

Development of High-strength, Nitrocarburized Crankshaft with Control of Vanadium Carbonitride Precipitation by Normalization

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ABSTRACT

A high-strength crankshaft with a high productivity has been developed. This crankshaft development sought to balance high fatigue strength, machinability and straightening ability. Vanadium is known as a precipitation strengthening element, and the development focused on the fact the amount of solid solution of vanadium in steel is dependent on the heating temperature. A material was developed in which a high level of strength could be achieved through control of the normalizing temperature, for which conditions could more easily be set, rather than controlled cooling following hot forging. Optimization of the normalizing temperature helped to enable the achievement of a 30% or more increase in fatigue strength against the existing material, while maintaining machinability and straightening ability.

1. Introduction

In addition to the traditional demands for high power and compactness, the achievement of further weight reductions in motorcycle engines is now demanded in order to increase fuel efficiency and thus reduce CO₂ emissions. This has made the achievement of weight savings in the crankshaft, the heaviest rotating engine part, an important issue. The crankshaft is required to be strong enough to resist the bending stresses generated by the explosive force from the combustion chamber and the inertial forces of the pistons, connecting rods, and other reciprocating parts. The necessity to reduce the weight of the crankshaft increases the load on the component.

Because motorcycle crankshafts pass through a wide variety of machining processes, including lathe machining, milling, drill machining, grinding, and gear machining, the materials employed are required to possess a high level of machinability. For this reason, it is necessary to consider a balance with productivity when seeking to increase crankshaft strength.

The development project discussed in this paper designed a hardness transition curve in an attempt to develop a crankshaft balancing high fatigue strength with machinability and straightenability. Vanadium, known as

a precipitation strengthening element, was added in order to increase fatigue strength⁽¹⁾⁻⁽³⁾, and the heating temperature-dependence of the amount of V in solid solution in the steel was focused on. A material was developed in which a high level of strength could be achieved through control of the normalizing temperature, for which conditions can be set more easily, rather than controlled cooling following hot forging. Optimization of the normalizing temperature helped to enable the achievement of a 30% or more increase in fatigue strength against the conventional alloy steel, while maintaining machinability and straightenability.

2. Development Goals

The majority of integrated crankshafts used in motorcycle engines are manufactured from quenched and tempered or normalized steels to which soft nitriding or nitriding treatments have been applied. The manufacture of crankshafts from quenched and tempered steels is advantageous from the perspective of fatigue strength, but their homogeneous metallic microstructures give them insufficient cuttability. Normalized steels have a ferrite-pearlite mixed microstructure and display better cuttability than steels with a homogeneous metallic microstructure;

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nitrogen also rapidly diffuses in the ferrite microstructures during soft nitriding or nitriding. The steels therefore display good productivity. A steel for which the normalizing process has been omitted but which achieves identical characteristics to normalized steels has also recently been put into practical use⁽⁴⁾.

Previously, the authors had employed a calcium-sulfur free-cutting steel for which the normalizing process could be omitted for standard crankshafts in order to reduce costs. For crankshafts in which high fatigue strength was necessary, a lead-sulfur free-cutting nitrocarburizing steel to which Al had been added in order to obtain high near-surface hardness following soft nitriding was used in order to help assure fatigue strength in areas in which stress concentrated. However, the near-surface hardness of these existing soft-nitrided materials was excessive in relation to the hardness transition curve demanded by the gradient of the stresses on the crankshafts.

The aim of the development was therefore set as the development of a material displaying the following characteristics, in order to reconcile the achievement of high fatigue strength with machinability and straightenability:

- (1) Able to achieve high level of strength without special heat treatments
- (2) Identical level of productivity to existing materials
- (3) Able to be made lead-free

3. Breakthrough Points in Development of High-strength Crankshaft Material

3.1. Design of Hardness Transition Curve

A hardness transition curve was designed prior to the design of the material composition (Fig. 1). In order to increase fatigue strength, it is necessary to obtain a hardness profile that exceeds the hardness transition curve demanded by the stress gradient^{(5), (6)}. To achieve increased strength, the internal hardness would be increased against the hardness transition curve of the existing material, and the nitrided diffusion zone deepened. In addition, the near-

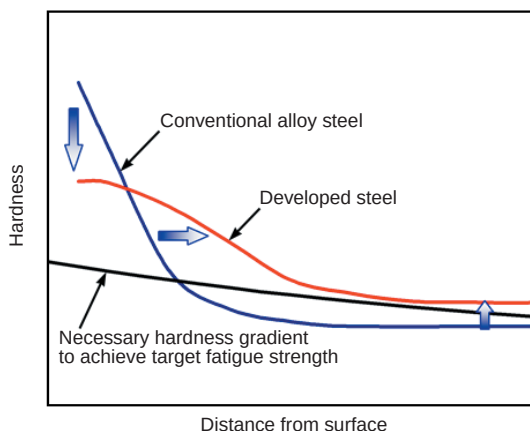


Fig. 1 Hardness transition curve design

surface hardness would be reduced in order to help guarantee straightenability. Given the need for increased nitrided depth and reduced near-surface hardness, the target for the practical depth of the nitrided case was set at 0.3 mm or more, and the target for near-surface hardness (hardness at a distance of 0.05 mm from the surface of the base material) was set at Hv500 or less. To help avoid a decline in machinability, the target for hardness following normalization was set at HRB100 or less.

3.2. Characteristics of Conventional Crankshaft Material and Study of Methods for Achievement of Increased Strength

Figure 2 shows the metallic microstructures of the steel used in Honda motorcycle crankshafts subject to standard loads (termed “conventional carbon steel” below) and in crankshafts from which high fatigue strength is demanded (“conventional alloy steel” below). Because the conventional carbon steel is not normalized following hot forging, its microstructure is coarse with a large crystal grain diameter. However, both materials display ferrite-pearlite microstructures, helping to assure a high level of machinability.

In the majority of cases, the hardness of the material used in large motorcycle crankshafts is increased by quenching and tempering, and the material’s fatigue strength is increased by soft nitriding or nitriding. However, homogeneous metallic microstructures such as a tempered martensite microstructure display insufficient cuttability in comparison to mixed microstructures such as ferrite-pearlite microstructures. In addition, because the speed of diffusion of N during nitriding is slower in martensite than in ferrite, it is necessary for nitriding to be conducted for a longer period in an attempt to increase the depth of the nitrided diffusion zone, resulting in a decline in productivity. Because of this, maintaining the ferrite-pearlite microstructure unchanged and strengthening the ferrite, which is the starting point for fatigue fractures, is an effective means of increasing fatigue strength without reducing machinability.

The addition of V and Ti for precipitation strengthening and the addition of P and Si for solid solution strengthening can be considered as methods for strengthening ferrite. The addition of Ti and P reduces the

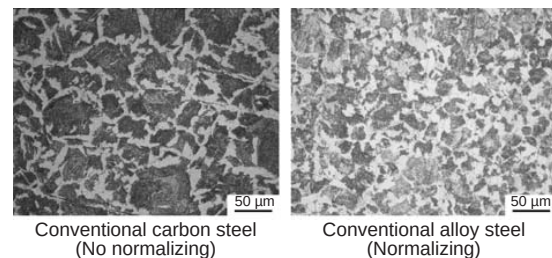


Fig. 2 Microstructure of conventional carbon steel and conventional alloy steel

impact value of the material, and is therefore undesirable in materials used in the crankshafts of large motorcycles, in some of which the primary drive gears are cut directly into the crankshaft. In addition, the fatigue strengthening effect of Si is low in comparison to the effect of V when added in identical amounts^{(1), (2)}.

Based on the above considerations, it was decided to attempt to increase fatigue strength in the developed material while minimizing any increase in hardness by adding V.

3.3. Study of Methods of Controlling Amount of V in Solid Solution

V-added steel is also known as microalloyed steel. Because identical characteristics to those displayed by quenched and tempered steels can be obtained despite the omission of the quenching and tempering process following hot forging, these steels are widely used for parts including crankshafts, connecting rods, and wheel hubs. Figure 3 shows the relationship between the heating temperature and the amount of V in solid solution, calculated using the total thermodynamics calculation system Thermo-Calc. The amount of V in solid solution increases as the heating temperature increases, but the additive amount in the case of microalloyed steels is generally 0.2% or less in order to achieve complete dissolution of the V at the heating temperature prior to hot forging (1100-1300°C).

Following hot forging, microalloyed steel crankshafts undergo controlled cooling using large blower fans, and their hardness reaches HRC20 and above⁽⁷⁾. The crankshafts are either machined at this level of hardness, or they are annealed in order to reduce their hardness. Given the challenge of finely controlling the cooling speed during controlled cooling under blower fans following hot forging, the development discussed here attempted to control hardness by controlling the amount of V in solid solution through adjustment of the normalizing temperature.

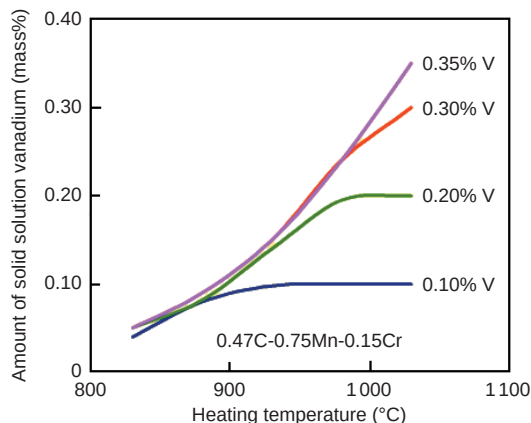


Fig. 3 Relationship between heating temperature and amount of dissolved vanadium

4. Alloy Design

4.1. Basic Composition

In order to increase wear resistance, timing sprockets and other parts that are cut directly into motorcycle crankshafts are subjected to high-frequency quenching, and quenching hardness values of HRC50 and above are obtained. To help assure stable high-frequency quenching hardness, a lower limit of 0.4% C was set. Al was not added because it bonds readily with N, markedly increasing near-surface hardness and impeding the diffusion of N during soft nitriding. S forms MnS in the steel, contributing to cuttability, but it can result in the occurrence of quenching cracks during high-frequency quenching. Because of this, the JASO S1 level of 0.06% was added. In order to promote the breaking of cutting chips, sulfite inclusions were finely dispersed in the steel, and by doing so, Pb was omitted as a free-cutting component. In addition, the amounts of C, Mn, Si, and V were adjusted.

C, Mn, Cr, and V were either added or removed in relation to the conventional alloy steel, and multiple alloys were produced in which the carbon equivalent, Ceq, was adjusted to achieve a hardness of HRB100 or below following normalization. Ceq was calculated using Eq. (1) below.

$$\text{Ceq} = \text{C} + 0.07\text{Si} + 0.16\text{Mn} + 0.19\text{Cu} + 0.17\text{Ni} + 0.2\text{Cr} + [\text{V}] \quad (1)$$

[V]: The amount of V that can exist in γ at the normalization heating temperature

Following normalization under identical conditions to the conventional alloy steel, these alloys were salt bath soft-nitrided, and the near-surface hardness and practical depth of the nitrided case were measured. Figure 4 shows the relationship between the amount of Cr and near-surface hardness. When the additive amount of Cr was greater than 0.3%, near-surface hardness following soft

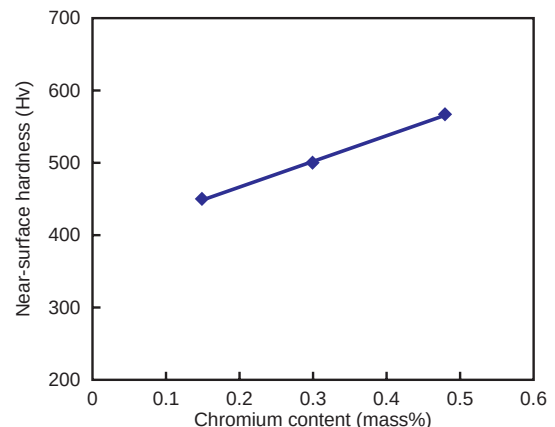


Fig. 4 Relationship between chromium content and near-surface hardness

Table 1 Chemical composition of conventional alloy steel and developed steel

Steel Grades	C	Mn	S	Cr	V	Al	Pb
Conventional alloy steel	0.23	1.00	0.055	1.00	-	0.016	0.08
Sample I	0.47	0.75	0.048	0.15	0.30	-	-
Sample II	0.45	0.74	0.049	0.30	0.29	-	-
Sample III	0.43	0.75	0.047	0.30	0.15	-	-
Developed steel *	0.47	0.75	0.060	0.15	0.30	-	-

* Based on Sample I

nitriding exceeded the target upper limit, and the additive amount was therefore set at 0.3% or below. Figure 5 shows the relationship between near-surface hardness and the practical depth of the nitrided case. The fact that no clear correlation existed between near-surface hardness and the practical depth of the nitrided case suggested that it would be possible to reduce near-surface hardness while increasing the nitrided depth by adjusting the additive amounts in the alloy.

4.2. Study of Fatigue Strength

The three steels that fell within the target area for near-surface hardness and practical depth of the nitrided case in Fig. 5 were subjected to an Ono-type rotating-bending fatigue test. The chemical compositions of the steels are shown in Table 1. The test specimens were shaped to

produce a stress distribution corresponding to the stress gradient on the R section of a crankshaft fillet (Fig. 6). Figure 7 shows the results of measurements of near-surface hardness and fatigue strength. Because the normalizing temperature of the test specimens was 900°C or below, identical amounts of V returned to solid solution in each when heated for normalization (Fig. 3). However, fatigue strength was lowest in sample III, which contained a lower additive amount of V than the other samples. It is conjectured that the crystal grains became coarse and fatigue strength declined in this sample because of the low amount of undissolved V when it was heated for normalization. Sample I, which displayed a good balance between near-surface hardness and fatigue strength, was selected as the new steel.

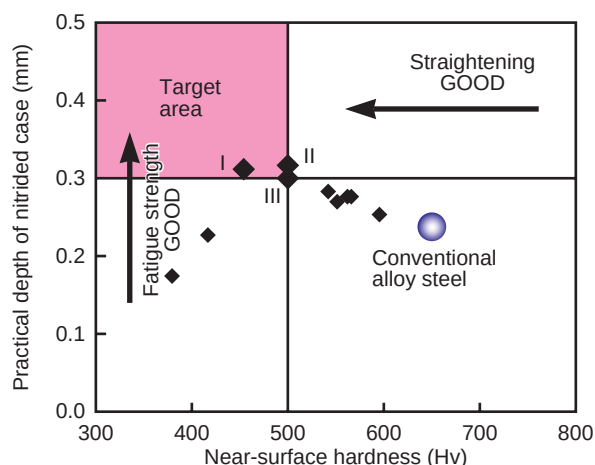


Fig. 5 Relationship between near-surface hardness and practical depth of nitride case

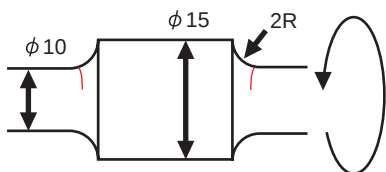


Fig. 6 Geometry of rotating-bending fatigue test specimen

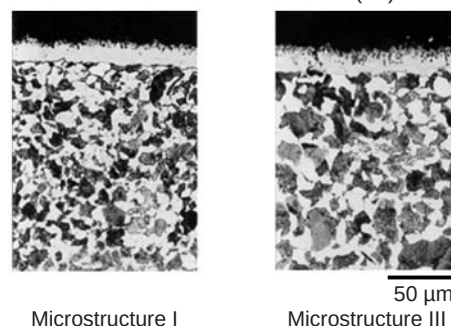
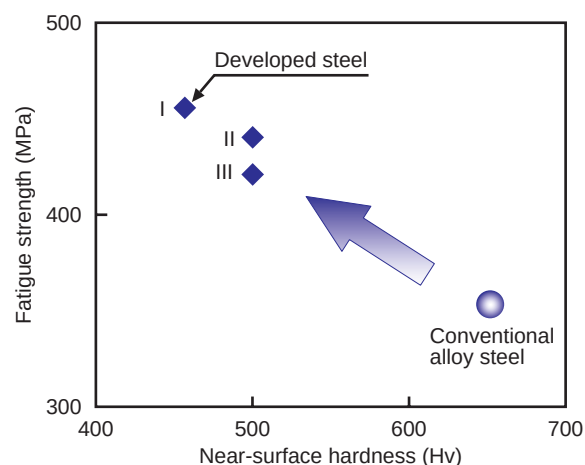


Fig. 7 Near-surface hardness and fatigue strength

5. Characteristics of Developed Steel

5.1. Normalization Characteristic

Because steels are normalized in order to restore the microstructure that has been disrupted by hot forging and to adjust hardness, it is necessary to use AC3 temperatures or higher. In the majority of cases, considering temperature variations and other factors, the work is conducted by heating the steel to AC3 temperature plus 50°C or more, followed by air cooling. The standard heating temperature range is around 50°C. The AC3 temperature of the developed steel was calculated as 770°C using Eq. (2) below, necessitating a heating temperature of 820°C or above.

$$AC3 = 854 - 180C + 44Si - 14Mn - 17.8Ni - 1.7Cr \quad (2)$$

In order to study the effect of the normalizing heating temperature, 40 mm x 40 mm test specimens were heated at temperatures of between 830 and 980°C, and their hardness was measured following air cooling. Figure 8 shows the relationship between the normalizing temperature and hardness. Hardness tends to increase with increased normalizing temperature. It is considered that this results from the V carbonitrides precipitated during cooling, following hot forging, returning to solid solution when the steel is heated for normalization; a greater amount of V carbonitrides return to solid solution with increased temperature, producing a greater effect of precipitation hardening during the following cooling process. This indicated that when a greater amount of V was added than the amount of V in solid solution calculated using Thermo-Calc, normalizing temperature control at temperatures lower than the temperature used in the calculations would make it possible to obtain any desired hardness level.

In order to study the effect of the cooling speed, hardness was measured after the steel was heated to temperatures of 820 and 880°C and cooled at speeds of between 0.1 and 2°C per second. Figure 9 shows the effect of cooling speed on hardness after normalizing.

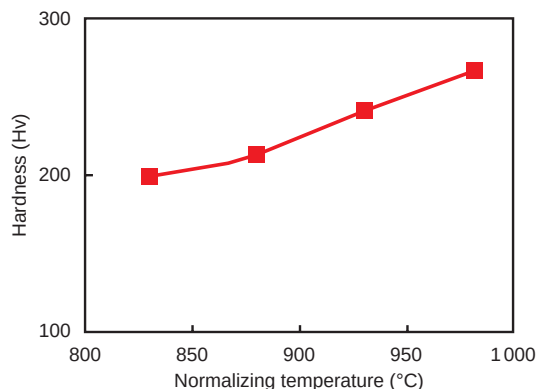


Fig. 8 Relationship between normalizing temperature and hardness

Hardness tends to be greater with faster cooling speeds. This is thought to be because at higher cooling speeds the V carbonitrides become finely dispersed in the cooling process and their ability to precipitation harden the steel increases, while at lower cooling speeds the V carbonitrides agglomerate, and their ability to precipitation harden the steel declines. In addition, the crystal grains become coarse at lower cooling speeds, and this may have a negative effect on fatigue strength and straightenability.

5.2. Fatigue Strength Characteristic

Ono-type rotating-bending fatigue tests were conducted on the test specimens shown in Fig. 6 in order to determine the effect of the normalizing temperature on the fatigue strength of the developed steel. 40 mm x 40 mm test specimens were normalized, machined, and salt bath nitrided. Figure 10 shows the relationship between the

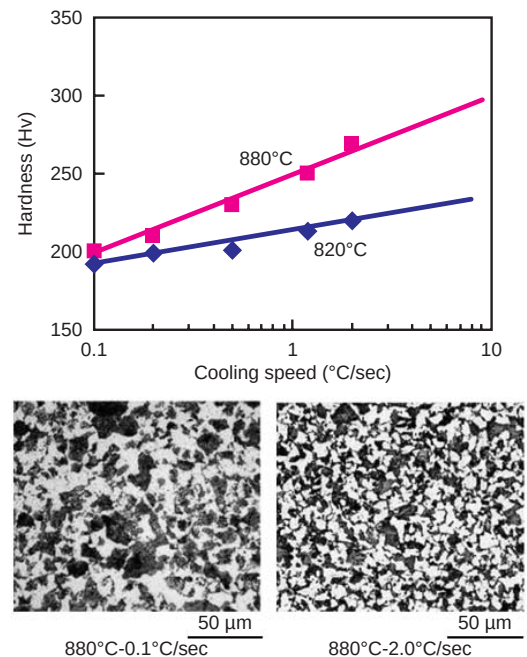


Fig. 9 Effect of cooling speed on hardness after normalizing

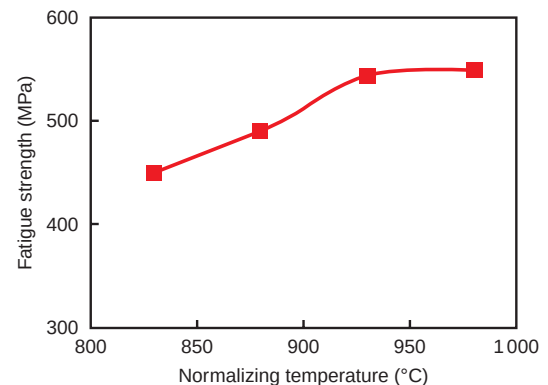


Fig. 10 Relationship between normalizing temperature and fatigue strength

normalizing temperature and fatigue strength. An increase in internal hardness is thought to be the reason that fatigue strength increases with increased normalizing temperature. However, fatigue strength at a normalizing temperature of 980°C is no higher than fatigue strength at a temperature of 930°C. Figure 11 shows the microstructures of the steels at normalizing temperatures of 930 and 980°C. It is conjectured that fatigue strength did not increase with increasing normalizing temperature due to a coarsening of the crystal grain. At temperatures of 930°C and below, it would be possible to control fatigue strength by means of controlling normalizing temperature.

5.3. Straightenability

3-point static bending tests were conducted using test specimens of the type shown in Fig. 6 in order to study the effect of the normalizing temperature on straightenability. With supports spaced 106 mm apart, the central sections of the test specimens were loaded until cracks appeared, and the change of runout was measured when the load was removed. Figure 12 shows the relationship between normalizing temperature and change of runout, and Fig. 13 shows the relationship between internal hardness and near-surface hardness. Internal hardness increases with increasing normalizing temperature, but there is no change in near-surface

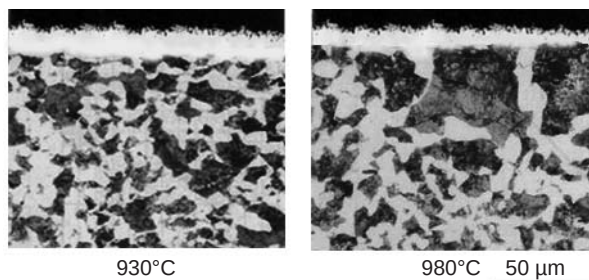


Fig. 11 Microstructure of developed steel at normalizing temperature of 930 °C and 980 °C

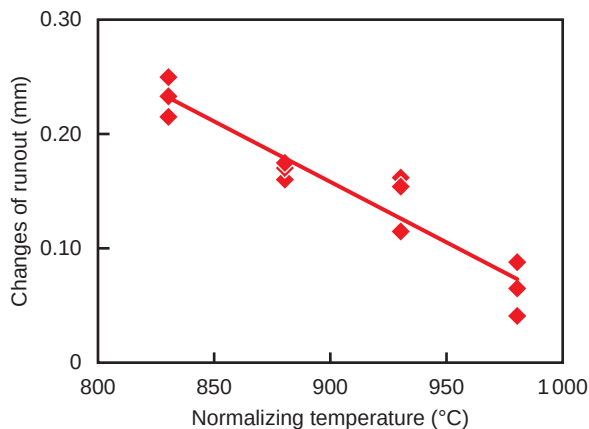


Fig. 12 Normalizing temperature and changes of runout

hardness, and therefore no change in the ductility of the surface, where stress is high. However, it is thought that straightenability declines with increasing normalizing temperature because the increase in hardness reduces the level of internal plastic deformation under bending.

6. Crankshaft Characteristics

6.1. Fatigue Strength Characteristic

Figure 14 shows the shape of the sample crankshaft. The normalizing temperature for the crankshaft was set at 820°C, but the machining processes were identical to those used for crankshafts manufactured from conventional alloy steel. Figure 15 shows hardness transition curves for the developed steel and the

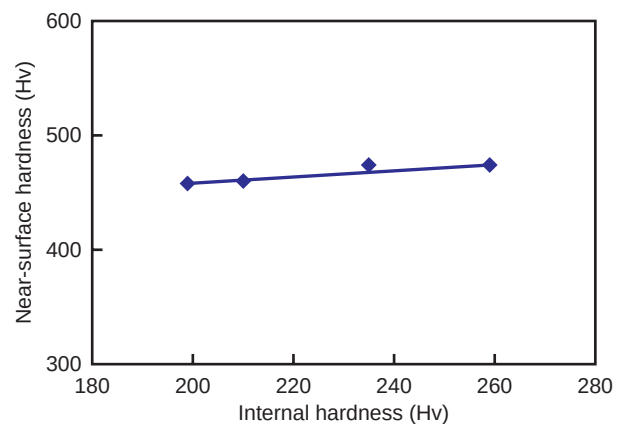


Fig. 13 Relationship between internal hardness and near-surface hardness

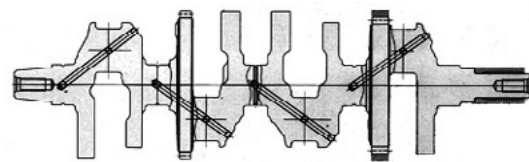


Fig. 14 Shape of sample crankshaft

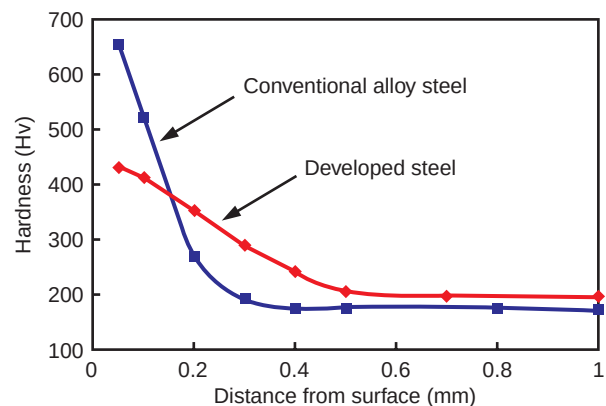


Fig. 15 Hardness transition curve of developed and conventional alloy steel

conventional alloy steel. The crankshaft manufactured from the developed steel displays greater internal hardness and depth of nitrided diffusion zone and lower near-surface hardness than the conventional alloy steel crankshaft. Next, the journals at the ends of the crankshafts were supported, and the central journals were subjected to reversed excitation. Strain gauges attached to the fillet sections of the center journals were used to measure the stresses generated (Fig. 16). Figure 17 shows the results of the bending fatigue tests. The developed material displayed a 30% increase in fatigue strength against the conventional alloy steel, even at a normalizing temperature of 820°C, at which fatigue strength is lowest.

6.2. Straightenability

The journals at both ends of a crankshaft of the shape shown in Fig. 14 were supported on V blocks, the center journal was loaded until cracks appeared, and the change of runout of the center journal was measured after the load was removed (Fig. 18). Figure 19 shows the relationship between the normalizing temperature and the change of runout. Straightenability declines with increasing normalizing temperature. Taking productivity into consideration, it would be desirable to set the normalizing temperature low. However, even when the normalizing temperature is set high, the fatigue strength of the

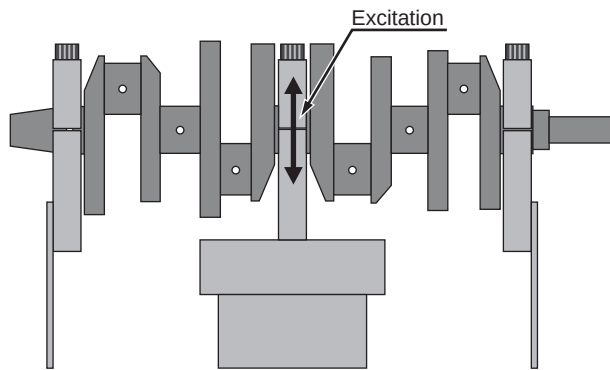


Fig. 16 Bending fatigue test method for crankshaft

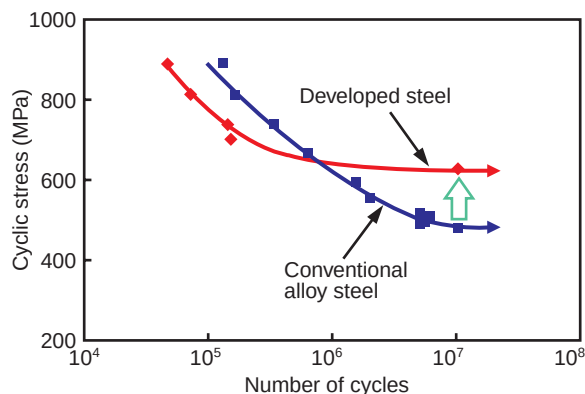


Fig. 17 Results of bending fatigue test for crankshaft

developed steel can be further increased, with no change in basic processes, through the achievement of increased accuracy in machining and the development of a method of controlling the amount of distortion following soft nitriding.

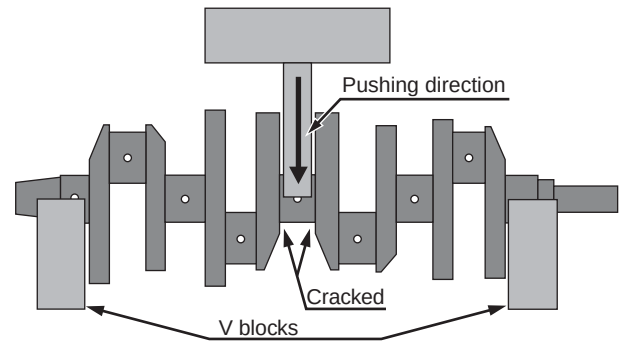


Fig. 18 Changes of runout test method for crankshaft

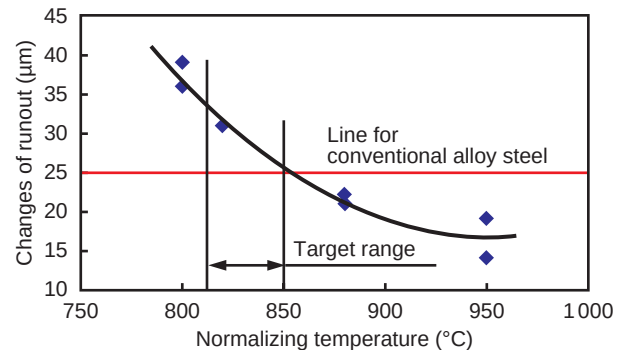


Fig. 19 Relationship between normalizing temperature and changes of runout

7. Effect of Application of Developed Steel

Crankshafts produced using the developed material was employed in the 2010 model VFR1200F (Fig. 20), which is fitted with a new geometry V4 engine. The use of the developed steel helped to enable the diameter of



Fig. 20 Mass production motorcycle VFR1200 using developed crankshaft



Fig. 21 Crankshaft with new geometry for new V-4 cylinder engine

the crank pins to be reduced by approximately 2 mm and the engine to be reduced in size and weight against the use of the conventional alloy steel (Fig. 21).

8. Conclusion

A crankshaft has been produced using a new material that achieves greater internal hardness and depth of the nitrided diffusion zone and reduced near-surface hardness against the conventional alloy steel. The following results were obtained in this development:

- (1) The addition of a greater amount of V than the amount of V in solid solution at the normalizing temperature made it possible to adjust hardness by controlling the normalizing temperature.
- (2) When the crystal grains became coarse due to the low amount of undissolved V while heated for normalization, a greater additive amount of V would result in a high level of fatigue strength.
- (3) Optimization of the normalizing temperature increased fatigue strength by more than 30% against the conventional alloy steel while maintaining machinability and straightenability.

The application of crankshafts produced using the new technology will enable the achievement of reduced size and weight of motorcycle engines, and contribute not only to higher power, but also to increased fuel efficiency, resulting in reduced CO₂ emissions.

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