

Development of Pb-free Free-cutting Microalloyed Steel with High Toughness for Crankshafts of Small Multipurpose Engines

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ABSTRACT

A ferrite-pearlite type microalloyed steel has been developed for use in the crankshafts of small multipurpose engines. Although the thermal refining process after hot forging has been eliminated, this steel possesses equivalent strength and toughness to thermally refined steel, and can also be induction hardened. The design of the alloy sought to ensure toughness by increasing the ratio of ferrite in the structure of the steel and refining the structure through the use of intragranular ferrite and, at the same time, to ensure strength by strengthening of solid solution and precipitation strengthening and increasing hardenability while still employing a carbon content within the range enabling induction hardening. In addition, conditions for the temperature of heating during hot forging and for cooling after hot forging were established to control coarsening of the structure and optimize the characteristics of the alloy. At the same time, the design ensured that while no lead was added, a level of machinability equivalent to that conventional free-cutting steel with added lead was achieved. This has reduced the cost of crankshaft manufacture by eliminating the thermal refining process and done away with the necessity of adding lead, an environmentally harmful substance.

1. Introduction

Steel that provides the required strength even when the quenching and tempering process (thermal refining process) after hot forging has been eliminated is called microalloyed steel. The basic microalloying method is to add trace amounts of vanadium (V) or other elements to normal structural steel and perform precipitation strengthening using carbonitrides to obtain a strength equivalent to thermal refined steel^{(1) - (6)}. Steel produced using only this mechanism is called basic (ordinary) microalloyed steel.

However, the structure of this steel is the coarse ferrite-pearlite structure after hot forging, so the toughness is much lower than thermal refined steel which has a fine structure. For this reason application is limited to the connecting rods within engines and other locations that do not require high toughness.

High-toughness microalloyed steel is applied to automotive suspension components and other locations that require high toughness. In this case the toughness is increased by methods such as reducing the carbon content and increasing the alloy content^{(1),(3) - (6)}, suppressing structural coarsening during hot forging through the use of precipitated particles^{(1),(4)}, and refining the structure by precipitation of intragranular ferrite^{(1),(3) - (5),(7)}. In addition, high-strength, high-toughness microalloyed steel has also been developed by adding the appropriate amounts of various alloy elements to steel with an extremely low to medium carbon content and then performing only natural cooling after hot forging to obtain a bainite structure^{(1),(4),(8) - (11)}.

In this manner, microalloyed steel with various characteristics has been developed thus far, and are being used in a wide range of fields from the perspective of reducing costs, shortening lead times and conserving energy, etc^{(2),(12)}.

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2. Using Microalloyed Steel for the Crankshafts of Small Multipurpose Engines

Unlike motorcycle and automobile engines, the crankshafts of small engines mounted in power products (hereafter, multipurpose engines) require not only strength but also high toughness. In power products such as the lawn mower shown in Fig. 1, the working part is sometimes connected directly to the crankshaft without a belt, clutch or other buffer mechanism, so a large impact load may be applied directly to the output shaft. In addition, induction hardening is generally performed on the pin, journal and other parts of multipurpose engine crankshafts in order to increase the wear resistance and the fatigue strength. For these reasons, the crankshafts used for these types of applications have thus far used S48C or other structural carbon steel that has been thermally refined after hot forging to provide the required strength and toughness.

When thinking of changing these parts to microalloyed steel, induction hardening can be performed on basic microalloyed steel, but as mentioned above this steel has lower toughness which makes it unsuitable. Conversely, the composition of high-toughness microalloyed steel is adjusted from low to medium carbon content to ensure toughness, so sufficient hardness of induction hardened parts cannot be obtained. Thus, existing microalloyed steels cannot be applied.

Therefore, this research not only designed new alloy contents, but also comprehensively studied the various process control conditions during hot forging. This resulted in the development of a new microalloyed steel that has the strength and toughness required for the crankshafts of multipurpose engines, and which also allows induction hardening.

In addition, the environmentally harmful substance lead was added to conventional structural steel to enhance machinability, but this research succeeded in eliminating the need for lead without deterioration of characteristics. These details are described below.

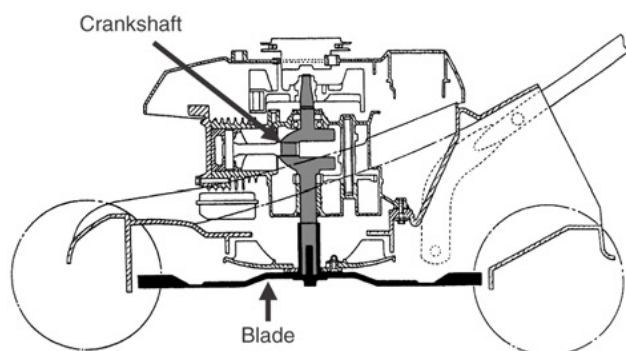


Fig. 1 Layout of lawn mower

3. Methods for Achieving Targets

3.1. Alloy Design

The hardness and tensile strength and the hardness of induction hardened parts of ferrite-pearlite steel are proportional, and the toughness is inversely proportional mainly to the carbon content. The induction hardened parts of multipurpose engine crankshafts require a hardness of HRC50 or more, so the lowest possible carbon content within the range that satisfies this hardness was used.

In addition, methods that refine the structure are effective

for ensuring toughness. Therefore, the above-mentioned method of refining the structure by precipitation of intragranular ferrite was employed for the newly developed steel. This method refines the structure and thus increases toughness by precipitating ferrite around a core of MnS that is finely dispersed in large quantities throughout the structure even within the former austenite grains during cooling after hot forging. For this reason, the Mn and S contents were increased compared to basic steel.

On the other hand, reducing the carbon content lowers the steel strength, but this can be compensated by strengthening the steel. This was done by increasing the Si which strengthens the ferrite by solid solution, adding a trace amount of V for precipitation strengthening, and also enhancing the hardenability with Mn and Cr. The hardness and tensile strength of ferrite-pearlite microalloyed steel that contains these elements is known to correlate with the carbon equivalent C_{eq} expressed by the following equation⁽¹²⁾.

$$C_{eq} = C + \frac{1}{10}Si + \frac{1}{5}Mn + \frac{5}{22}Cr + 1.65V - \frac{5}{7}S$$

A stable tensile strength equivalent or greater than that of S48C thermal refined steel, which was used as the comparison material, can be obtained by adjusting the C_{eq} value to 0.73 or more.

The above-mentioned MnS exhibits the same machinability effects as the lead in free-cutting steel with added lead⁽¹³⁾⁻⁽¹⁶⁾, so it was decided to use MnS.

Table 1 shows the chemical composition of the newly developed steel.

Table 1 Chemical composition of newly developed steel

(Wt.%)								
C	Si	Mn	P	S	Cr	V	Pb	C_{eq}
0.33	0.68	1.33	≤ 0.020	0.055	0.20	0.08	—	0.80

3.2. Forging Process Conditions

The carbon content of the newly developed steel is slightly higher than that of existing high-toughness microalloyed steel in order to ensure induction hardening performance. However, this is disadvantageous for ensuring toughness, so in addition to refining the structure by designing the alloy as mentioned above, it was also necessary to prevent coarsening of the structure by controlling the process conditions during hot forging.

The first condition is the material heating temperature. Here, a lower heating temperature is better to prevent coarsening of the austenite grains. The structure of normal thermal refined steel can be adjusted in a later process, so a temperature of around 1 250 °C is often used in consideration of forgeability, die life and other factors. However, the structure of microalloyed steel is determined in the forging process, so a temperature of 1 150 to 1 200 °C is set, which is the lowest possible within the range that does not have a significant effect on the die life.

Next, after forging, the residual heat of the work causes the austenite to recrystallize and promotes grain growth, so it is necessary to cool the material quickly through the temperature range to transformation temperature to prevent coarsening of the structure. For this reason, forced (fan) cooling was introduced. Figure 2 shows the fan cooling conditions on a conveyor after hot forging. The cooling speed was investigated and determined as follows.

Of the various uses for multipurpose engines, the one with the potential to apply the harshest impact load to the crankshaft is that of the previously shown lawn mower. Based on the results of low-temperature blade-hit tests using an actual lawn mower as described hereafter, the shape specifications of the crankshaft output shaft that is directly connected to the lawn mower blade, and other factors, the impact value required for the crankshaft of a multipurpose engine was set at 40 J/cm² or more at -40 °C. On the other hand, the pearlite grain size and the impact value of the newly developed steel have the relationship shown in Fig. 3. This shows that the required impact value can be satisfied with sufficient margin by ensuring a pearlite grain size of No. 5 or more. Various cooling tests were conducted in the actual processes based on these observations, and the results showed that a cooling speed setting of 50 to 80 °C/minute



Fig. 2 Fan cooling after hot forging

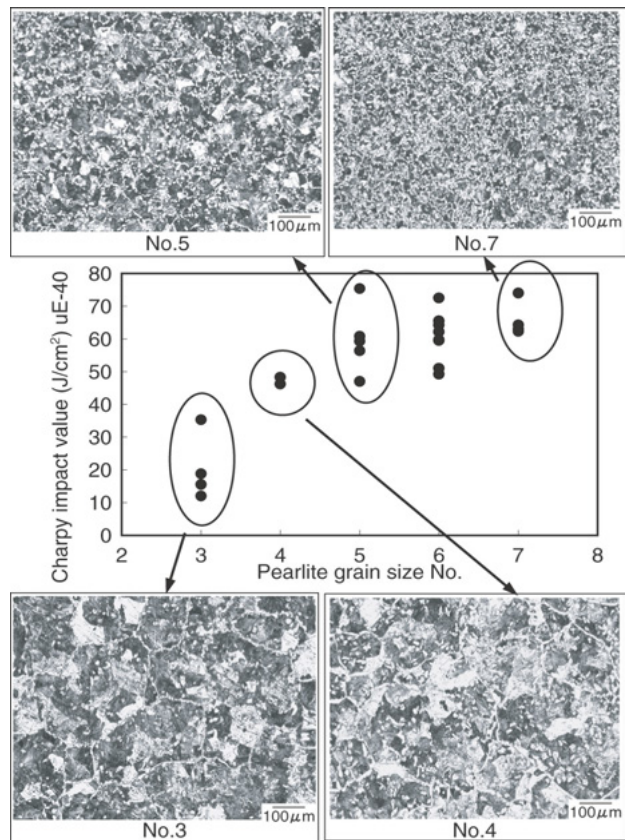


Fig. 3 Relation between pearlite grain size and Charpy impact value

between 800 °C and 550 °C is optimum for obtaining the above impact value.

These results are summarized in Fig. 4.

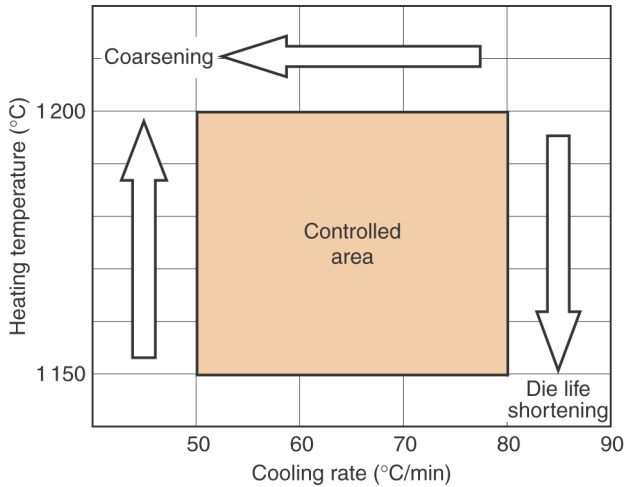


Fig. 4 Hot forging conditions

4. Test Results

4.1. Material Test Results

4.1.1. Charpy impact test

Figure 5 shows the results of Charpy impact tests conducted at various temperatures using JIS type 3 test pieces cut from actual crankshafts. This shows that the newly developed steel provides an impact value of 40 J/cm² or more even at -40 °C. In addition, when the test pieces were induction hardened to a depth of 1 to 3 mm in the U-notch portion, the results for the newly developed steel exceeded the impact value of the comparison material S48C thermal refined steel in all temperature areas. This is thought to be because the newly developed steel has a lower carbon content and thus a lower quenching hardness than the comparison material.

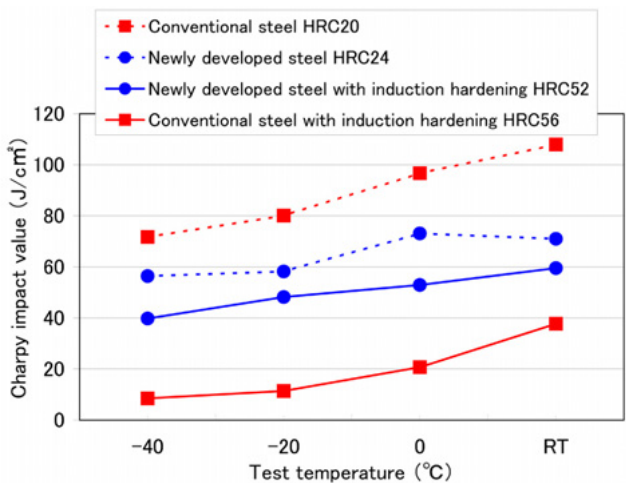


Fig. 5 Charpy impact value of newly developed and conventional steels

4.1.2. Other mechanical properties

Table 2 shows the results of material tests of other properties such as tensile strength and fatigue strength for the newly developed steel and the comparison material. Values equivalent to those for the comparison material were obtained for all items. In addition, the newly developed steel exhibited roughly the same amount of wear as the conventional steel in pin-on-disk type wear tests.

Table 2 Mechanical properties of newly developed and conventional steels

	Newly developed	Conventional
Hardness (HRC)	20	20
Tensile strength (MPa)	813	764
Yield point (MPa)	549	549
Elongation (%)	19	23
Rotating-bending fatigue strength (MPa)	412	372

4.2. Crankshaft Test Results

4.2.1. Low-temperature blade-hit tests

Impact tests were performed by assembling crankshafts into actual lawn mowers, and having a steel rod sprung up from the ground surface to collide with the lawn mower blade in an operating condition at -15°C . Figure 6 shows an example of the results. Like the comparison material, the newly developed steel experienced no output shaft breakage, and the bending amount was also similar. These could be considered excellent results.

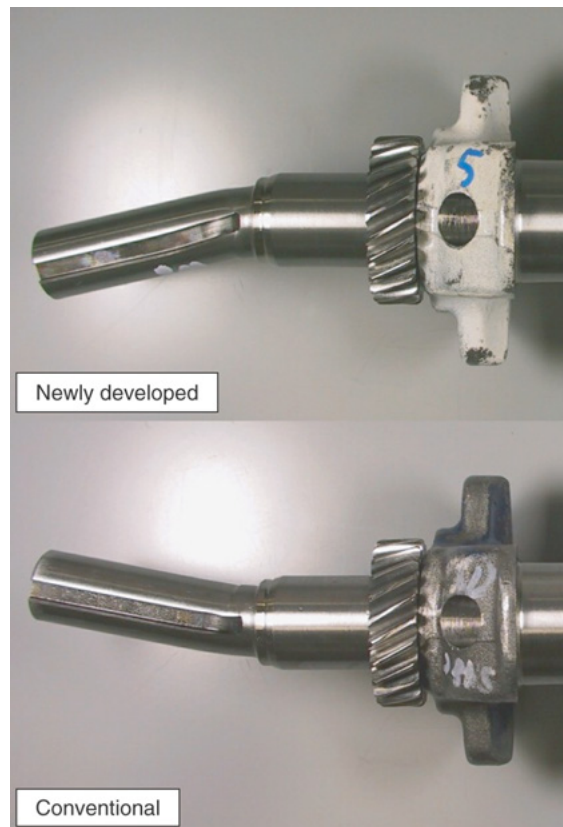


Fig. 6 Result of low temperature blade-hit test for crankshaft

4.2.2. Induction hardening ability

The pin portion of a crankshaft was induction hardened using actual mass production facilities, and the hardness at different depths was measured. Figure 7 shows the results, and confirms that the newly developed steel satisfies the quenching surface hardness of HRC50 or more required by the crankshafts of multipurpose engines, and that the hardening depth was also equivalent to the comparison material. Thus, there are no concerns with the hardening ability.

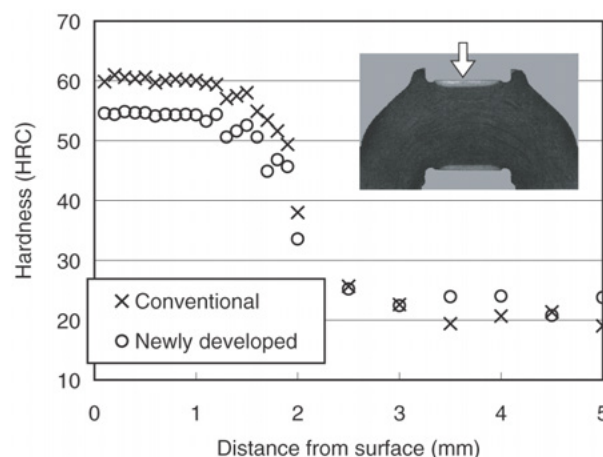


Fig. 7 Hardness of crank pin surface after induction hardening

4.2.3. Other tests

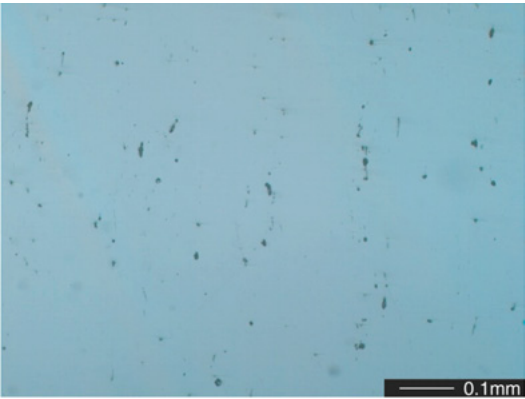
Table 3 shows the results of crankshaft fatigue tests. Both the bending fatigue tests and the torsion fatigue tests are completely reversed stress tests. Like the material test results, results roughly equivalent to those for the comparison material were obtained for each item. In addition, the newly developed steel was confirmed to satisfy the standard values of all confirmation items in the same manner as the conventional steel in various durability tests using actual engines.

Table 3 Result of various fatigue tests for crankshaft

		Newly developed	Conventional
Bending fatigue strength of crank pin (MPa)	Without induction hardening for fillet	402 (HRC24)	402 (HRC20)
	With induction hardening for fillet	647 (HRC52)	666 (HRC60)
Torsion fatigue strength of power take-off shaft (MPa)		182 (HRC20)	106 (HRC20)

4.3. Machinability

Figure 8 shows the free-cutting structure distribution formats for the newly developed steel and the comparison material. This shows that the MnS in the newly developed steel is distributed in a similar format as the Pb in the comparison material.



(a) Newly developed steel (MnS)



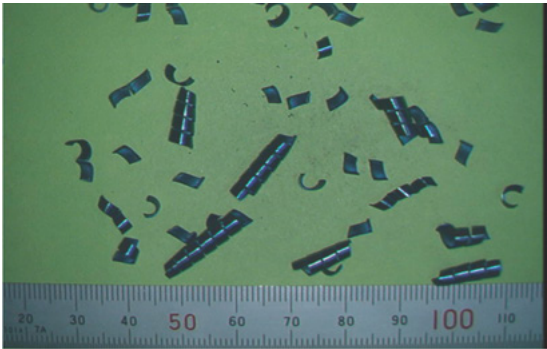
(b) Conventional steel (Pb)

Fig. 8 Distribution of inclusions

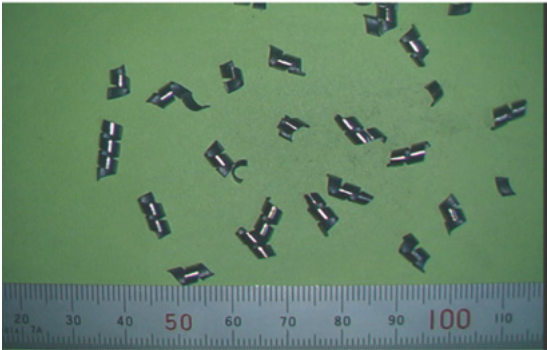
Tests were conducted to confirm the bite machinability and drill machinability of both steels under the same conditions. Table 4 shows the amount of tool wear, and Figs. 9 and 10 show the respective lathe turning and drilling chip shapes at that time. The newly developed steel showed a lower amount of tool wear than the comparison material, which is advantageous. The chips produced from the newly developed steel had a shape that was slightly more difficult to handle than the comparison material, but this difference was not of a degree that would be of any concern in an actual mass production machining line.

Table 4 Comparison of amount of tool wear between newly developed and conventional steels

	Newly developed	Conventional
Amount of wear of tip flank after 30 min. turning (mm)	0.07 (HRC19.4)	0.18 (HRC21.2)
Amount of wear of drill flank after drilling 200 holes (mm)	0.08 (HRC22.6)	0.09 (HRC20.1)

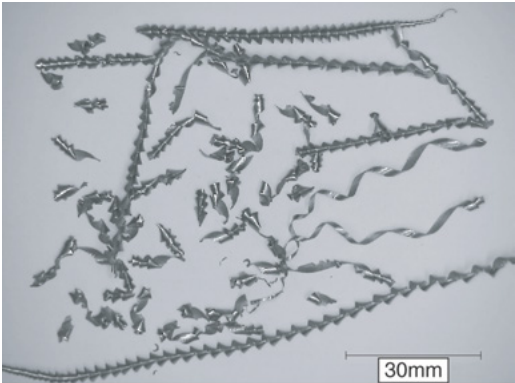


(a) Newly developed steel

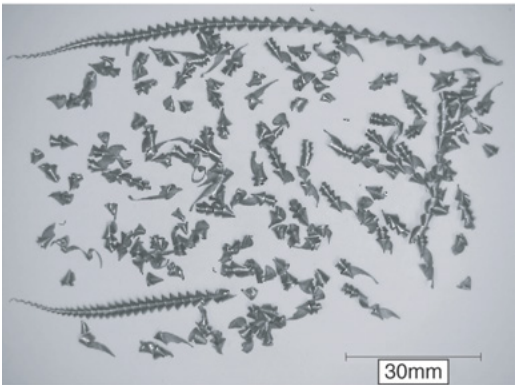


(b) Conventional steel

Fig. 9 Chips of newly developed and conventional steels produced by 30 min. of lathe turning



(a) Newly developed steel



(b) Conventional steel

Fig. 10 Chips of newly developed and conventional steels produced by drilling 200 holes

5. Conclusion

- (1) A microalloyed steel was developed by comprehensively studying the alloy content and the forging conditions. This new microalloyed steel provides the same strength and toughness as conventional thermal refined steel even though the thermal refining process after hot forging has been eliminated, and it can also be induction hardened.
- (2) The need to add lead, which is an environmentally harmful substance, has been eliminated while still maintaining a level of machinability equivalent to conventional free-cutting steel with added lead.

This newly developed steel is currently being applied to mass production as the crankshaft material for professional use multipurpose engines with a displacement of 160 to 390 cm³.

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