

Development of High-strength Case-hardened Boron Steel

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ABSTRACT

A high-strength case-hardening steel maintaining good cold forgeability has been developed for use in the manufacture of transmission shafts. The cold forgeability of the steel enables workability to be maintained when the steel is used in the form of wire in a multiple-stage former, as has now become standard. The developed material is also able to match the strength increase that was previously achieved using a special heat treatment (cold quenching) by using a standard carburization quenching (hot quenching). Higher strength represents an impediment to the straightening process that follows carburization, and it was therefore necessary to achieve a balance between high strength and straightenability. In order to do so, flattening of the hardenability curve (Jominy curve) was focused on. Boron was added to a conventional JIS SCr alloy steel and Cr content was adjusted to develop a new steel. During the development process, the mechanism by which the addition of boron causes a decline in the hardenability of the carburized case was clarified, and hardenability was enhanced by the addition of Cr, enabling the achievement of the development goals.

1. Introduction

There is a demand for small, lightweight, high-powered motorcycles, making it desirable to develop a stronger transmission shaft. A sufficient level of strength to resist torsion produced by sudden increases in torque, for example when the bike contacts the ground following a jump, and bending due to gear reaction force is called for, in particular motorcycles used in off-road racing. In addition, the load on the transmission shaft is increasing as motorcycles become smaller, lighter, and more powerful.

Cold forging from a coil offers reliable productivity and is the standard method of manufacturing transmission shafts. A multiple-stage former forges the spline section up to the final shaping procedure. From the perspective of manufacturing costs, it is not acceptable to allow productivity to decline if the strength of the shaft is increased. In addition, the shaft should undergo a process of straightening following carburization. Straightenability and high strength are opposing properties, and it is therefore important to attempt to achieve a balance between them.

Seeking a suitable material for a transmission shaft that reconciled the achievement of high strength with low cost, the project discussed in this paper selected a boron steel in which hardenability could be enhanced by reducing alloying elements. The boron factor (fB) of boron steels is known to be determined by the amount of carbon present in the steel; as carbon content increases, fB decreases⁽¹⁾. During the development process, however, it was shown that the hardenability of the carburized case declined with the addition of boron. Because of this, the project attempted to increase hardenability through the addition of alloy elements.

2. Development Goals

Honda has conventionally employed carburized HSCM420H, a similar steel to JIS Cr-Mo steel, in the transmission shafts of its motorcycles. For models that will be placed under high loads, such as the off-road bikes mentioned above, the oil temperature is reduced during carburization quenching ("cold quenching") in order to increase internal hardness, resulting in increased shaft strength.

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With the aim of removing special heat treatments of this type in order to develop a high-strength, low-cost shaft, the project discussed here attempted to design a material that would fulfill the following standards:

- (1) The achievement of a level of strength using hot quenching equivalent or superior to that achieved by the present material using cold quenching
- (2) The achievement of an equivalent level of manufacturability to the current material
- (3) Low cost

With regard to standard (1), it was assumed that the treatment would be conducted in a standard gas carburizing furnace, and the design attempted to produce a material that would achieve the level of strength previously achieved using cold quenching (60-80°C) through the use of normal hot quenching (110-130°C).

In addition, when cold quenching is used, there is considerable distortion following carburization, while internal hardness increases to a certain level, which reduces deformation during straightening, generating the issue of a decline in yield during the straightening procedure. The composition design of the developed steel therefore attempted to realize no too-high level increase in internal hardness.

With regard to standard (2), the constraint for manufacturability, because cold forging in a multiple-stage former using steel wire treated with a zinc phosphate coating is the standard manufacturing method in use, the ability to manufacture the developed steel using existing mass production processes was established as a prerequisite.

The removal of Mo, which has increased in cost, from the composition of the developed steel and the removal of the normalization procedure following cold forging were projected as methods of achieving low cost, standard (3).

3. Material Component Design Process

3.1. Quench Curve Design

Prior to the design of the steel composition, the quench curve (Jominy curve) was designed.

In order to satisfy the target of increasing internal hardness and achieving high strength using hot quenching, the hardness of the material was increased in the J7-J15 area. In addition, the hardness of the water quenched end was reduced and the Jominy curve was flattened. The hardness of the water quenched end was reduced in order to help prevent an excessive increase in internal hardness, which would result in reduced straightenability.

In the mass production process, variations in the speed of cooling during carburization quenching cause the internal hardness of the shaft to vary, which in turn causes variation in strength. It is therefore important to flatten the Jominy curve and reduce the level of variation of the internal hardness of the shaft (Fig. 1).

3.2. Basic Composition

Given that the removal of Mo from the material and the achievement of low cost had been established as development guidelines, SCr was selected as the basic composition of the new steel. In order to increase cold workability, Si content was reduced and boron was added, increasing hardenability. In order to flatten the Jominy curve, the carbon content was reduced from 0.20% to reduce the hardness of the water quenched end, and boron, Cr, and Mn were added to increase the hardness of areas further away from the water quenched end.

In addition, Nb was added as a pinning element to control crystal grain growth so that the removal of the normalization process following cold forging did not result in the formation of duplex grains in the carburization quenching process that followed.

3.3. Study of Effect of Boron on Hardenability of Carburized Layer

As discussed above, the boron factor (fB) is determined by carbon content, decreasing with increasing carbon content⁽¹⁾. Considering carburized parts, the fB enhances the hardenability of an internal structure with a carbon content of 0.2%, but does not significantly contribute to increased hardenability in a carburized layer in which carbon content reaches 0.8% during carburization. This is thought to be because the boron forms a compound ($M_{23}(CB)_6$) inside the carburized layer, reducing the amount of dissolved boron necessary to provide good hardenability⁽²⁾. Therefore, the hardenability of the carburized layer in SCr boron steels was evaluated prior to the design of the alloy composition of the developed steel.

First, a steel formed by adding boron to SCr420 (steel A) and the current material, HSCM420H, were compared. The steels were melted using 150 kg vacuum induction melting (VIM), and underwent cogging at 1 250°C and normalization (925°C/1h/A.C.). Test pieces ($\phi 25 \times 40$ mm) were prepared and carburized in mass production furnaces, after which the quality of the heat treatment was

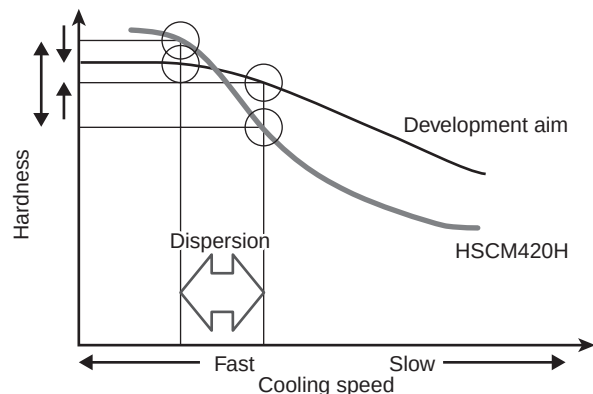


Fig. 1 Flattening quenching curve

examined. Quenching temperatures of 125°C (corresponding to hot quenching) and 80°C (corresponding to cold quenching) were used. Measured cross-sectional hardness distribution is shown in Fig. 2.

As Fig. 2 shows, when steel A is cold quenched, the hardness of the carburized layer is equivalent to that achieved using SCM420, but when hot quenched, the hardness of the surface of the carburized layer is lower than that of the current material, and insufficient hardenability of the carburized layer is achieved.

Next, in order to study the effect of the addition of boron on the hardenability of the carburized layer, steel A as shown in Table 1 was used as a base, and the carbon content was set to 0.8% to correspond to the figure following carburization. Hardenability was then studied with and without the addition of boron (Table 2).

As in the previous study, Jominy tests were conducted following cogging and normalization of the steels. The heating pattern used in the Jominy tests was based on the carburization heating pattern. Following heating at 930°C for 30 min, the steels were heated at 840°C for 20 min, after which they were quenched.

The test results are shown in Fig. 3. Hardness declined in the boron additive steel from the J15-J25 positions.

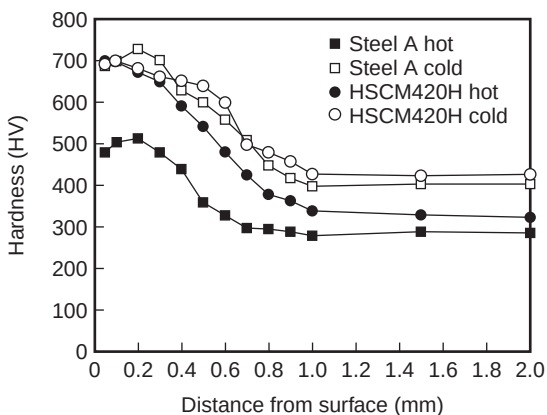


Fig. 2 Cross-sectional hardness distribution

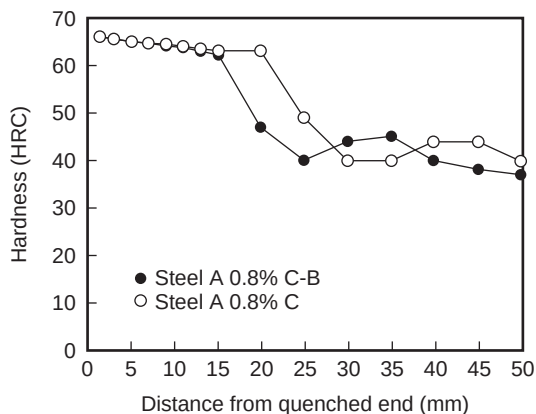


Fig. 3 Hardening-related test results

Table 1 Chemical composition and measured DI value

	(mass%) (in)							
	C	Si	Mn	Cr	Mo	Nb	Ti	B
Steel A	0.20	0.03	0.60	1.06	—	0.031	0.031	0.0012
HSCM420H	0.20	0.20	0.70	1.10	0.10	—	—	—
								2.50

Table 2 Chemical composition

	(mass%)							
	C	Si	Mn	Cr	Mo	Nb	Ti	B
Steel A 0.8%C-B	0.79	0.05	0.75	1.06	—	0.036	0.028	0.0017
Steel A 0.8%C	0.79	0.05	0.75	1.06	—	0.036	0.028	—

Detailed study of the structure of the steel following quenching using an optical microscope showed the presence of troostite, a material lower in hardness than martensite, at a greater distance from the water quenched end than the area in which the decline in hardness occurred. At a shorter distance, i.e., closer to the quenched end where sufficiently rapid cooling had taken place, the steel displayed either a full martensite structure or a structure with low troostite content.

Observation of the area at a greater distance from the quenched end where a decline in hardness occurred using a field emission scanning electron microscope (FE-SEM) showed the presence of comparatively large precipitates (several μm in width), surrounded by troostite.

Microanalysis using an auger electron spectroscopy (AES) was conducted in order to determine the status of boron segregation in these relatively large precipitates. Figure 4 shows AES element mapping images of the

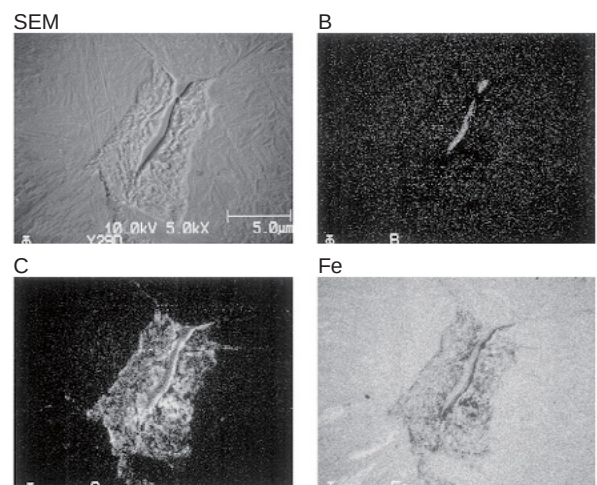


Fig. 4 Boron compound (AES mapping) separated at grain boundary in steel A 0.8%C-B

troostite areas formed close to the grain boundary in steel A (0.8% C-B). These results suggested the possibility of the presence of boron carbide.

A line analysis using an electron probe microanalyzer (EPMA) was conducted next in order to determine the level of variation in element concentration around the boron carbide. The results are shown in Fig. 5. It was considered that the low level of boron content in the precipitates would make line analysis challenging, and therefore it was not used to study boron. Cr content was approximately 17%, and there was an approximately 3 μm area of Cr depletion, at levels lower than the matrix. Areas of slightly depleted Mo and Mn were observed, but were not clear. No area of depleted C was observed. Electron diffraction analysis using transmission electron microscopy / energy dispersive X-ray spectrometry (TEM/EDS) was employed to identify the crystal structure of the precipitated boron carbide. The precipitate was judged to be $\text{M}_{23}(\text{CB})_6$. Figure 6 shows TEM images and electron diffraction patterns.

From these results, it is conjectured that hardness declines in Cr boron additive steel (steel A: 0.8% C-B) because: (a) the boron carbide $\text{M}_{23}(\text{CB})_6$, containing Cr, forms at the grain boundaries; (b) a Cr depletion layer forms around this compound; (c) during cooling, troostite forms from this Cr depleted layer; (d) resulting in a structure that contains troostite. From the perspective of carburizing conditions, it was not necessary to consider this phenomenon while employing cold quenching, in which the cooling speed is rapid, but the insufficient hardenability of the carburized layer becomes an issue

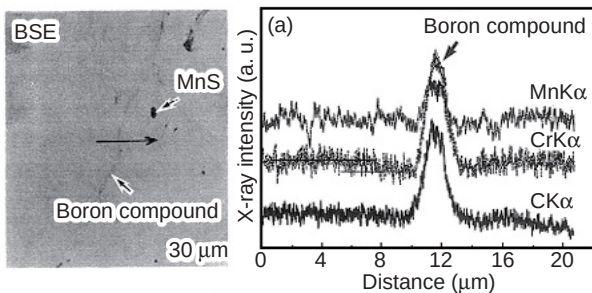


Fig. 5 Effect of boron compound vicinity in EPMA line analysis

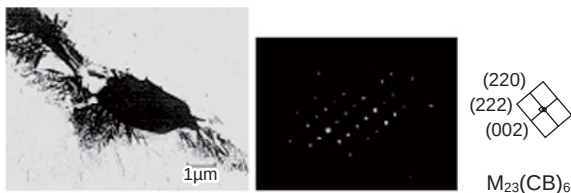


Fig. 6 TEM image of steel A 0.8%C-B steel and electron diffraction pattern

when using hot quenching, in which the speed of cooling is slower. Given the fact that hot quenching is the standard method in use today in the carburizing process in mass production, and that distortion should be avoided when using this method, this is an important issue to be considered when using SCr boron additive steels.

3.4. Method of Evaluation of Hardenability of Carburized Layer

The use of a “carburized Jominy test” (a Jominy test conducted following carburization of the material) was examined as a method of evaluating the hardenability of the carburized layer when designing the composition of the steel under development.

The test method involved the formation of test pieces of similar specifications to JIS G 0561 test pieces ($\phi 25 \times 100 \text{ mm}$), which were then carburized. The test pieces were heated at 930°C for 30 minutes and at 840°C for 20 minutes after which they were quenched using the JIS method. A Vickers hardness tester was used to measure hardness from the surface of the test pieces to a depth of 0.1 mm.

Figure 7 shows a carburized Jominy curve for steel A. Steel A clearly shows insufficient hardenability in comparison to the current material. The achievement of a level of hardenability greater than that of the current material, as indicated by the Jominy curve, was therefore established as a target of the composition design of the new steel. From the perspective of the substitution of the developed steel for the current material, if the developed steel demonstrated an equivalent or higher level of hardenability to the current material in this test, evaluating the hardenability of the carburized case for different component shapes and under different cooling conditions during carburization would not be necessary, making the test an effective method of evaluating the hardenability of the carburized case during the process of material development.

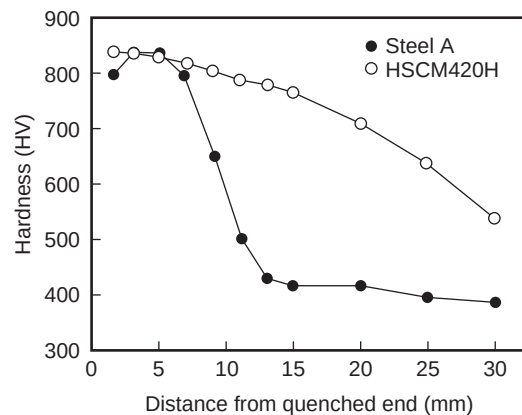


Fig. 7 Carburization Jominy curve

Table 3 Chemical composition

	(mass%)							
	C	Si	Mn	Cr	Mo	Nb	Ti	B
1.6% Cr	0.14	0.05	0.50	1.60	—	0.028	0.025	0.0016
1.8% Cr	0.14	0.05	0.50	1.80	—	0.028	0.025	0.0016
2.0% Cr	0.14	0.03	0.49	1.99	—	0.028	0.024	0.0015
HSCM420H	0.20	0.20	0.70	1.10	0.10	—	—	—

3.5. Establishment of the Material Composition

The composition of the material was established on the basis of the tests and studies conducted to this point. Mn and Cr were candidates for use as an additive element to enable hardenability to be increased, but because the ferrite intention index of Mn is higher than that of Cr, considerations of cold forgeability led to the optimization of Cr content.

Steels were formulated with varying Cr content, as shown in Table 3. The hardenability of the steels was evaluated in carburized Jominy tests and the quality of the heat treatment was checked following carburization

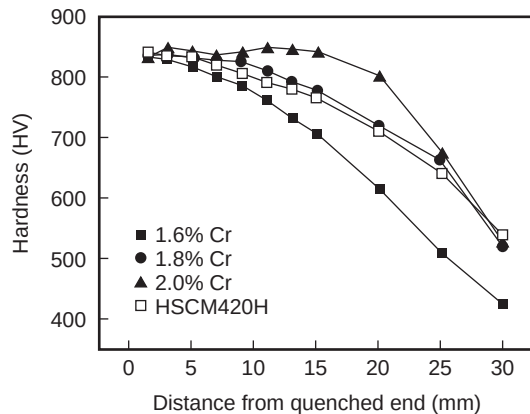


Fig. 8 Carburization Jominy test results

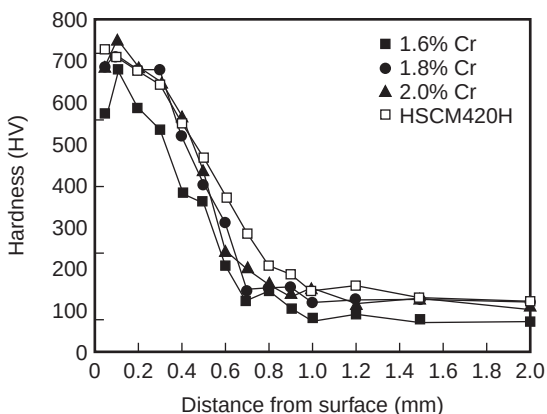


Fig. 9 Cross-sectional hardness analysis

Table 4 Chemical composition of developed steel

	(mass%)							
	C	Si	Mn	Cr	Mo	B	Ti	Nb
Developed steel	0.16	0.05	0.55	1.93	—	0.0015	0.040	0.040
HSCM420H	0.20	0.20	0.70	1.10	0.10	—	—	—

quenching (hot quenching) in furnaces used in the mass production process in order to establish the quantity of Cr to be added.

The results of these tests showed that a Cr content of 1.8% or higher would enable the achievement of a level of hardenability of the interior of the component and the carburized case equivalent or superior to that achieved using the current material (Figs. 8 and 9). Table 4 shows the composition of the developed steel.

4. Manufacturability of the Developed Steel

The conditions used in the coating and machining processes were modified to enable the developed steel to be manufactured using the same processes as the current material.

4.1. Coating Process

Steel wire to which a zinc phosphate treatment has been applied is employed in cold forging using a multiple stage former. The zinc phosphate treatment involves acid pickling to remove scale, dipping in a zinc phosphate solution, and drying. It was found that the conditions used in the acid pickling process can have a negative effect on the adhesion of the coating. Figure 10 shows the difference in the amount of coating that results from different acid pickling conditions. One set of conditions resulted in an insufficient coating in a short period, and cracking

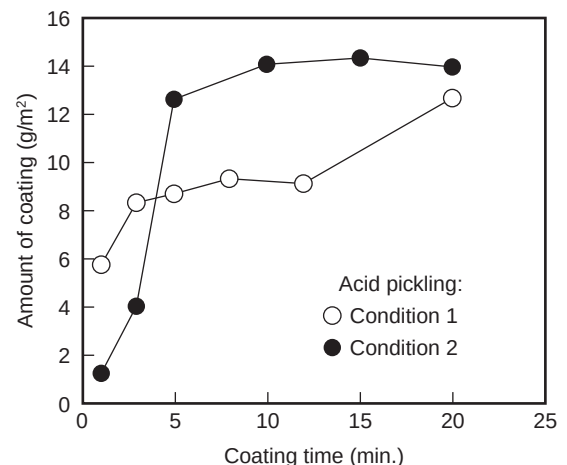


Fig. 10 Amount of coating in different acid pickling

occurred in this coating during cold forging (Fig. 11). Because it has a high Cr content, by contrast with the current material, there is a high concentration of Cr directly underneath the scale layer following rolling in the developed steel. It was hypothesized that, depending on the acid pickling conditions, this Cr layer and the corrosion residue (smut) from acid pickling affected the formation of the coating.

4.2. Change in Dimensions following Carburization

Grooves for the clips that are used to hold the gears in position are machined into transmission shafts. These grooves are cut following cold forging, and the positioning of the grooves during machining takes into consideration the change in dimensions that will occur after carburization.

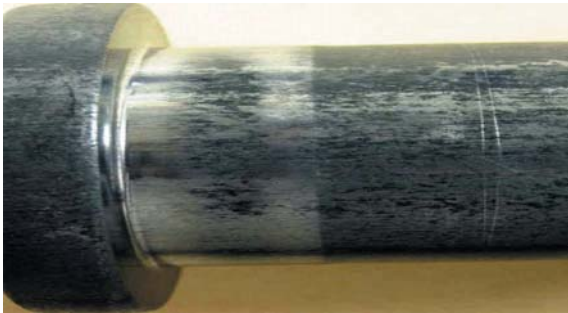


Fig. 11 Cracking of anodic oxide coating

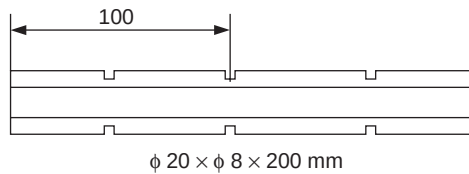


Fig. 12 Test piece

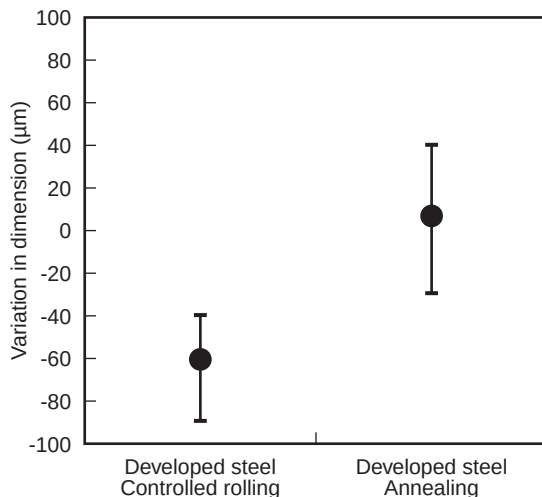


Fig. 13 Change in dimension

The change in dimensions after carburization in the developed steel differed from that of the current material, and the positioning of the grooves was therefore reset. The developed steel demonstrated a different tendency in terms of dimensional change when it was used to produce steel wire by controlled rolling and when the wire was produced by rolling followed by annealing. As part of the study conducted of the change in dimensions of the material, test pieces of the type shown in Fig. 12 were produced from each type of wire. Figure 13 shows an example of the change in dimensions of the test pieces following carburization.

The variation in dimensions was greater in the controlled rolled rods than in the annealed rods. Because it resulted in a lower level of dimensional change, the use of annealing would be better suited to achieving dimensional accuracy in components, and this method was therefore selected for use in the mass production process.

5. Characteristics of Transmission Shaft

5.1. Torsional Strength

Prototype countershafts for 1100 cc engines were produced and torsional strength was compared. Both hot quenched and cold quenched shafts were produced using the current material. Figure 14 shows test results. Considering the results in terms of internal hardness and the torque factor when cracking occurred, strength can be seen to have increased as internal hardness increased. The results for the developed steel fall on the higher-strength side of the line, and the increased grain boundary strength achieved by the use of boron is thought to have contributed to this result⁽³⁾.

In addition, straightenability has been enhanced by controlling internal hardness to a lower level than that of the cold quenched steel.

5.2. Manufacturing Cost

The use of the developed steel has enabled the removal of the normalization process following cold forging, the

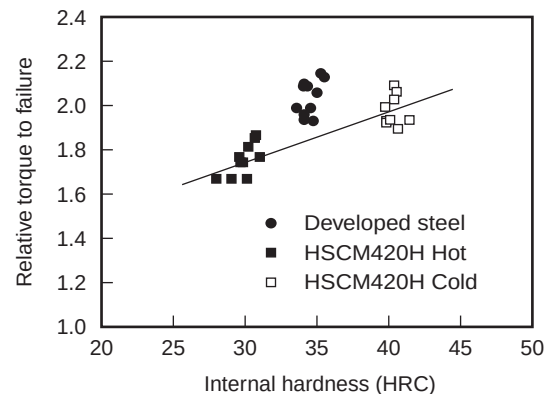


Fig. 14 Relationship between shaft torsional strength and internal hardness

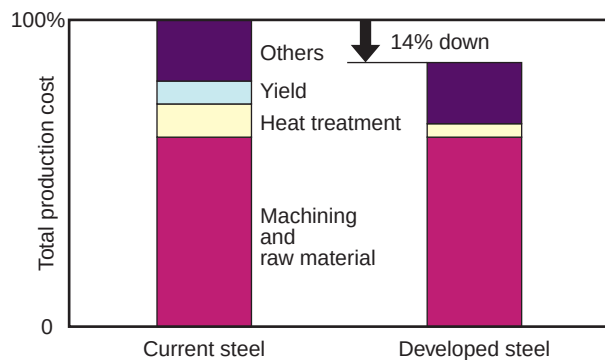


Fig. 15 Comparison of total production cost

removal of the use of cold quenching, and the achievement of an increased yield rate during straightening, resulting in a 14% reduction in the cost of transmission shafts (Fig. 15).

The developed steel has been employed in the transmission shaft of the 2008 CRF250R off-road racing motorcycle.

6. Conclusion

A high-strength, low-cost case-hardening boron steel has been developed. The main points of this development are as follows:

- (1) The addition of boron to JIS SCr420 steel resulted in a decline in the hardenability of the carburized layer. This occurred because a boron carbide containing Cr was formed at the grain boundary, and troosite formed from a Cr depletion layer around this boron carbide compound, causing a decline in hardness.
- (2) The addition of 1.8% Cr to SCr boron steel enables the achievement of a level of hardenability of the carburized case equivalent or superior to that of SCM420.
- (3) "Carburized Jominy" is an effective method of evaluating the hardenability of the carburized case.
- (4) When the developed steel is used to manufacture transmission shafts, the conditions employed in the coating and machining processes should be modified, but the shafts can be mass-produced using existing manufacturing facilities.
- (5) The composition of the developed steel has enabled torsional strength to be maintained and straightenability to be enhanced despite the use of hot quenching in place of cold quenching.

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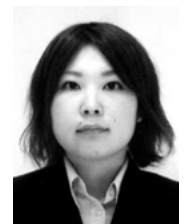
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