

Development of Pb-free Free-cutting Steel Enabled to Omit Normalizing for Crankshafts

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ABSTRACT

A Pb-free free-cutting steel for crankshafts was developed which resulted in the omission of the normalizing process. In order to omit the normalizing process, adequate hardness and fine microstructures, as obtained in normalized steel, must be achieved in the free-cutting steel after forging and air-cooling. These requirements were met by adjusting chemical composition of steel. A target was to achieve productivity of the developed steel based on Ca-S free-cutting steel, equal to that of the conventional Pb-S free-cutting steel. As a result of examining non-metallic inclusion's composition, volume, shape and dispersion in the steel, it was found that the shape and dispersion contributed to an improvement in machinability. By manufacturing a crankshaft with this steel, the cost of the normalizing process was eliminated and the reduction of Pb by 13 g became possible for a motorcycle equipped with a 954 cm³ engine.

1. Introduction

The normal method used to manufacture crankshafts for large motorcycles has involved hot forging and nitrocarburizing. S48CL1S1 Pb-S free-cutting steel has typically been used to achieve satisfactory strength and productivity.

This present work investigates a steel composition that enables omission of the normalizing process, which is usually required in the production process for automobile components, and the application of an optimized form of this steel material to a motorcycle engine. A study was also undertaken to make this steel Pb-free. The crankshaft production procedure is shown in Fig. 1. The machining process involves the four steps of lathe turning, drilling, grinding, and gear cutting. Depending on the machines and tools used, and on the machining conditions, 120 or more

different machining operations may be necessary; consequently, it is extremely difficult to determine the machinability of a crankshaft material by means of simplified cutting tests alone.

This project, therefore, used material forged from sulfur free-cutting steel made from conventional Pb-S free-cutting steel (hereafter referred to as conventional steel) which had been processed to be Pb-free. This forged material was then subjected to the crankshaft mass production process, and the problems involved were identified. Although there were no problems with drilling, grinding, or gear cutting, in which this material was equal to the conventional steel, it is apparent from the chips shown in Fig. 2 that this material had inferior frangibility when lathe turned, and the machining equipment was unable to eject it automatically.

The study was accordingly focused on ways of improving chip frangibility in order to produce a Pb-free free-cutting steel.

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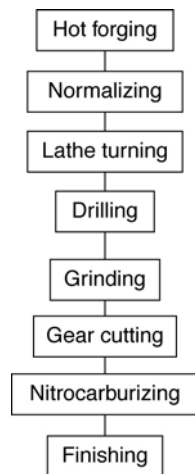


Fig. 1 Production process for crankshaft

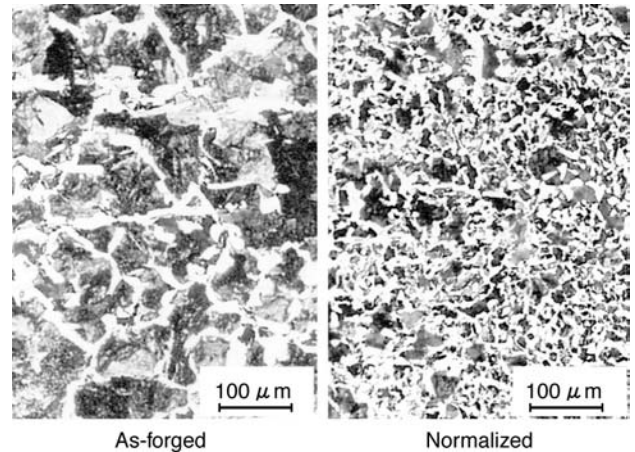


Fig. 3 Microstructure of conventional steels



Fig. 2 Chips of sulfur free-cutting steel generated by lathe turning

2. Alloy Design

2.1. Study on the Omission of Normalizing

The purpose of normalizing is to improve the coarse microstructure resulting from the effects of heating, forging, and cooling that occur during hot forging.

Figure 3 shows the microstructure of steel that had been heated to 1,200 °C, forged and then cooled, and of steel that had been normalized after similar processing. The effect of normalizing was to change the coarse ferrite-pearlite grains into fine ferrite-pearlite grains.

On the other hand, reducing the amount of carbon (C) and manganese (Mn) increases the ferrite area fraction, while the addition of nitrogen (N) increases the number of nucleation sites for ferrite. This is known to have the effect of yielding a fine microstructure, even when normalizing is omitted after a forging operation.⁽¹⁾

The target ferrite area fraction for the required steel, therefore, was set to 40%, which is equivalent to normalized S48C. The gears, splines, timing sprockets, etc. on a motorcycle crankshaft are frequently machined directly, and the timing sprockets are induction hardened to increase their wear resistance, giving them an induction hardened hardness of HRC50 or better. Consequently, the lower limit for the C content was set at 0.40%.

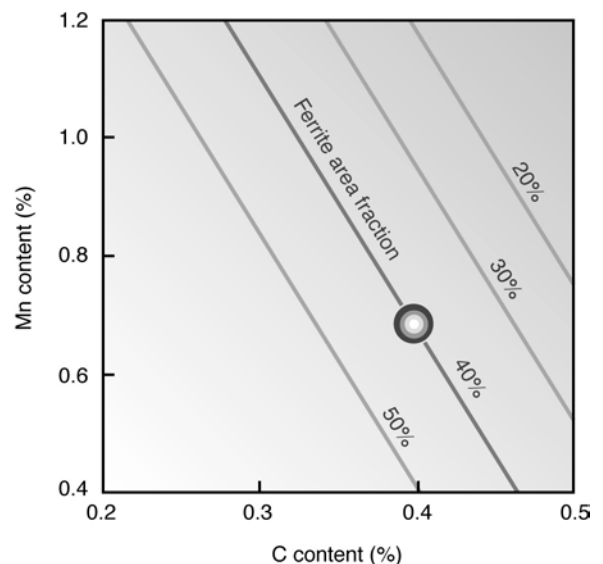


Fig. 4 Influence of carbon and manganese on ferrite area fraction

The C content, Mn content, and ferrite area fraction are related as shown in Fig. 4. Reducing the C content results in a significant increase in the ferrite area fraction. With the reduced C content set at 0.40%, the Mn content could be set at 0.70% in order to achieve the ferrite area fraction target. The hardness increased markedly when the N content was 0.020% or greater, so 0.020% N was set as the upper limit.

2.2. Study of Methods for Making Steel Pb-Free

Methods for making Pb-free steel have been addressed in reports^{(2), (3)} on regulatory trends and machining effects, as well as in proposals for Pb-free free-cutting steel made by steel manufacturers.^{(4)–(12)} These methods can be broadly classified under the two following types:

- The addition of previously unused substances such as Bi or BN as a lead substitute^{(4)–(6)}
- The improvement of conventional free-cutting steel^{(7)–(10)}

Table 1 Target of chemical composition of developed steel

	C	Si	Mn	P	S	Cr	N	Pb	Ca
Developed steel	0.40	0.20	0.70	0.017	0.050	0.06	0.017	—	0.0020

mass (%)

Table 2 Chemical composition of developed and conventional steels

	C	Si	Mn	P	S	Cr	N	Pb	Ca
Developed steel	0.40	0.19	0.72	0.017	0.049	0.06	0.017	—	0.0022
Conventional steel S48CL1LS1 *	0.47	0.18	0.78	0.025	0.047	0.17	0.010	0.07	—
Comparison steel S40CS1U *	0.40	0.18	0.70	0.010	0.049	0.07	0.016	—	0.0017

mass (%)

* JASO M 106-92

The former method leaves many questions unanswered regarding regulatory trends for previously unused substances, the future availability of such substances and so on. The latter method takes the approach of adding elements that have a proven history of effectiveness for free cutting. This study proceeded on the basis of adding S and Ca.

Machinability is commonly evaluated by the criteria of chip frangibility, tool life, cutting force, and hardening cracks. The main effect of adding lead to free-cutting steel is improved chip frangibility resulting from embrittlement during machining and stress concentration.⁽⁴⁾

Crankshaft cutting tests conducted with conventional steel and sulfur free-cutting steel processed to be Pb-free also confirmed this within the effective region of embrittlement for the lead in chips that had been discolored blue. At that point, the target chip frangibility for the developed steel in the lathe turning process was set to be equal to that for the conventional steel, and the type, quantity, shape, and dispersion of non-metallic inclusions were determined on the basis of added S and Ca.

The non-metallic inclusions were mainly of the sulfide type (MnS) and low-melting-point oxides (CaO-Al₂O₃-SiO₂, etc.). Improved machinability was apparent with increasing MnS content, although quenching cracks sometimes occurred during induction hardening. Consequently, the S content was set to 0.050%, which is equal to the JASO S1 level. The constitution and shape of CaO inclusions changed according to the amount of Ca added, the amount of oxygen in the molten steel, and so on.⁽¹²⁾ The Ca content was therefore set

to 0.0020%, and the oxygen content was optimized to adjust the low-melting-point oxide inclusions.

The plan was to make the non-metallic inclusions finer in size and more evenly dispersed. The target values for the basic chemical composition of the developed steel are shown in Table 1.

3. Testing Methods and Results

3.1. Testing the Steel Properties

Samples were prepared of the developed steel, conventional steel, and a comparative steel, the latter being a calcium-sulfur free-cutting S40CS1U steel with non-metallic inclusions dispersed differently from those in the developed steel. The chemical compositions of the test materials are shown in Table 2. The developed steel and comparative steel were melted in a 70-ton steel converter, continuously cast, and then hot rolled into round bars of 80 mm in diameter. The conventional steel was melted in a 90-ton electric furnace, continuously cast, and then hot rolled into round bars of 78 mm in diameter in order to easily differentiate it from the other samples to the extent that it would not affect the properties of the steel. Each of these steel materials was heated to 1,200 °C, the temperature envisaged for hot forging, and air cooled. The conventional material was then maintained at a temperature of 880 °C for four hours, after which it was normalized by air cooling.

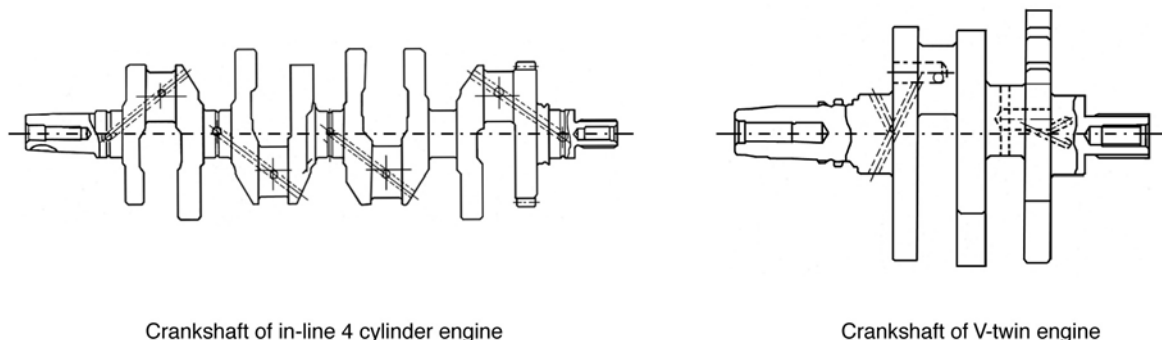


Fig. 5 Geometry of crankshafts for motorcycle

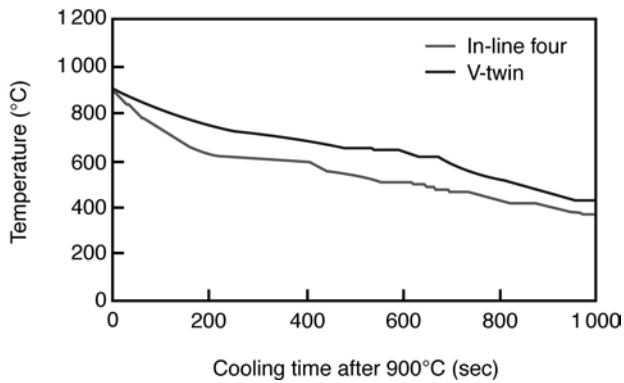


Fig. 6 Cooling curve of air-cooled crankshafts after hot forging

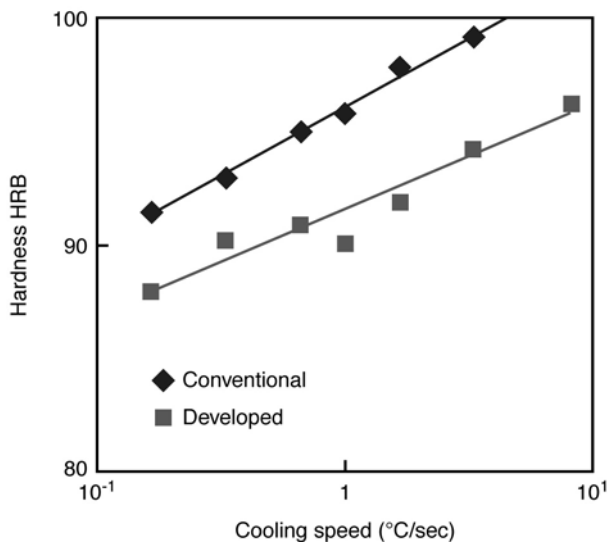


Fig. 7 Influence of cooling speed on hardness after hot forging

3.1.1. Microstructure and hardness of the air-cooled materials after hot forging

If normalizing is to be omitted, it is necessary to use air cooling alone to obtain the required microstructure and hardness after hot forging. Accordingly, an investigation was made of the cooling rate by air cooling after hot forging typical crankshafts. Figure 5 shows the geometry of crankshafts for in-line 4-cylinder and V-twin engines, and Fig. 6 shows the cooling curve. The average rate of cooling from 900 °C to 700 °C after hot forging the crankshafts was 0.56–1.56 °C/sec.

Each material was next heated to 1,250 °C in a hot-deformation simulator (Thermecmastor), subjected to 50% forming by compression at a process temperature of 1,100 °C, and then cooled at 0.17–8.33 °C/sec, after which the hardness was measured. Figure 7 shows the relationship between the cooling rate and hardness. The developed steel achieved a hardness approximately 3–6 points lower than the conventional steel. When cooled at a rate of 1 °C/sec, which is equivalent to the usual air cooling rate for a crankshaft after forging, the developed material achieved a hardness of HRB90, this being equal to that for the normalized conventional steel sample.

3.1.2. Non-metallic inclusions

The dispersion and types of non-metallic inclusion in the developed steel and comparative steel were verified in longitudinal sections. The upper photographs in Fig. 8 show the dispersion of non-metallic inclusions. It is apparent that the sulfide type of non-metallic inclusion in the developed steel was more finely dispersed than that in the comparative steel.

A qualitative analysis of the oxide type of non-metallic inclusion by an electron probe X-ray micro-analyzer (EPMA) is shown at the bottom of Fig. 8. The oxide type of non-metallic inclusions in the developed steel are of the low melting point variety containing Ca, Al, and Si.

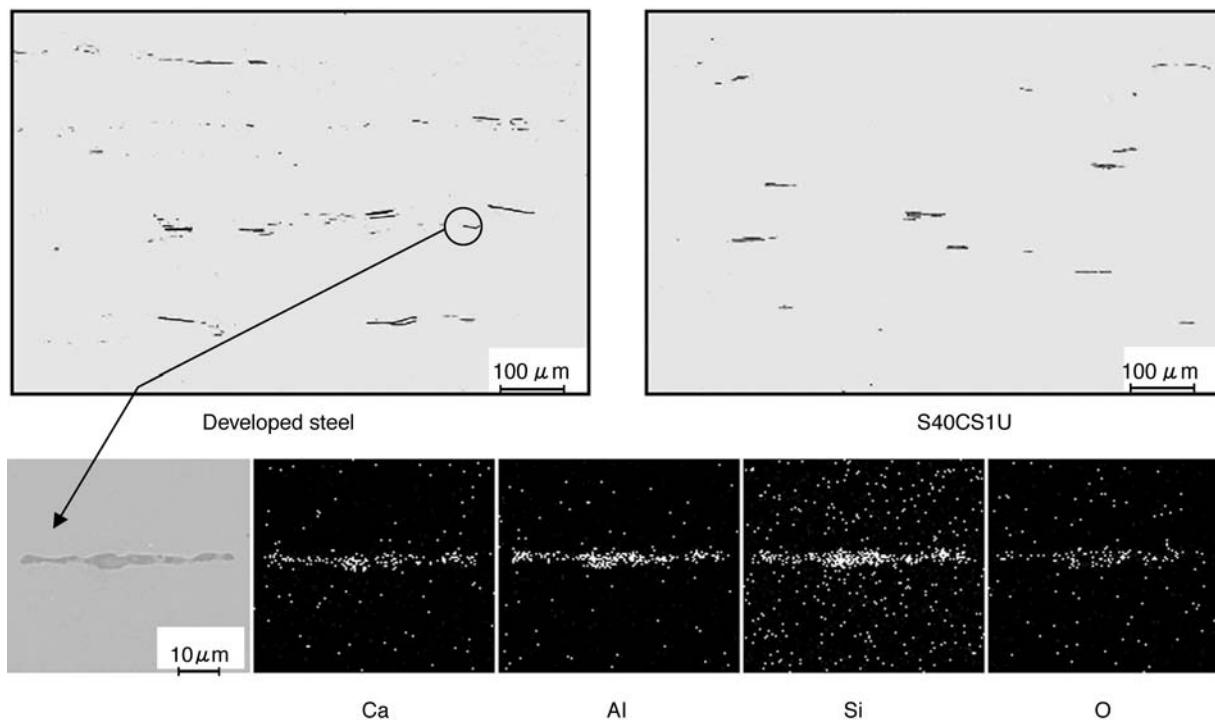


Fig. 8 Distribution of non-metallic inclusions and oxide inclusion image by EPMA

3.1.3. Chip frangibility

The effect of the shape and dispersion of non-metallic inclusions on chip frangibility for the developed steel and comparative steel were compared. The crankshaft machining operation with the least favorable conditions for chip frangibility was used for the evaluation, Fig. 9 showing the machining geometry and conditions.

In order to evaluate the chip frangibility, ten of the larger chips generated by cutting to a total depth of 6 mm were recovered and their weight was measured. Photographs were taken of longitudinal sections with a 100-power microscope and measurements were made of the number of non-metallic inclusions in eight visual fields in order to evaluate the shape and dispersion of the non-metallic inclusions. Figure 10 shows the relationship between the chip weight and number of non-metallic inclusions. An index was generated for the number of non-metallic inclusions, whereby a level of 1 represents a chip that can be ejected automatically. It is

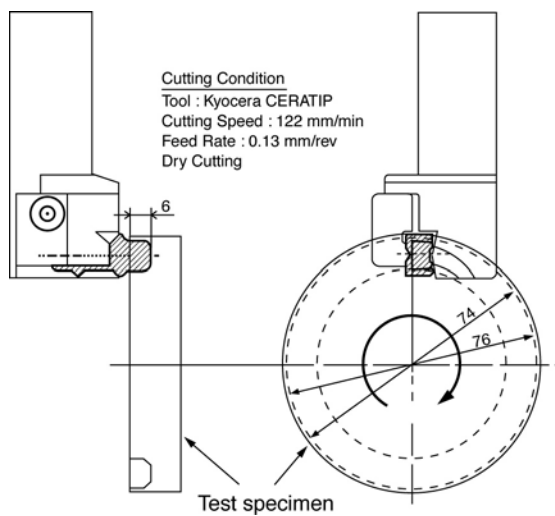


Fig. 9 Geometry of cutting test specimen and cutting condition

apparent that the chip weight decreased as the number of non-metallic inclusions increased, thus improving the chip frangibility. The chemical compositions of the developed steel and comparative steel were similar to those of S40CS1U, Fig. 8 showing the only major difference to be in the distribution of sulfide-type non-metallic inclusions. It can be concluded that the fine dispersion of sulfide-type non-metallic inclusions made the main contribution to favorable chip frangibility for the developed steel.

3.1.4. Mechanical properties

The mechanical properties of the developed steel and conventional steel are shown in Table 3. The developed steel has a tensile strength (TS) equal to that of the conventional steel, while the yield strength (YP), elongation (EL), and Charpy impact strength of the developed steel are approximately 20–30% lower than the figures for the conventional steel. Nevertheless, the Charpy impact strength ratio (C/L) in the cross-sectional direction (C) and longitudinal direction (L), which is an index used for Pb-free free-cutting steel, is 0.35 for the developed steel and 0.31 for the conventional steel. The anisotropy of the developed steel is thus equal to that of the conventional steel.

Table 3 Mechanical properties of developed and conventional steels

	Direction	TS (MPa)	YP (MPa)	EL (%)	Impact value (J/cm ²)	Impact value Ratio C/L
Developed steel	L	660	311	23.8	52.0	0.35
	C	638	303	10.9	18.4	
Conventional steel	L	699	455	28.6	76.0	0.31
	C	704	448	14.6	23.6	

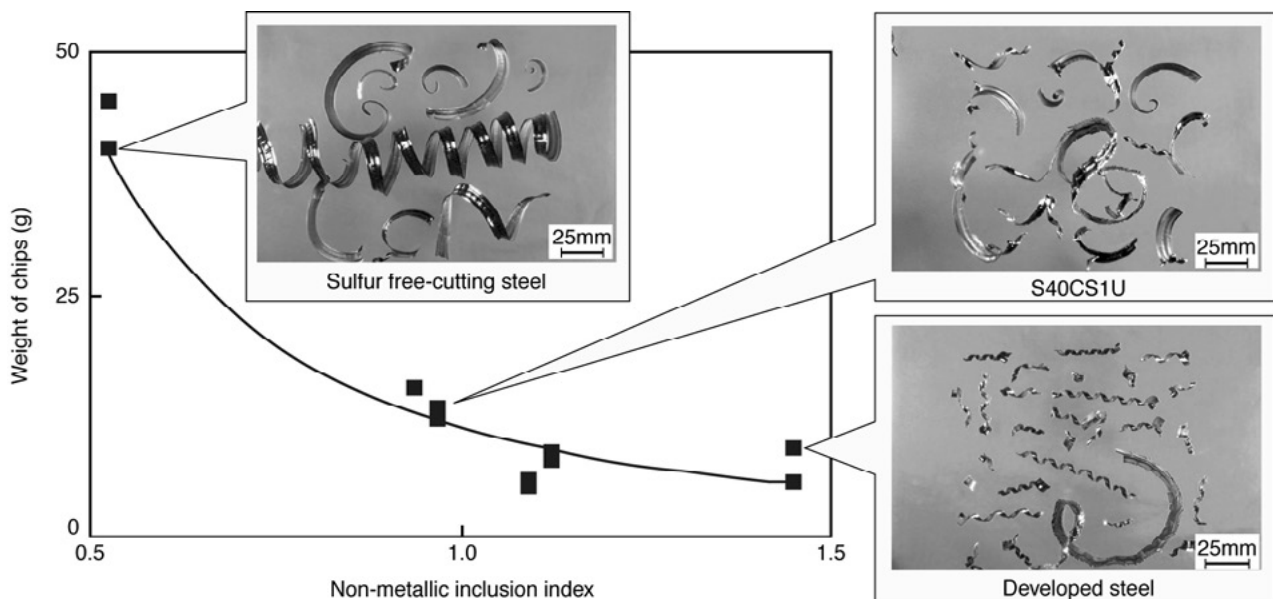


Fig. 10 Influence of non-metallic inclusion index on weight of chips generated by lathe turning

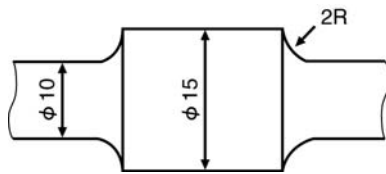


Fig. 11 Geometry of rotating-bending fatigue test specimen

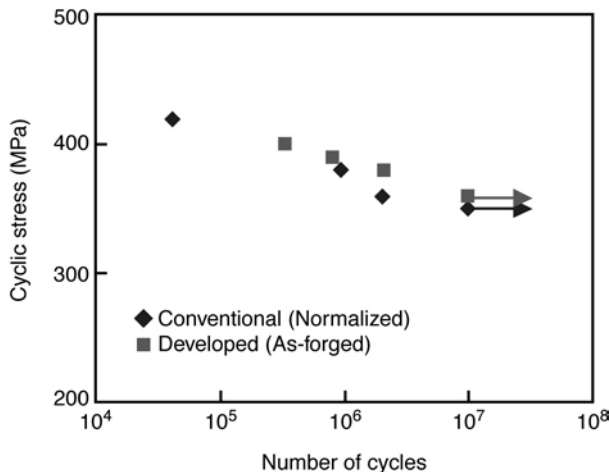


Fig. 12 Result of rotating-bending fatigue test

3.1.5. Rotating-bending fatigue strength

The developed steel and conventional steel were subjected to a rotating-bending fatigue test, each test specimen first being salt-bath nitrocarburized at 580 °C for 70 minutes. The test specimen geometry is shown in Fig. 11, and the test results are shown in Fig. 12. It is apparent that the developed steel has the same fatigue strength as the conventional steel.

3.2. Crankshaft Testing

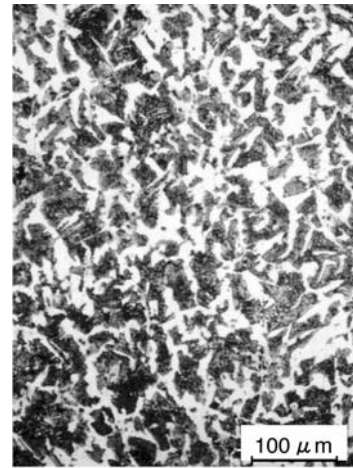
The developed steel and conventional steel were subjected to comparative tests of their properties. The crankshaft for an in-line 4-cylinder engine shown on the left in Fig. 5 was used as the specimen, the developed and conventional steel materials being produced as described in section 3.1. The machining processes shown in Fig. 1 were used on both materials, except that the normalizing process was omitted for the developed steel.

3.2.1. Microstructure and hardness of materials air-cooled after hot forging

Figure 13 shows the microstructure of the crankshaft air-cooled after hot forging. The target hardness of HRB89 and the desired fine microstructure were obtained with hot forging and air cooling alone.

3.2.2. Machinability

A comparison was made of the frangibility of chips from each of these materials generated by lathe turning during the mass production process. The chips from the developed steel and conventional steel are shown in Fig. 14. The chip weight, measured by the method described in section 3.1.3, was 5.5 g for the developed steel and 8.2 g for the



In-line four type crankshaft HRB 89

Fig. 13 Microstructure of developed steel after hot forging



Developed steel



Conventional steel

Fig. 14 Chips of developed and conventional steels generated by lathe turning

conventional steel. The developed steel therefore achieved more favorable chip frangibility than the conventional steel, as well as machinability equal to that of the conventional steel in the drilling, grinding, and gear-cutting processes. In addition, the developed steel allowed lathe turning under the same conditions and tool change criteria the same as those for the conventional steel.

3.2.3. Nitrocarburized properties

Each crankshaft sample was salt-bath nitrocarburized at 580 °C for 70 minutes, and the resulting properties are shown in Table 4. The surface hardness, practical nitrocarburized case depth, and compound layer depth of nitrocarburizing were similar for both the developed steel and conventional steel samples.

Table 4 Comparison of nitrocarburized properties between developed and conventional crankshafts

		Developed steel	Normalized conventional steel
Compound layer depth after lapping	mm	0.008	0.008
Surface hardness	Hmv	630	639
Practical case depth	mm	0.35	0.26

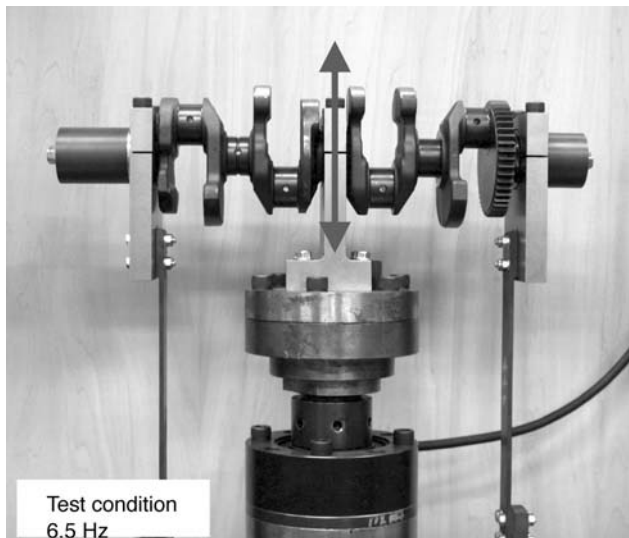


Fig. 15 Bending fatigue test method for crankshaft

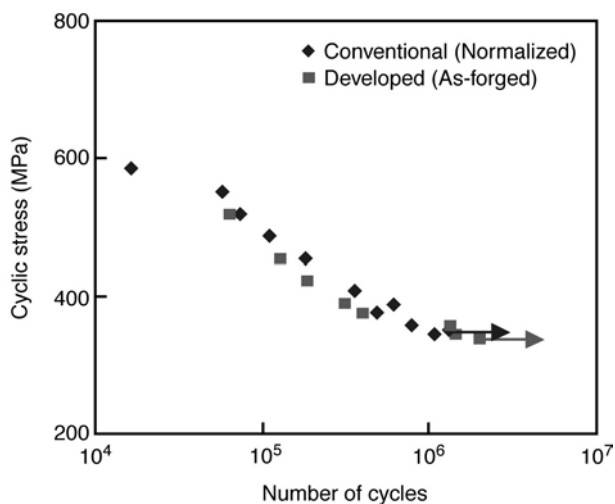


Fig. 16 Result of bending test for crankshafts

3.2.4. Bending fatigue strength

A comparison between the bending fatigue strength of the developed steel and conventional steel crankshafts was performed by the method shown in Fig. 15. The journals at both ends of the crankshaft were held in place, and the center journal was subjected to completely reversed bending stress. A strain gauge mounted on the fillet portion of the center journal was used to measure the resulting stress. As shown in Fig. 16, the bending fatigue strength of the developed steel was equal to that of the conventional steel.

4. Conclusion

The technique of omitting normalizing after forging, which has already been applied to the mass production of automobile crankshafts, was optimized for application to motorcycle crankshaft steel. This steel was at the same time treated to provide Pb-free free-cutting steel. The distinctive features of this steel are summarized below.

- (1) Omission of normalizing after forging was enabled by adjusting the carbon, manganese, and nitrogen contents of the steel.
- (2) Adjustment of the type, quantity, shape, and dispersion of non-metallic inclusions in calcium-sulfur free-cutting steel to appropriate values made it possible to achieve a chip frangibility equal to that of conventional Pb-sulfur free-cutting steel. It also made it possible to maintain the same machining conditions and tool change criteria as those used conventionally after making the steel Pb-free.
- (3) The developed steel also has nitrocarburized properties and fatigue strength equal to those of conventional Pb-sulfur free-cutting steel when used to produce a crankshaft.

This project sought to optimize the composition of steel for crankshaft use in motorcycles and automobiles. A Pb-free composition was attained without detriment to the various properties of the steel, and this steel has been adopted for mass production in the 2002 model year CBR954RR motorcycle and the lightweight That's automobile.

5. Acknowledgements

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