and the bearings. This reduces stiffness, which increases the load on the crankshaft, so high fatigue strength is required. Crankshafts are generally formed by hot forging or casting, and hardening processes such as induction hardening, surface rolling, or nitrocarburization are used and residual compressive stress is applied to increase the fatigue strength⁽¹⁾⁻⁽⁵⁾.

Various methods have been used to increase the hardness of nitrocarburized high-strength crankshafts. For example, the nitriding elements aluminum (Al) and chromium (Cr) were added to steel with a relatively high carbon content of 0.45 mass% or more on the assumption that normalization is performed. Currently, the rare metal molybdenum (Mo) is added to steel with a relatively low carbon content of 0.35 mass% in order to secure high fatigue strength and

straightenability without normalization, and also to enhance machinability by suppressing the material hardness⁽⁶⁾. Adding Mo enables the achievement of high fatigue strength and good straightenability even for non-normalized steel with a relatively low carbon content. However, rare metals easily become objects of speculation so prices are unstable, and expanding demand in developing countries is predicted to further destabilize supply⁽⁷⁾. Therefore, this development investigated a means of omitting Mo in the electric furnace manufacturing method.

2. Development Goals

The crankshafts used in Honda automotive gasoline engines are formed by forging, machined, and then nitrocarburized to enhance the fatigue strength characteristics. A crankshaft that satisfies the following characteristics was investigated with the target of realizing a high-strength material.

- (1) No need to add rare metals
- (2) High fatigue strength (equal to that of the conventional high-strength material)
- (3) Good straightenability (equal to that of the conventional high-strength material)

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3. Component Design

3.1. Approach toward Component Design

Bending fatigue strength for nitrocarburized crankshafts that assume straightening is secured by increasing the hardness near the surface layers (hereafter “surface hardness”) during nitrocarburization. However, increasing the surface hardness reduces the straightenability, so it is important to create a component design that simultaneously realizes both bending fatigue strength and straightenability. The conventional high-strength material uses the rare metal Mo to increase the surface hardness to an appropriate level during nitrocarburization, and generation of Mo clusters also strengthens the ferrite. This simultaneously achieves both high fatigue strength and good straightenability. In addition to Mo, surface hardness can also be increased during nitrocarburization by adding elements such as Cr, vanadium (V) or Al. However, while these elements effectively increase strength, they also lower straightenability, which makes active use a challenge for crankshafts that assume straightening⁽⁶⁾. As an example of an element that increases surface hardness, Table 1 shows an actual case with 0.15 mass% Cr added instead of Mo to steel with a carbon content of 0.36 mass%, which is equal to that of conventional high-strength materials. This shows that while fatigue strength equal to that of the conventional high-strength material can be achieved, the straightenability drops. Straightenability here was evaluated by applying bending deformation to a test piece and measuring the strain value (cracking limit strain) at which cracking occurred⁽⁸⁾. This shows that high fatigue strength and good straightenability equal to those of the conventional material cannot be simultaneously achieved simply by adding Cr and performing nitrocarburization to increase the hardness. In order to use the strengthening effects of Cr, V and Al to omit Mo, it is thought that some means must be found to strengthen the ferrite, which is the other effect of Mo, and to suppress the required content of these elements. Therefore, the elimination of Mo and substitution of other elements with ferrite strengthening functions was investigated as a means of addressing these issues in the developed material.

3.2. Ferrite Area Fraction Setting

Ferrite strengthening was investigated by setting the ferrite area fraction of the metallic structure of a crankshaft made of ferrite and pearlite, and then investigating strengthening methods. The ferrite area fraction is greatly influenced by the C and manganese (Mn) contents, so first the quantities of these two elements were set. Reducing the C content is said to be an effective means of enhancing straightenability without lowering the bending fatigue strength⁽⁶⁾. This is thought to mean that straightenability can be enhanced by increasing the ferrite area fraction, even at the same hardness. Figure 1 shows the results of investigating the straightenability of steel with the C and Mn contents adjusted so that surface hardness is

Table 1 Bending fatigue strength and cracking limit strain of Cr added steel after nitrocarburization (Conventional steel = 100)

	Bending fatigue strength	Cracking limit strain
Cr added steel	106	51

approximately the same after nitrocarburization and the ferrite area fractions are adjusted to 63.2%, 41.5% and 11.1%, respectively. These results confirmed that even at approximately the same surface hardness, increasing the ferrite area fraction increases the cracking limit strain value and enhances straightenability. This means that setting a high ferrite area fraction is an effective means of obtaining good straightenability. However, crankshafts also need wear resistance against the oil seal, and reducing the C and Mn contents more than is necessary to increase the ferrite area fraction lowers the hardness, so wear resistance becomes an issue. Figure 2 shows the results of investigating the relationship between the internal hardness and wear resistance of crankshafts with different internal hardness manufactured by adjusting the C and Mn contents. The internal hardness needed to secure the same

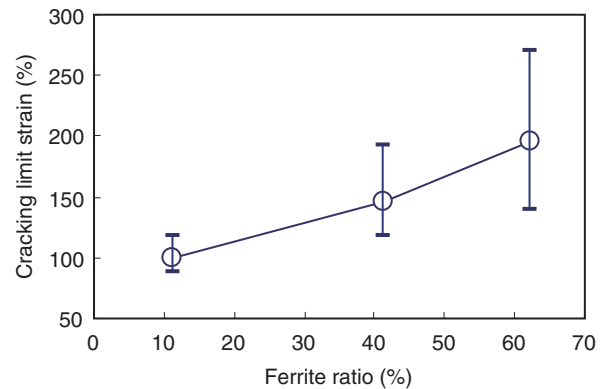


Fig. 1 Relationship between ferrite ratio and cracking limit strain (Ferrite ratio 11.1% data = 100)

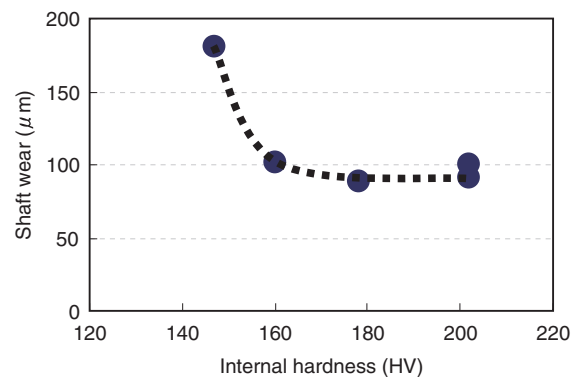


Fig. 2 Relationship between internal hardness and wear loss at oil seal section of crankshaft

wear resistance as the conventional crankshaft is HV 160 or more. Figure 3 shows the relationship between the C and Mn contents and the ferrite area fraction when the C and Mn contents are adjusted to change the ferrite area fraction. The aim is to reduce the C and Mn contents and secure the highest ferrite area fraction possible, but when the ferrite area fraction exceeds 70%, the hardness falls below the required hardness of HV 160. In consideration of these results, the ferrite area fraction was set between 50% and 70%, and 0.30 mass% of C and 0.80 mass% of Mn were used as the typical values for the developed material.

3.3. Ferrite Solid Solution Strengthening

As a substitute for the ferrite strengthening effects of Mo, the use of ferrite solid solution strengthening by other elements was investigated. The aim was to suppress the required content of Cr and the like and enhance straightenability. The cluster generation effects of Mo strengthen the ferrite evenly from the surface to the interior. Therefore, the substitute elements should also strengthen the ferrite evenly from the surface to the interior, without affecting the change in hardness before and after nitrocarburization, by generating nitrides and other compounds during nitrocarburization that increase the surface hardness and suppressing the hardened layer depth. Various elements known as typical ferrite solid solution strengthening elements were added to steel having the base composition shown in Table 2, and nitrocarburization was performed. Figure 4 plots the difference in the hardness at a depth of 50 μm of the base composition steel and the steel with each element added. The amount of increase in hardness at a depth of 50 μm did not depend on the added Cu and nickel (Ni) contents and was relatively constant, which indicates that these elements are unaffected by nitrocarburization and can be used to strengthen ferrite⁽⁹⁾. Compared to Ni, Cu is an element that can be easily used by adjusting the scrap materials used as raw materials. Therefore, since it is thought that the same effects can be obtained from either Cu or Ni, the use of Cu was investigated.

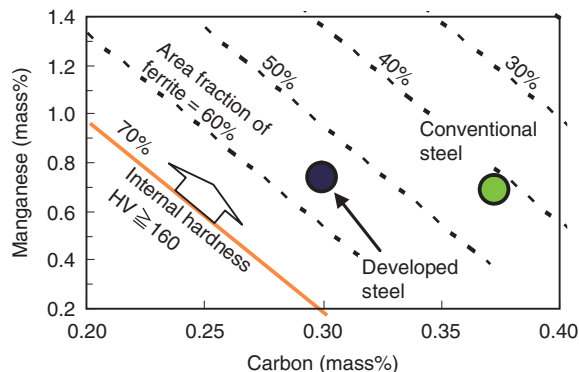


Fig. 3 Relationship between added alloying element contents and area fraction of ferrite

Table 2 Chemical composition of original test steel

	C	Si	Mn	Cu	Ni	Cr
Original test steel	0.36	0.07	0.65	0.10	0.10	0.15

Figure 5 shows the relationship between surface hardness and bending fatigue strength when the surface hardness is varied by adjusting the C, Mn, Cr and other alloying element contents, assuming a ferrite area fraction between 50% and 70%. A hardness of HV 300 is required to secure bending fatigue strength equal to that of the conventional material. Figure 6 compares the

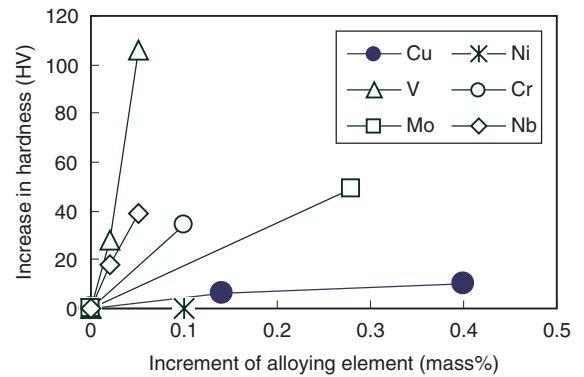


Fig. 4 Influence of alloying elements on surface hardness after nitrocarburization

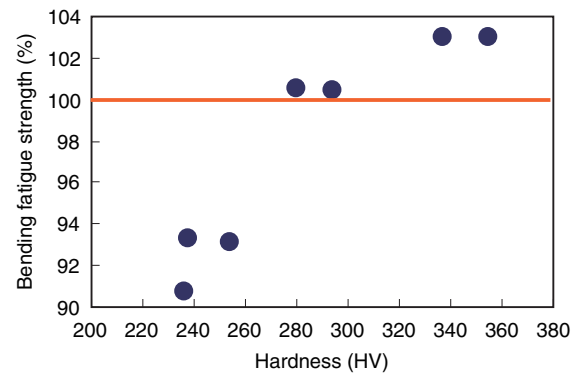


Fig. 5 Relationship between hardness and bending fatigue strength (Conventional steel = 100)

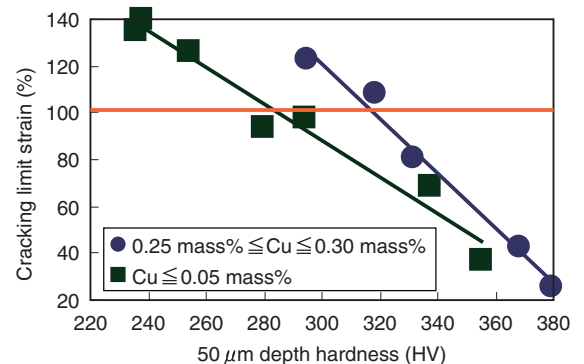


Fig. 6 Relationship between 50 μm depth hardness and cracking limit strain

straightenability for a Cu content of 0.05 mass% or less and a Cu content between 0.25 mass% and 0.30 mass%. This shows that when the Cu content is between 0.25 mass% and 0.30 mass%, the straightenability at the same hardness is enhanced, and straightenability equal to or greater than that of the conventional material is secured at the required hardness of HV 300. In addition, the required Cu composition range can be secured without addition by adjusting the scrap materials. Therefore, Cu between 0.25 mass% and 0.30 mass% was used as the solid solution strengthening element.

3.4. Strengthening by Nitrocarburization

Cr, V, Al⁽⁶⁾ and other elements are known to increase the surface hardness during nitrocarburization, and Cr can be secured without addition by adjusting the scrap materials used as the steel raw materials. Figure 7 shows the change in the surface hardness and the internal hardness after nitrocarburization for different Cr contents. Cr has almost no influence on internal hardness, so the surface hardness can be controlled during nitrocarburization without affecting the forgeability and machinability. For this reason, Cr was selected as the element used to increase the surface hardness during nitrocarburization. Figure 8 shows the relationship between the Cr content and the surface hardness assuming a Cu content between 0.25

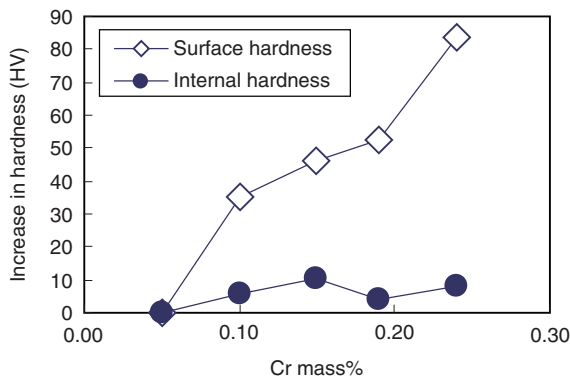


Fig. 7 Influence of Cr on surface hardness and internal hardness after nitrocarburization

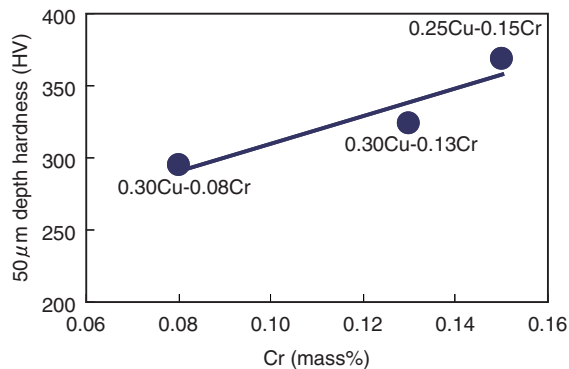


Fig. 8 Relationship between Cr mass% and 50 μm depth hardness

mass% and 0.30 mass%. This shows that a Cr content of 0.10 mass% or more is required to achieve the hardness of HV 300 needed to secure bending fatigue strength equal to that of the conventional material. A higher Cr content than is necessary reduces the straightenability, so a Cr content of 0.12 mass% was used as the typical value for the developed material in consideration of the balance between bending fatigue strength and straightenability.

4. Strengthening Mechanism

The ferrite strengthening mechanism of the developed material is solid solution strengthening by Cu⁽⁹⁾. In the case of carbon steel, the strengthening mechanism of nitrocarburization is generally said to be nitrogen solid solution strengthening, but Cr is also known as an element that forms nitrides⁽¹⁰⁾. Therefore, investigation was conducted to confirm whether the strengthening mechanism during nitrocarburization of steel with a relatively low Cr content of approximately 0.10 mass% such as the developed material is nitrogen solid solution strengthening or nitride precipitation strengthening. When the solid solution strengthening mechanism is dominant, the lattice constant of ferrite is thought to vary according to the solid solution nitrogen concentration. Figure 9 shows the results of measuring the nitrogen concentration using an electron probe microanalyzer and measuring the lattice constant of the ferrite using X-ray analysis, at the depths of 30 μm, 100 μm and 1000 μm from the surface. This shows that the lattice constant is nearly constant and independent of the nitrogen concentration, which infers that solid solution strengthening has little contribution. Next, Fig. 10 shows the analysis results at a depth of 50 μm from the surface obtained using a field emission transmission electron microscope. Here, large numbers of precipitates with a crystalline structure similar to chromium nitride (CrN) can be confirmed. Figure 11 shows the results of analyzing these precipitates using energy dispersive X-ray spectrometry. The precipitates contain Cr, and are thought to be CrN precipitates. Therefore, CrN precipitation strengthening is thought to be more dominant than nitrogen solid solution strengthening as the strengthening mechanism

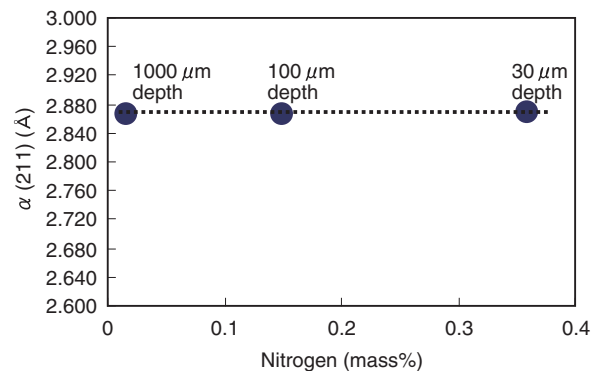


Fig. 9 Lattice constant of ferrite after nitrocarburization

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

	C	Si	Mn	P	S	Cu	Cr	Mo
Developed steel	0.30	0.08	0.80	0.013	0.05	0.25	0.12	-
Conventional steel	0.37	0.20	0.82	0.015	0.05	-	-	0.16

during nitrocarburization of steel with a relatively low Cr content of approximately 0.10 mass%. This precipitation strengthening mechanism is thought to be the reason why the straightenability drops when strengthening is performed using only Cr. Precipitation strengthening is thought to lower the crack propagation energy⁽¹¹⁾, and this is thought to be the reason for the marked drop in straightenability. However, by using Cu instead of Mo to obtain ferrite strengthening effects for the developed material, it is thought that the Cr content required for strengthening could be reduced, which enabled simultaneous achievement of both high fatigue strength and straightenability.

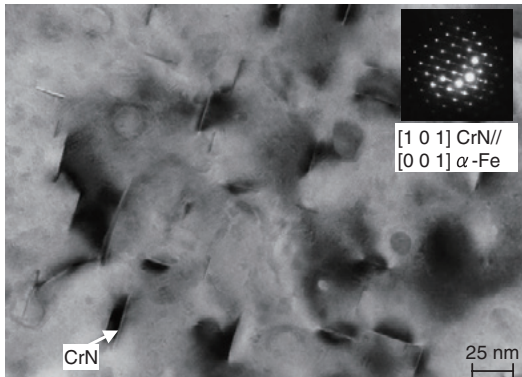


Fig. 10 Transmission electron micrograph taken from diffusion layer of steel containing 0.10 mass% Cr

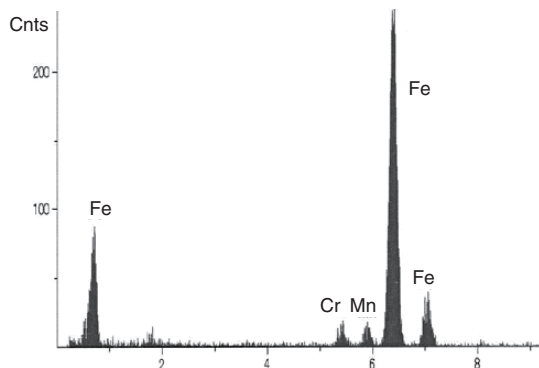


Fig. 11 Energy dispersive X-ray spectrometry analysis of precipitate

5. Crankshaft Characteristics

Table 3 lists the typical composition values for the developed material set according to the above investigation results and the typical composition values for a conventional high-strength crankshaft. Compared to the conventional

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

	Bending fatigue strength	Cracking limit strain
Developed steel	102	99

material, the developed material has a chemical composition that omits Mo but also uses Cu and Cr within the ranges that can be secured by adjusting the scrap materials, which makes the addition of rare metals unnecessary. Next, a crankshaft for a 3.5-liter V6 engine was manufactured and the cross-section hardness was measured to confirm the crankshaft characteristics of bending fatigue strength and straightenability. Figure 12 shows that the crankshaft surface hardness satisfied the required hardness of HV 300, and Table 4 shows that bending fatigue strength and straightenability equal to those of the conventional crankshaft were achieved.

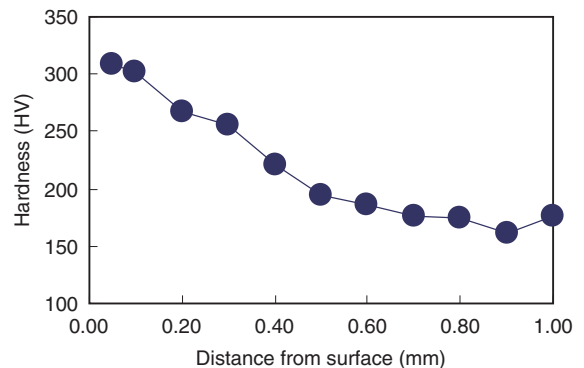


Fig. 12 Hardness profile after nitrocarburization

6. Conclusion

A high-strength crankshaft that does not require the addition of Mo or other rare metals was developed by manufacturing materials with a component design that optimizes the Cu and Cr contents, using the electric furnace manufacturing method. This reduced the cost by 2% and avoided the risk of future increases in the price of rare metals. This development clarified the following items.

- (1) The combination of precipitation strengthening by Cr during nitrocarburization and ferrite solid solution strengthening by Cu enables the achievement of high fatigue strength and good straightenability equal to those of the conventional high-strength material without

adding rare metals.

- (2) The Cu and Cr needed for strengthening are contained in the scrap materials used as raw materials, and the required quantities can be secured by adjusting the scrap materials.
- (3) CrN precipitation strengthening is the dominant strengthening mechanism instead of nitrogen solid solution strengthening when performing nitrocarburization with a Cr content of approximately 0.10 mass%.

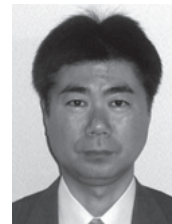
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