

Development of Light Weight Connecting Rod

Zenji IIDA*
Shigeru SUZUKI*

Kentaro TAKADA*
Chikashi SATO*

ABSTRACT

The conventional middle carbon non-heat-treated steel used in connecting rods has been used as a base in the development of a new material. High fatigue strength has been achieved by increasing the toughness of the ferrite, which tends to act as a crack origin, while optimal control of the reduction of toughness achieved through addition of Ti has been effective in enabling fracture splitting of the material.

Connecting rods produced using the new steel demonstrate 30% higher fatigue strength than connecting rods produced from conventional non-heat treated steel, and possess stable fracture splitting characteristics. In addition, the new connecting rods show identical strength to connecting rods made of the conventional material, but are 13% lighter.

1. Introduction

It is becoming increasingly necessary to reduce the weight of automotive parts to achieve both increased power and fuel economy. Because of their rotary motion, the mass of connecting rods (hereinafter referred to as connrods) affects engine layout and performance, and the achievement of size and weight reductions in these parts is therefore a particular requirement. In addition, reducing the weight of connrods can be expected to lead to reductions in the weight of other parts.

Titanium and aluminum alloys have been employed to reduce the weight of the connrods in certain sports cars. However, the cost of these lightweight materials is prohibitive⁽¹⁾, and non-heat-treated steel is generally used in the production of connrods for mass-market vehicles; this steel is strengthened to enable weight savings to be achieved⁽²⁾.

Fracture splitting of the connrod big end has recently been increasingly used as a manufacturing method in the United States and Europe. Figure 1 shows a conventional connrod and a fracture splitting connrod, and Fig. 2 shows the respective production processes. The use of fracture splitting enables the number of steps in the production process to be reduced, and does away with the need for pins to align the rod and cap. It also enables the bolt tightening pitch to be reduced, thus reducing the size and weight

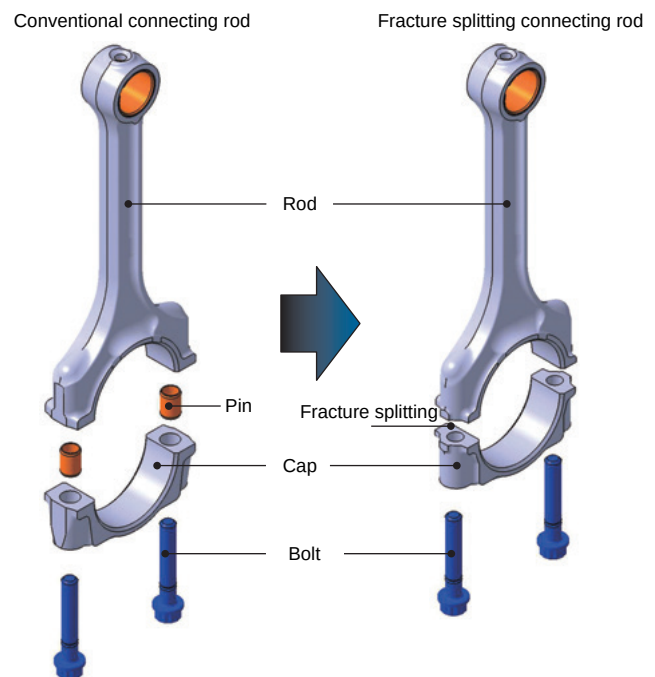


Fig. 1 Comparison of conventional connecting rods and fracture splitting connecting rods

* Tochigi R&D Center

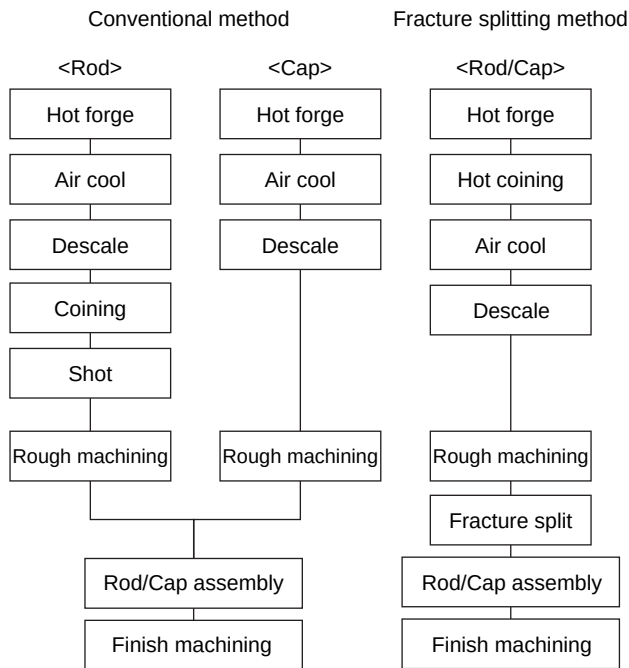


Fig. 2 Production process of connecting rod

of the connrod. However, the fatigue strength of the C70S6 steel (DIN standard) used in the fracture splitting process is identical to that of conventional middle carbon non-heat-treated steel, making it difficult to achieve further weight savings. The project discussed in this paper therefore developed a stronger steel for use in the fracture splitting process, to enable the production of a smaller, lighter fracture splitting connrod.

2. Development Goals

2.1. Fracture Splitting

The following are essential factors in the achievement of stable quality in the fracture splitting process:

- (1) Stable fracture split surface characteristics
- (2) Fracture splitting with a stable cracking force

One of the goals of the development project was to enhance these parameters against those of the C70S6 steel conventionally used in fracture splitting.

2.2. High Strength

Reducing the weight of the connrods by increasing material strength could be expected to contribute to increasing the seizure limit of the crank bearings, increasing the strength margin by reducing the load on the crank, and reducing engine vibration and friction. Past results suggested that a weight reduction of 10% or more would be necessary to ensure the achievement of these benefits⁽²⁾.

A weight reduction of 10% against the current non-heat-treated steel was therefore established as a development target.

Strength can be increased both by increasing fatigue strength and by increasing yield strength. Given the type of engines in which the connrods would be employed, increasing fatigue strength was judged to be most effective in achieving weight savings, and this was therefore the focus of the project.

Table 1 Chemical composition for impact test

(mass %)							
C	Si	Mn	P	S	Cr	Ti	V
0.30	0.70	0.80	0.004 ~ 0.072	0.055	0.20	—	0.200
0.30	0.70	0.80	0.060	0.060	0.20	0 0.190	—

3. Composition of Material

3.1. Concept of Steel under Development

Using conventional middle carbon non-heat-treated steel as a base, the composition of the new steel was designed on the basis of the following concepts, with consideration of increased hardness from the perspective of machinability:

- (1) Reduced toughness
 - Addition of elements to reduce toughness of ferrite, because ferrite has high toughness in ferrite-pearlite structures
- (2) Increased fatigue strength
 - Solid solution strengthening and precipitation strengthening of ferrite, which tends to act as a point of origin for cracks

3.2. Composition Design for Reduced Toughness

Increasing the strength and hardness of the ferrite in ferrite-pearlite non-heat-treated steel is an effective means of reducing the toughness of the ferrite. V is already widely used as an additive to increase the strength of the ferrite⁽³⁾, and the addition of Ti has been reported as a means of strengthening ferrite and achieving optimum toughness⁽⁴⁾. P is also known to act as an impurity and make the grain boundary brittle, reducing the toughness of the ferrite. Tests were therefore conducted using steel with added V, to which P was added in quantities of between 0.004 and 0.072%. Ti was also added in quantities of between 0.10 and 0.19%. The changes in toughness with different quantities of P and Ti were then measured. Table 1 shows the compositions of the steels used in tests. After being heated to 1 250 °C and left to cool to reproduce the conditions employed in hot forging, JIS Z 2202 V notch impact test pieces were formed from the materials. These impact tests were conducted at room temperature. Figure 3 shows the effect of the addition of P, and Fig. 4 shows the effect of the addition of Ti.

Impact value declines as the amount of P and Ti is increased, and Ti is particularly effective in reducing toughness. This is believed to be because of the different precipitation morphology of the V carbonitride and Ti carbonitride precipitating in the ferrite. Figure 5 shows transmission electron microscope (TEM) images of the ferrite thin film in V-added steel and Ti-added steel⁽⁴⁾. In the V-added steel, tiny V carbonitrides can be observed precipitating from the ferrite. By contrast, in the Ti-added steel, there are fewer carbonitrides and they are larger. This causes dislocation loops to form around the Ti carbonitrides, which results in dislocations tending to build up when the material is deformed. Studies by K. Watari have indicated that this results in reduced toughness^{(4), (5)}.

In terms of fracture morphology, fractures occur in both steels within the grain; fractures at the grain boundary were not observed in the P-added steel. Therefore, the reduction in toughness occurring with the addition of P is believed to be the result of solid solution strengthening.

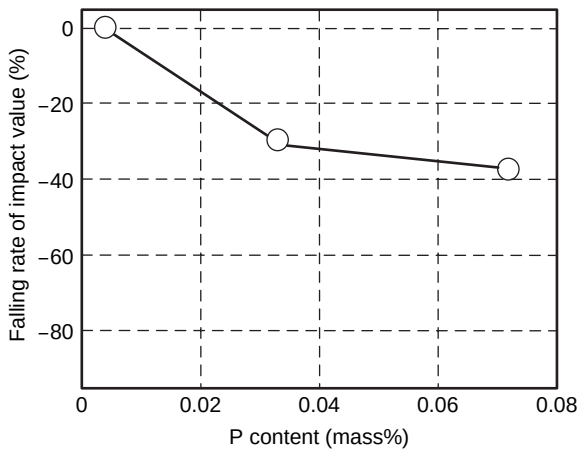


Fig. 3 Relationship between P content and impact value

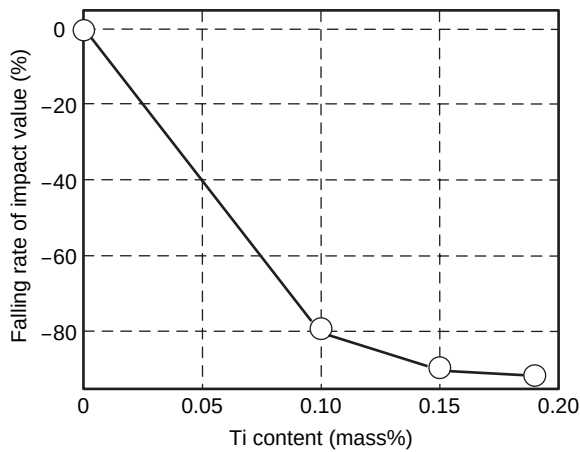


Fig. 4 Relationship between Ti content and impact value

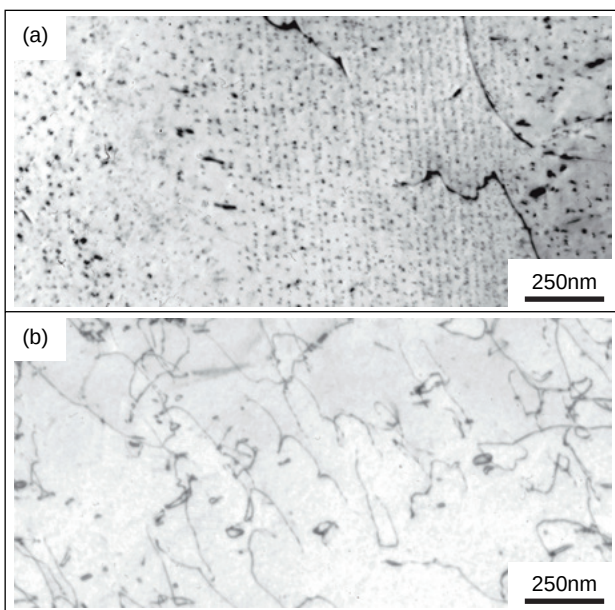


Fig. 5 TEM micrographs of (a) V added steel and (b) Ti added steel

To ensure that the toughness of the new steel was sufficiently low for stable fracture splitting, a design involving addition of both P and Ti in quantities of more than 0.04% and more than 0.15% respectively was decided upon.

3.3. Composition Design for High Fatigue Strength

To ensure adequate machinability, it is desirable that hardness does not increase despite an increase in fatigue strength. It was therefore essential to design the material to increase the endurance ratio, which expresses the ratio between tensile strength and fatigue strength.

Figure 6 shows the effect on the endurance ratio of varying the C content of a carbon structural steel from 0.1-0.6%⁽⁶⁾. This steel has a ferrite-pearlite structure; tensile strength is determined by the ratio between the volume of ferrite and the volume of pearlite, and fatigue strength is determined by the strength of the ferrite, the point of origin of cracks. Therefore, reducing the C content and increasing the strength of the ferrite can be considered to be an effective means of increasing the endurance ratio. In Fig. 6, good correlation was observed with plots of the endurance ratio of the current non-heat-treated steel and C70S6 steel, and therefore a C content lower than that of the currently used non-heat-treated steel was decided upon.

Ferrite can be strengthened by both precipitation strengthening and solid solution strengthening. Figure 7 shows the correlation between increases in hardness and increases in fatigue strength when the composition of different alloys and elements is varied in

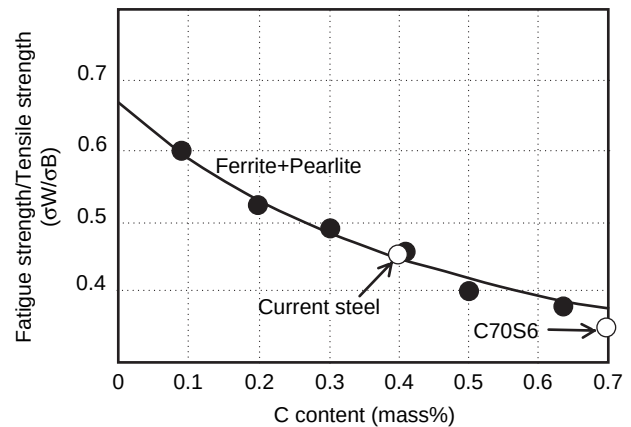


Fig. 6 Relationship between C content and $\bar{\sigma}_W/\bar{\sigma}_B$

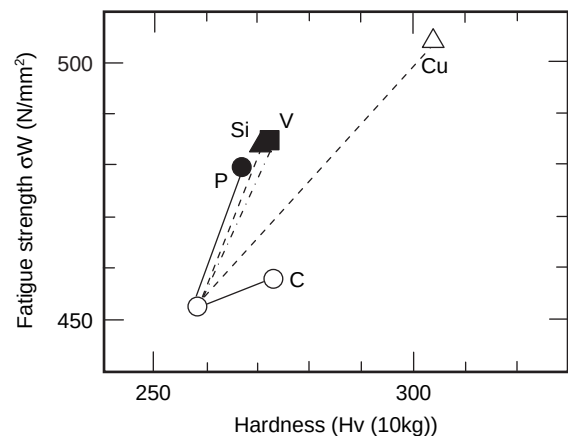


Fig. 7 Relationship between hardness and fatigue strength

middle carbon non-heat-treated steel⁽⁷⁾. These results indicate that solid solution strengthening by the addition of P and Si and precipitation strengthening by the addition of V would be effective in increasing fatigue strength, without increasing hardness. Ti is also known to be a precipitation-strengthening element⁽⁸⁾.

The amounts of P and Ti to be added to the material under development had already been established, and therefore the effect of the addition of Si and V in increasing fatigue strength was studied. The steels shown in Table 2 were subjected to an Ono-style rotating bending fatigue test. JIS Z 2274 1 test pieces were manufactured after the steel had been heated to 1 250 °C and cooled to simulate hot forging conditions.

Figure 8 shows the relationship between Si and V content and fatigue strength. Increasing the V content is highly effective in increasing fatigue strength, while increasing the Si content has little effect on this parameter. Ferrite hardness was studied to determine the reason for this. Figure 9 shows the relationship between Si and V content and ferrite hardness. Increased V content has a noticeable effect in increasing ferrite strength, while increasing Si content does not affect ferrite strength. This is believed to be because it is difficult for the Si to exert a solid solution strengthening effect on the ferrite, because it has already undergone precipitation strengthening by Ti and V carbonitrides. The precipitation strengthening effect of adding V is believed to depend on the respective precipitation strengthening effects of the different

Table 2 Chemical composition for fatigue strength

(mass %)								
No.	C	Si	Mn	P	S	Cr	Ti	V
1	0.28	0.53	0.72	0.045	0.100	0.14	0.154	0.159
2	0.28	0.56	0.73	0.054	0.090	0.17	0.173	0.168
3	0.31	0.68	0.74	0.058	0.066	0.15	0.184	0.199
4	0.32	0.19	0.60	0.035	0.063	0.15	0.179	0.199
Current steel	0.39	0.45	1.05	0.010	0.110	0.09	—	0.110
C70S6	0.70	0.20	0.53	0.008	0.060	0.12	—	0.029

precipitation morphologies of Ti carbonitrides and V carbonitrides, as discussed above. The above results indicated that achieving precipitation strengthening by adding V is effective in increasing ferrite strength in Ti-added steel.

Figure 10 shows the relationship between hardness and fatigue strength in the test steel, the current non-heat-treated steel and C70S6 steel. In the test steel, with its ferrite strengthened, fatigue strength is higher than hardness.

In terms of composition design, a Si content equivalent to that of the former non-heat-treated steel was decided on, and V content was established to achieve a balance between hardness and strength.

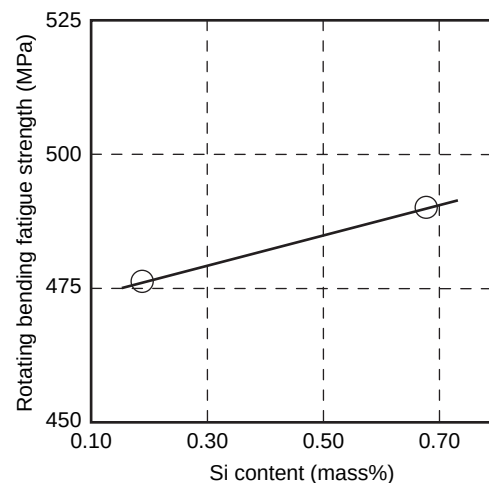
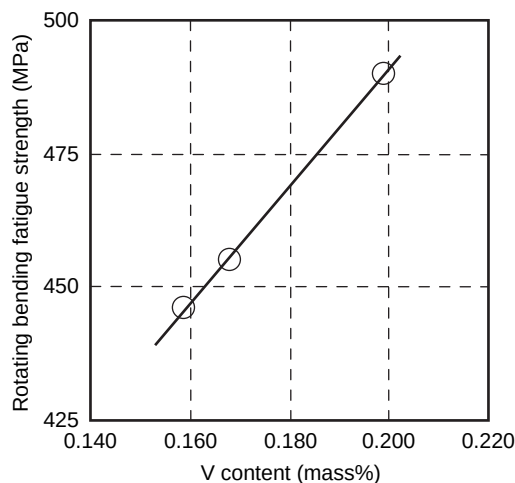


Fig. 8 Relationship between V/Si content and fatigue strength

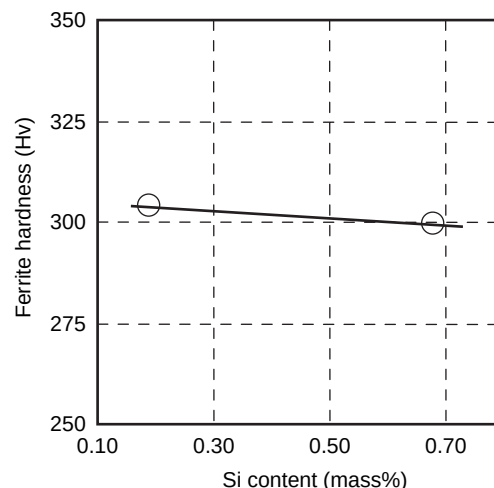
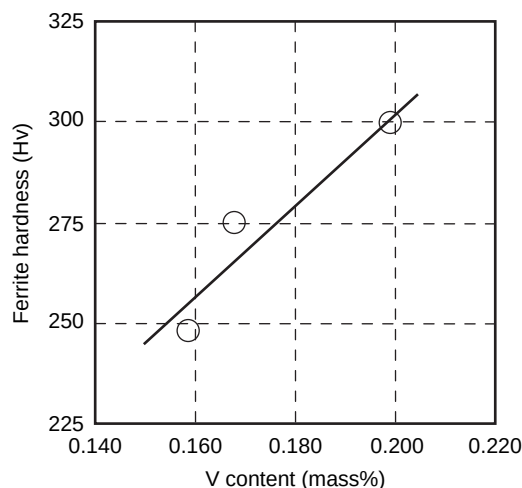


Fig. 9 Relationship between V/Si content and ferrite hardness

3.4. Composition Design

The studies discussed above led to the establishment of a composition design that would ensure ease of fracture splitting while achieving increased fatigue strength by strengthening the ferrite, and with a level of hardness ensuring machinability. Table 3 shows the composition. Figure 11 shows a comparison of the structures of the newly developed steel and C70S6 steel. The new steel has a ferrite-pearlite structure.

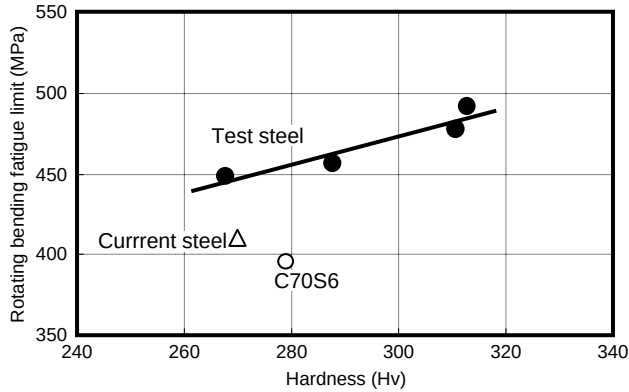


Fig. 10 Relationship between hardness and fatigue strength

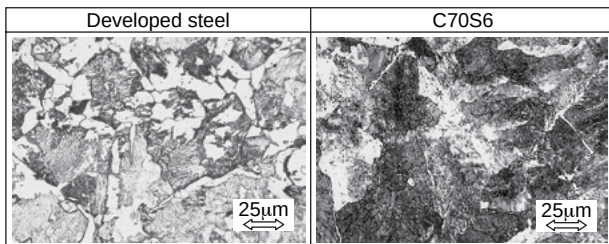


Fig. 11 Micro structure of actual connecting rod

4. Fracture Splitting Characteristics of Newly Developed Connrod

The features and characteristics required when fracture splitting a connrod big end are as follows:

- (1) Required features
 - a: Matching fracture surfaces
 - b: Stable bolt tension
 - c: Close fit between cap and rod when assembled
- (2) Required characteristics
 - a: Brittle fracture of the fracture surface
 - b: Stable level of roughness of the fracture surface
 - c: Alignment of the fracture surfaces within tolerances between parts

With regard to a, when ductile fractures occur on the fracture surface, the sections undergoing plastic deformation prevent the fracture surfaces from fitting together.

With regard to b, when the level of roughness of the fracture surface is high, the surface area increases and the bolt tension is absorbed in achieving a fit between the fracture surfaces; when the level of roughness is low, the bolt tension is low. There is therefore concern that the stability of the bolt tension will decline with

Table 3 Chemical composition of developed steel

(mass %)							
C	Si	Mn	P	S	Cr	Ti	V
0.30	0.50	0.70	0.050	0.100	0.10	0.180	0.180

variations in the level of roughness.

With regard to c, if the rod and cap are not aligned, it will not be possible to correctly fit the connrod to the crankshaft, and its function will be impaired.

4.1. Achieving Stable Roughness of the Fracture Surface

The newly developed steel was used to hot forge a connrod (rod and cap), and it was machined to the desired shape and dimensions. Following this, a notch was machined around the inner circumference of the big end for fracture splitting, and the connrod was placed in the cracking device shown in Fig. 12 for testing.

In this device, after the connrod is fixed in place, a wedge is drawn out, and a mandrel inserted into the big end is extended to produce a fracture split.

To enable quantification of the roughness of the fracture surfaces, a measurement device was used to take 3D measurements of roughness; the measured roughness was defined as surface area ratio (AR) in the following equation. Figure 13 shows the measuring area.

$$AR = \frac{SA}{PA}$$

AR : Surface area ratio

SA : Measurement area

PA : Projection area

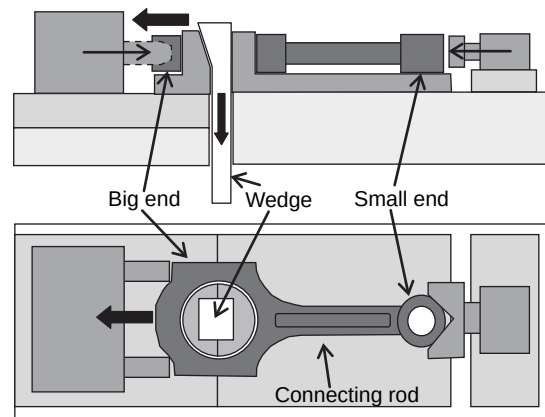


Fig. 12 Fracture splitting device

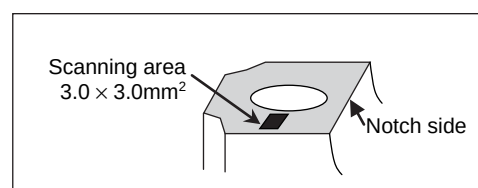


Fig. 13 Measuring area

The effect of the depth of the notch cut around the inner circumference of the big end was studied to enable the roughness of the fracture surface to be controlled. Tests were conducted using conrods with machine-cut and laser-cut notches. A conrod produced using C70S6 steel with a machine-cut notch was also tested for comparison.

As Fig. 14 shows, surface area ratio declines as the depth of the notch increases; a stable surface area ratio is achieved with a notch depth of 1 mm and higher. Results are identical for both machine-cut and laser-cut notches.

The reason for this appears to be that when the notch is shallow, the level of concentration of stress at the edge of the notch is low, and there is therefore a high level of variation in the positions at which cracks occur and in the range of direction of cracks. Because of this, the relative size of the surface area ratio increases, and the level of variation also increases. By contrast, when the notch is deep, there is a high level of concentration of stress, and the position

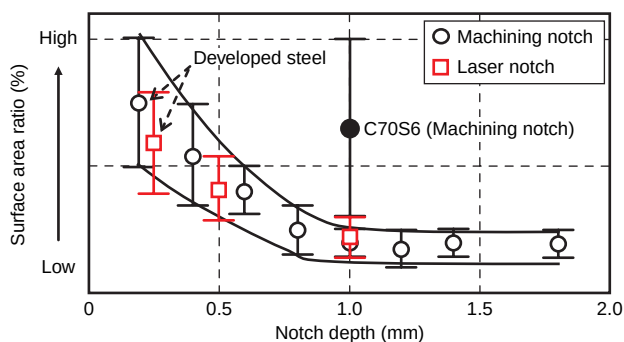


Fig. 14 Relationship between notch depth and surface area ratio

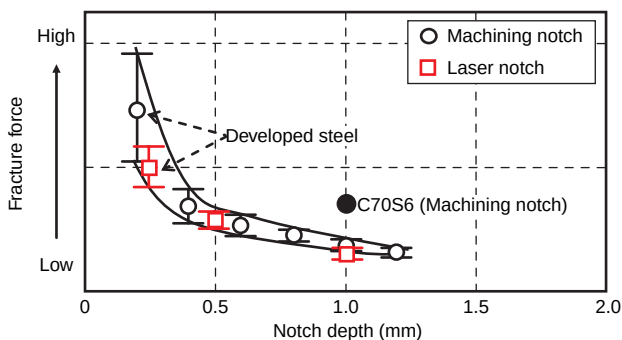


Fig. 15 Relationship between notch depth and fracture force

of occurrence of cracks and the range of directions of cracks are confined within a narrow area; the surface area ratio is relatively small, and therefore the range of variation is lower. In the newly developed steel, a stable fracture surface is obtained with a notch depth of 1 mm and higher.

Figure 15 shows the relationship between notch depth and cracking force. Cracking force is determined by monitoring the change in hydraulic pressure in the hydraulic cylinder used to extract the wedge in the cracking machine.

As was the case in the relationship between notch depth and surface area ratio, as notch depth increases, the cracking force is reduced and the level of variation becomes lower. The cracking force becomes stable with a notch depth of 1 mm or higher. The cracking force is the same whether the notches are machine-cut or laser-cut.

The newly developed steel displays lower variation in fracture surface roughness than C70S6 steel, and can be fracture split with a lower cracking force. These results indicate that the newly developed steel has superior fracture splitting characteristics to those of C70S6 steel. In addition, both machine-cut and laser-cut notches can be employed when fracture splitting the newly developed steel.

Figure 16 shows Scanning Electron Microscope (SEM) images of a fracture split surface. The surface shows a cleavage fracture from the bottom of the notch where the fracture originates to the end of the fracture.

4.2. Self-fitting of Fracture Surface

When a fracture split conrod is assembled, the cap and the rod are required to fit together tightly in alignment.

The concavities and convexities of the fracture surfaces act as a guide in self-fitting, and the control of surface roughness is therefore also important from this perspective.

5. Fatigue Strength of Developed Conrod

Because conrods are used as forged, the tension-compression fatigue strength of the I-beam cross-section of actual conrods was tested. Figure 17 shows the results of these tests. Results for a conrod manufactured from C70S6 steel using the same production process are also shown for comparison. While displaying the same level of hardness, the newly developed steel has a 30% higher fatigue strength than that of the current non-heat-treated steel and C70S6 steel.

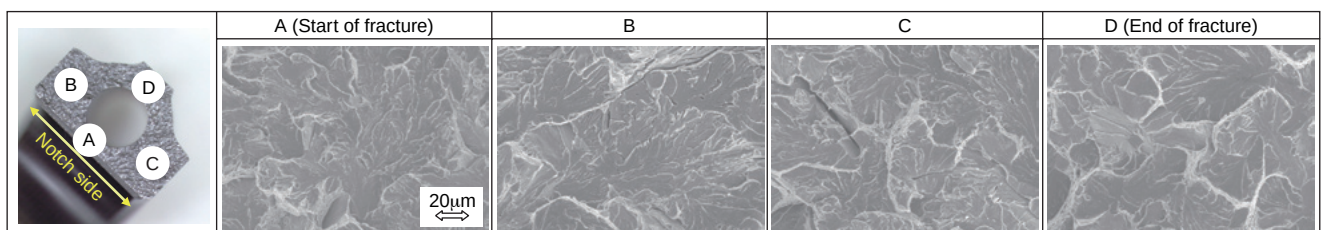


Fig. 16 SEM micrographs of fracture surface

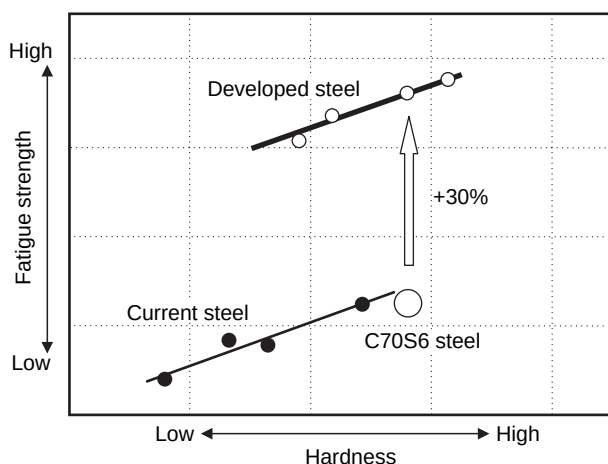


Fig. 17 Comparison of tension and compression fatigue strength between developed connecting rods and C70S6 connecting rods

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6. Weight Savings

The use of the newly developed steel has enabled the area of the I-beam cross-section to be reduced, while the employment of fracture splitting has made it possible to eliminate the pins for alignment of the rod and cap and reduce size, resulting in a 13% reduction in weight. This weight saving, together with a consequent reduction in the weight of the crankshaft, has reduced the weight of the engine used in the 2005 full model change CIVIC by approximately 450 g.

7. Conclusion

The project discussed in this paper succeeded in reducing the weight of an automotive connrod through the development of a new steel combining increased fatigue strength with fracture splittability of the big end. The project can be summarized as follows:

- (1) Strengthening the ferrite in the material was effective in enhancing fracture splitting performance. Carbonitride precipitation strengthening of the ferrite by the addition of Ti in particular enabled the achievement of superior fracture splitting characteristics to those displayed by conventional steels.
- (2) Reduction of the C content of the newly developed steel to less than that of the current non-heat-treated steel and the employment of carbonitride precipitation strengthening by the addition of V and Ti were effective in increasing the endurance ratio.
- (3) Use of the newly developed steel has increased connrod fatigue strength by 30% while reducing weight by 13%.

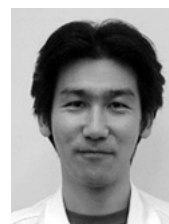
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■ Authors ■



Zenji IIDA



Kentaro TAKADA



Shigeru SUZUKI



Chikashi SATO