

# Strength Enhancement of Nitrocarburized Crankshaft Material

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## ABSTRACT

When improving the mechanical properties of a crankshaft by nitrocarburizing, it is important to achieve both strength as well as toughness (straightenability). By designing a material composition to provide maximum strengthening, a nitrocarburized crankshaft material has been developed without the use of a normalizing thermal treatment that has about 16% higher fatigue strength than previous crankshafts with the same material hardness, similar machinability and straightenability. The achievement of both high fatigue strength and straightenability of the developed material was made by adjusting the basic material composition for optimum microstructural control and by adding a small quantity of Mo to attain suitable ferrite strengthening. Furthermore, by omitting the normalizing treatment, the CO<sub>2</sub> emitted during the post-hot forging processes could be reduced by up to 22%, and cost savings of up to 8% could be achieved in comparison with previous high strength crankshafts.

## INTRODUCTION

The crankshaft is a main engine component that operates in a severe operating environment; it therefore has to have adequate strength, wear resistance, and toughness. In addition, a reduction of production costs and energy savings are also important aspects that have a significant impact. Generally, an automobile crankshaft will undergo a normalizing thermal treatment, surface rolling, induction hardening and nitrocarburizing in order to enhance the mechanical properties(1)-(9).

A nitrocarburizing treatment can be applied to complex shapes and, since it is performed at a relatively low temperature, the distortion is minimal. For these reasons, it is widely used as a heat treatment for enhancing wear resistance and fatigue strength (10). Although the distortion is low following the nitrocarburizing treatment

of the crankshaft, the high dimensional precision required of the final product makes it necessary to apply a straightening operation as shown in the production process diagram in Fig.1. Material modifications to enhance the strength following the nitrocarburizing process include using a high carbon steel with 0.45 mass% C or higher and heat treating to increase the strength of the actual material or by using an alternate material that includes elements such as Al, Cr, or V that form nitrides. These methods are available to increase the surface hardness achieved after nitrocarburization (7)(11)(12). However, heat treatment increases production energy usage and cost whereas excessive hardening reduces machinability and straightenability, so a different method that did not involve such issues was desirable. A material that could be nitrocarburized without the use of a normalizing process was therefore developed to provide high strength with acceptable machinability and straightenability; it was then applied to crankshaft mass production (Fig.2). This paper describes the design method for the material composition, the strengthening mechanism, and the effects of the application to a crankshaft.

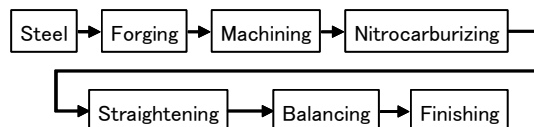


Fig. 1 Production process of Nitrocarburized crankshaft

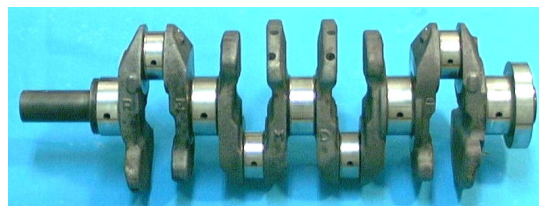


Fig. 2 Developed crankshaft

## GOAL AND STRATEGY

The objective was to develop a steel composition without a normalizing treatment while having both the straightenability of a crankshaft steel with normalizing treatment, "Steel A" in Table 1, as well as the fatigue strength of the steel with normalizing treatment shown as "Steel B". Therefore, the hardness profile shown in Fig. 3, that has the internal hardness of Steel A and the surface hardness of Steel B, was considered. The method used to achieve this was to focus attention on enhancing the basic properties of the steel without the normalizing treatment while suppressing the increase in material hardness; strengthening ferrite and increasing the hardness of the nitride layer. Details of the results of this study are given below.

Table 1 Chemical composition and mechanical properties of steels  
(Mechanical properties of steel A = 100)

| Material |                | Mechanical properties |                   |
|----------|----------------|-----------------------|-------------------|
|          |                | Fatigue strength      | Straightenability |
| Steel A  | Non-normalized | 100                   | 100               |
| Steel B  | Normalized     | 113                   | 73                |

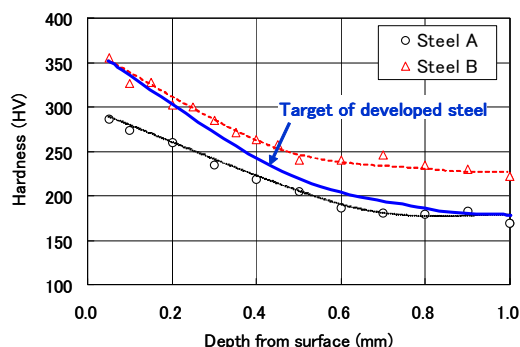


Fig. 3 Hardness distribution of crankshafts after nitrocarburization

### The Enhancement of Basic Properties of the Steel without a Normalizing Treatment

In general, to achieve both strength and toughness in steel without the normalizing treatment, increasing the ferrite percentage content with low carbon and high Mn is known to be effective(13),(14). In the same way, fatigue strength and straightenability can be improved for the nitrocarburized steel without the normalizing treatment for the crankshaft, with low C and high Mn content as shown in Fig. 4. Bending deformation was applied to a test piece and straightenability was evaluated by measuring the strain value (crack strain) measured at the time of crack propagation (9). In other words, if the amount of plastic deformation is large, the amount of bending that can be applied for straightening will be large, indicating high straightenability.

On the other hand, in places like the abrasion surface of the crankshaft oil seal section, wear resistance is also important. This is shown in Fig. 5, where it can be seen that as the C content is reduced, the amount of wear increases indicating that there is a limit to what extent C can be reduced. Therefore, the C content was set to same level as that of crankshaft Steel A at 0.38 mass% and, to achieve the same ferrite percentage content as Steel A, the Mn content was set to 0.82 mass% in accordance with the relationship shown in Fig. 6.

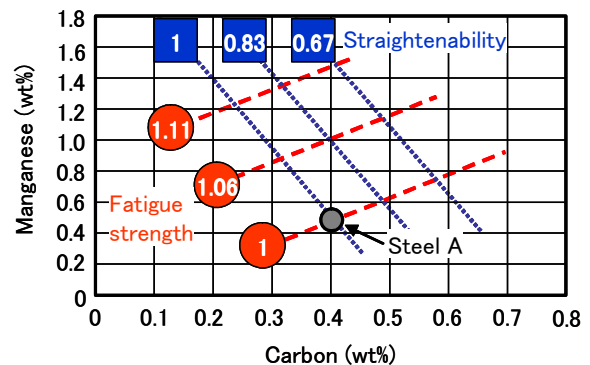


Fig. 4 Correlation between content of alloy additions and properties of non-normalized specimen through nitrocarburization

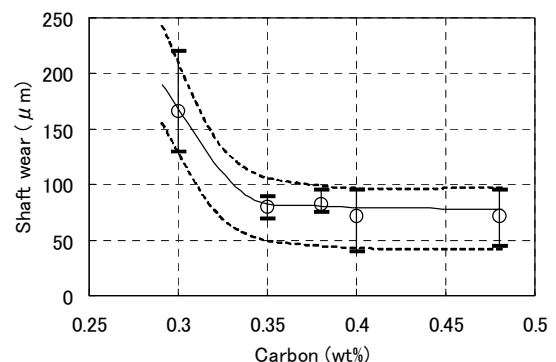


Fig. 5 Relationship between content of alloy additions and volume fraction of ferrite

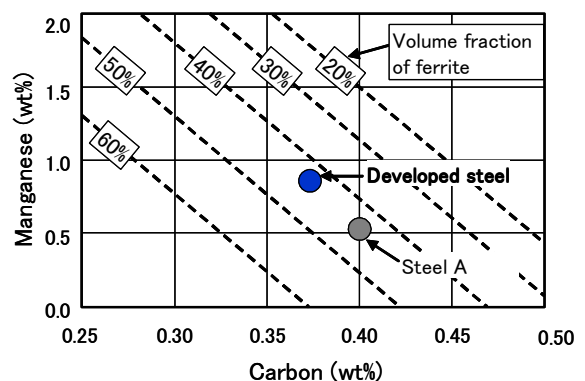


Fig. 6 Relationship between carbon content in steel and wear loss at oil seal section of crankshaft

## Ferrite Strengthening and Nitride Hardening

To achieve the target strength it was essential to achieve ferrite strengthening and to harden by nitrocraburizing through modification of the alloying content. As mentioned above, the likely elements for the modification are those that form stable nitrides such as Al, Cr, and V, as well as the element Mo, which, in addition to strengthening the ferrite, raises the post nitrocarburizing hardness to the required level(11),(15).

Molybdenum was the principal alloying element to raise strength and it was compared with Cr, which also has an affinity for nitrogen, to verify similar characteristics. First, the main question with regard to strengthening, namely the effect of Mo and Cr on the straightenability after nitrocarburizing, was studied. Next, the effect of Mo on the post nitrocarburizing fatigue strength was examined and the optimum quantity in which to add was evaluated. An analysis of the strengthening mechanism using Mo was also performed.

## EXPERIMENTAL PROCEDURE

### Straightenability and Fatigue Strength Evaluation for Steel Containing Cr and Mo

For the two test specimens shown in Table 2, the basic material composition was Fe - 0.4 C - 0.2 Si - 0.8 Mn (units are mass% - omitted below); three steels with different Mo percentages (0.12, 0.15, and 0.18) and three steels with different Cr percentages (0.05, 0.10, and 0.15) were used to give a total of six steels. Note that the steel compositions for Mo-1 and Cr-2 are identical. The same tests were also performed on the steel with the base composition, Steel A (Table 1). These steel modifications were machined and heat treated according to the procedure shown in Fig. 7. The geometry of the test piece used to confirm the straightenability is shown in Fig. 8. The central portion of the test piece was loaded at a constant rate and the loading stroke was taken as the crack propagation stroke when a crack was sensed at R2; the straightenability was evaluated from the various values obtained. A Vickers hardness tester was also used to measure hardness. Next, a surface bending fatigue test piece was prepared as indicated in Fig.7, and the effect on the fatigue strength from the addition of Mo was investigated.

Table 2 Chemical composition of steels tested

| Material | C   | Si  | Mn  | Cr   | Mo   |
|----------|-----|-----|-----|------|------|
| Steel A  | 0.4 | 0.2 | 0.6 | 0.1  | 0.01 |
| Mo-1     | 0.4 | 0.2 | 0.8 | 0.1  | 0.12 |
| Mo-2     | 0.4 | 0.2 | 0.8 | 0.1  | 0.15 |
| Mo-3     | 0.4 | 0.2 | 0.8 | 0.1  | 0.18 |
| Cr-1     | 0.4 | 0.2 | 0.8 | 0.05 | 0.12 |
| Cr-2     | 0.4 | 0.2 | 0.8 | 0.1  | 0.12 |
| Cr-3     | 0.4 | 0.2 | 0.8 | 0.15 | 0.12 |

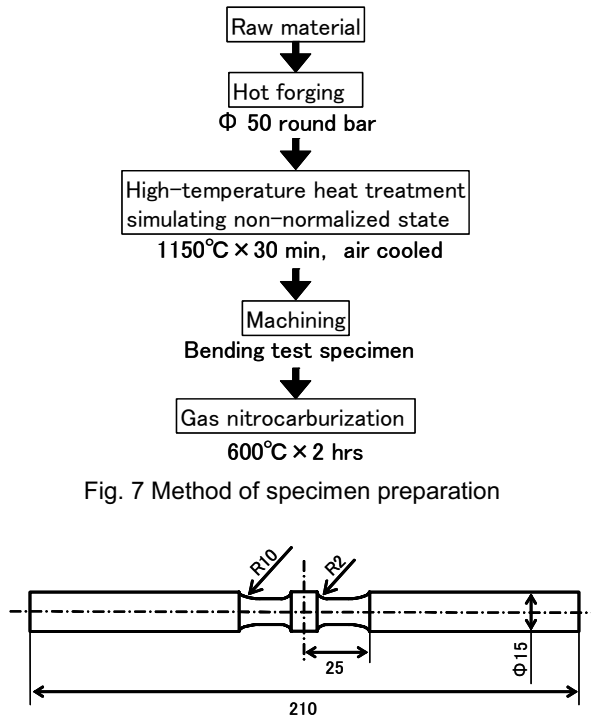


Fig. 8 Geometry of bend test specimen

### Investigation of the Properties of Mo Modified Steel Before and After Heat Treatment

It is well known that steel containing Mo displays high strength after nitrocarburizing. The reasons have been reported as being solid solution ferrite strengthening and the formation of carbide and nitride precipitates (11),(16). An attempt was made to clarify the Mo strengthening mechanism that occurs in the material composition selected for the current investigation. First, the change in mechanical properties before and after the application of the heating cycle equivalent to nitrocarburization (600°C × 2 hr) was studied. For comparative purposes, a material with essentially no Mo was given the same tensile test. The preparation process of the test specimens is outlined in Fig. 9 and the chemical composition of the two test materials is given in Table 3. In addition, an Atom Probe Field Ion Microscope (APFIM) (17)-(19) was used to analyze the state of the Mo present at the atomic level.

Table 3 Chemical composition of Mo-added and Mo-free steel, in mass %

|                | C    | Si   | Mn   | P     | Cu   | Ni   | Cr   | Mo   |
|----------------|------|------|------|-------|------|------|------|------|
| Mo-added steel | 0.35 | 0.21 | 0.76 | 0.016 | 0.01 | 0.02 | 0.08 | 0.16 |
| Mo-free steel  | 0.41 | 0.19 | 0.58 | 0.014 | 0.01 | 0.02 | 0.06 | 0.01 |