

Research of High Fatigue Strength for Powder-forged Connecting Rods

Kentaro TAKADA*

Ryosuke KOGURE*

Teruo KOBAYASHI*

ABSTRACT

This paper reports the results of research on increasing the fatigue strength of powder-forged connecting rod materials.

The fatigue strength of powder-forged materials was increased without adding special alloy elements or lowering workability by adjusting the ratios of the conventional main mixed powders (iron, carbon, copper) and by controlling the sintering temperature conditions. In addition to solid solution strengthening of the ferrite using copper, reducing porosity, which is a material internal defect, is also an effective method of increasing fatigue strength. Reducing carbon content greatly reduced the occurrence of defects in the forging stage.

The results of this research showed that the fatigue strength of high strength powder-forged materials can be increased by 30% or more over that of conventional materials, resulting in powder-forged connecting rods to be applied to even higher output and higher load engines than before.

1. Introduction

Weight reduction is an important means of increasing automobile fuel economy and output, and this applies to engine components as well. In particular, reducing the weight of the main moving components, such as the pistons, crankshaft, and connecting rod, has a large effect on enhancing engine performance. In addition to steel materials, titanium alloys and other materials are sometimes applied to reduce the weight of connecting rods⁽¹⁾. However, the cost is high. So for passenger car engines, the connecting rod weight is reduced by increasing the steel material strength to enable a reduction in size⁽²⁾.

In Europe and Japan, hot forging technology has advanced, and is often used to increase the steel material strength. In contrast, powder forging is the main method used in North America, and has had the advantage of being able to make use of the brittleness of the materials to fracture-split the large end of the connecting rod to streamline the shape and reduce weight. However, progress in weight reduction has been made in the hot forging method, with the development of steel materials that not only have high strength, but also result in fracture splitting in the same manner as that of powder-forged materials⁽³⁾⁻⁽⁵⁾. The strength of powder-forged materials can be enhanced by increasing the amounts of additive alloy

elements⁽⁶⁾ or adding new components. However, as the hardness increases, the machinability decreases, and the resulting drop in efficiency makes it impractical for mass production.

For this reason, the strength of connecting rods manufactured by hot forging is 30% or more than that of powder-forged connecting rods. This means that the two types cannot be designed with the same weight, which has hindered a flexible production response according to the production base.

Therefore, powder-forged materials that have the same strength and productivity as hot-forged materials were necessary to provide interchangeability in engines with the same specifications.

2. Research Goals

The material strength should be increased to reduce the connecting rod weight. This increase in strength is primarily responsible for an increase of the fatigue strength.

In addition, assuming a high-volume mass production line flow like that for conventional powder-forged connecting rods, lower machinability means increased replacement frequencies for cutters and other tools. This may cause costs to rise, and gives rise to concerns about drops in productivity. Therefore, the goals were to provide

* Automobile R&D Center

the same machinability as the conventional method, and to utilize the existing mass production lines without modifications. It was assumed that the fracture splitting method, which has become the main machining method for connecting rods in recent years, would be used.

3. Material Component Design

3.1. Approach towards Material Component Design

The main components of conventional powder-forged connecting rods are Fe-0.5%C-2.0%Cu, and MnS as the free-cutting component.

Possible methods for increasing the strength of this type of connecting rod are as follows.

- (1) Increasing the base material strength by increasing the C and Cu contents
- (2) Increasing the hardenability by adding Cr, Si, and Mn
- (3) Strengthening the base by adding V, Ti, and Nb to precipitate carbides

However, the base material strengthening method (1) causes the machinability to drop as the hardness rises. For this reason, there are reports of adding special powders that effectively increase machinability⁽⁷⁾, but this increases the cost relative to the conventional powder mix. Elements (Cr, Si, Mn) that are effective at increasing hardenability (2) oxidize easily during the sintering process, and these oxides form defects that lower the connecting rod strength, so this method is not appropriate. In addition, elements (V, Ti, Nb) that strengthen the base through carbide precipitation (3) also oxidize easily when mixed

simultaneously in powder form, so reduction is necessary. However, reduction of carbides is challenging when mixing the powders, so these elements should be alloyed and mixed as pre-alloy powders. In this case, work should start from development of the pre-alloy powders, so costs are expected to rise. Therefore, optimization of the powder ratios and sintering conditions, without changing the main components, was investigated with the target of increasing strength without lowering machinability.

3.2. Adjusting the Ratios of the Main Material Components

First, the relationship between hardness and fatigue strength was investigated with respect to the ratios of C and Cu, which are main components in conventional powder-forged connecting rods. Figure 1 shows the relationship between the material hardness and rotary bending fatigue strength with respect to the C and Cu contents. Both the fatigue strength and the hardness increase with the C or Cu content, but the C content has a greater effect on the increase in hardness than the Cu content. Thus, reducing the C content and increasing the Cu content is an effective means of increasing the fatigue strength, while at the same time minimizing the increase in hardness which influences the machinability. Figure 2 shows the structure of these materials. This figure shows that reducing the C content reduces the hard pearlite, which is a cause of increased hardness, and increases the soft ferrite. However, this also lowers the strength, so the ferrite is strengthened using the solid solution

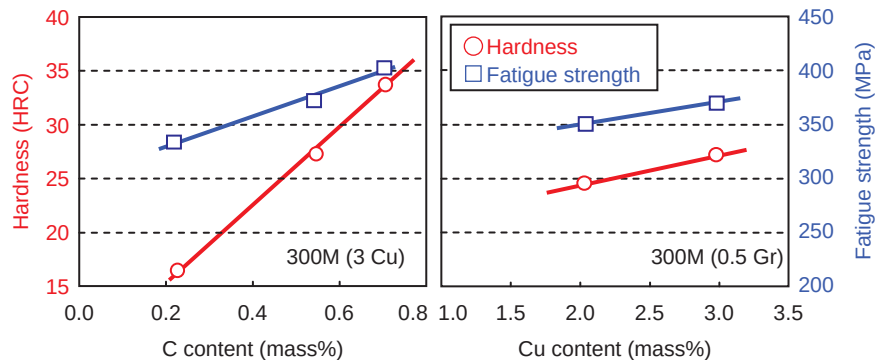


Fig. 1 Relationship between C, Cu content and hardness, fatigue strength

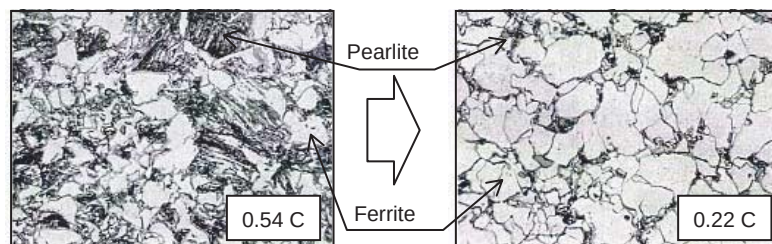


Fig. 2 Change in microstructure due to decreased C% of powder metal-forged test pieces (originally at 400X)

strengthening element Cu. Increasing the ratio of ferrite, which easily forms a solid solution with Cu, also increases the Cu saturation limit, resulting in larger amounts of Cu to enter the solid solution. This effectively reduces the hard pearlite that is a cause of increased hardness, and strengthens the soft ferrite, achieving to increase the fatigue strength without raising the hardness.

Next, the effects of C and Cu on machinability were investigated. The machined test material consisted of powder-forged materials manufactured under approximately the same conditions as those of an actual connecting rod, and the cutter was a carbide drill used to machine connecting rod joint holes. Figure 3 shows the drilling test conditions and results. When the C content is kept constant and the Cu content is increased, the hardness rises, causing the cutter wear to increase. However, when the C content is reduced to reduce the hard pearlite and the Cu content is increased, the hardness increases slightly, but the cutter wear can be decreased. This indicates that reducing the C content and increasing the Cu content is an effective method.

In addition, the sintering density is generally an important factor affecting the fatigue strength of sintered materials, and when powder forging is performed, the sintering density rises to near the true density throughout the entire part. However, a large number of microscopic pores are present near the surface layers. In the outermost surface layers, this porosity can be crushed by shot peening or other methods, but it remains in the inner layers and becomes a starting point for fatigue fractures, which lowers the fatigue strength. Figure 4 shows the porosity in the pole portion of a conventional powder-forged connecting rod. This type of porosity is generally said to be generated when the material is cooled by contact with the die during hot forging. In other words,

when a powder compact formed by pressurizing and hardening powder is sintered, the mixed powder Cu (melting point 1083°C) melts and disperses in a solid solution into the ferrite. At this time, if the gaps produced from the melting copper, are completely crushed during hot forging, then there would be no porosity. The center portion of the materials and portions with large degrees of deformation are almost completely filled. However, the surface layers contact the forging die, causing the temperature to drop and increasing the deformation resistance, so the gaps in these portions are resisting crush and could easily remain as porosity. Therefore, it is expected that surface layer porosity can be reduced by lowering the deformation resistance at low temperatures. In addition, the material temperature during hot forging is around 1000°C, so the generation of surface layer

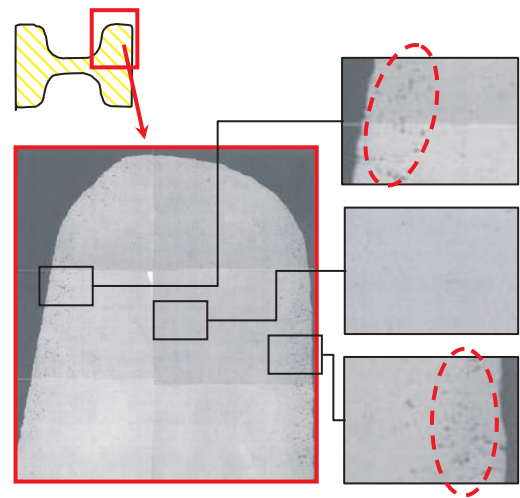


Fig. 4 Porosity of "I-Beam" for connecting rod (after shot-peening)

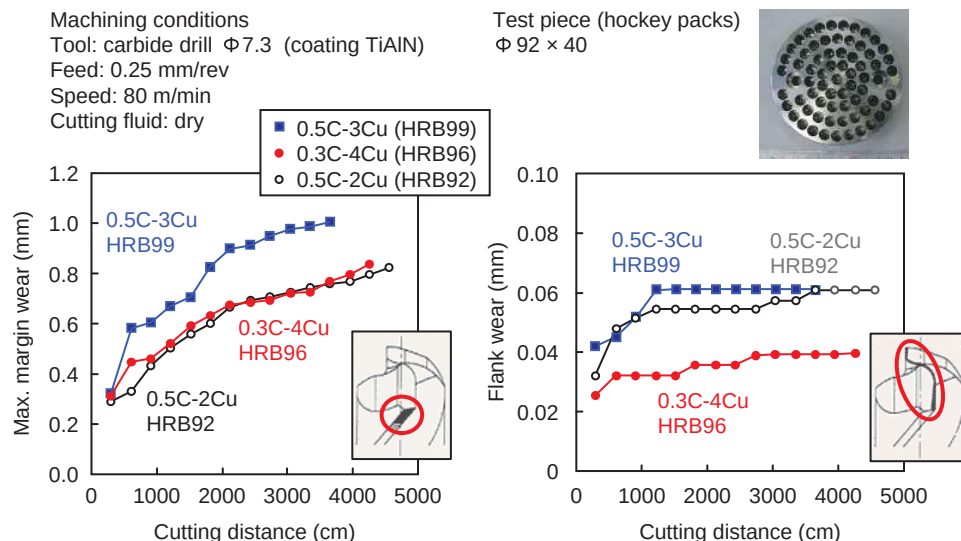


Fig. 3 Margin and flank wear in function of drilling length

porosity should be suppressed in the temperature range somewhat lower than this temperature. Figure 5 shows that reducing the C content lowers the deformation resistance within the temperature range of 850 to 900°C⁽⁸⁾, so porosity existing in the surface layers is considered to be less than that of the conventional materials.

The above results indicate that reducing the main component C and increasing the main component Cu is an effective method of increasing the connecting rod strength without lowering the machinability.

3.3. Material Component Design of the Developed Connecting Rod

As part of the material component investigations, prototype connecting rods were manufactured and verified to take into account the fracture splitting performance and effects of surface porosity on fatigue strength. The powder mixture consisted of atomized pure iron powder (300 ME), graphite, 2.0% Cu powder by weight, and 0.32% MnS alloy powder. The mixture was adjusted so that the component ratios, after forging, varied between 0.13 to 0.57% C and 1.6 to 4.6% Cu. Figure 6 shows the test connecting rod prototype manufacturing process.

First, optimization of the C content was investigated. Figure 7 shows the relationship between the C content and the results of image analysis of the number, size and shape of the pores over a section 0.5 mm wide and 0.5 mm deep from the surface of the I-Beam of the test connecting rods. Reducing the C content, which was approximately 0.5% with the conventional method, reduced both the size and number of pores. In addition, the pore shapes were confirmed to be spherical when the

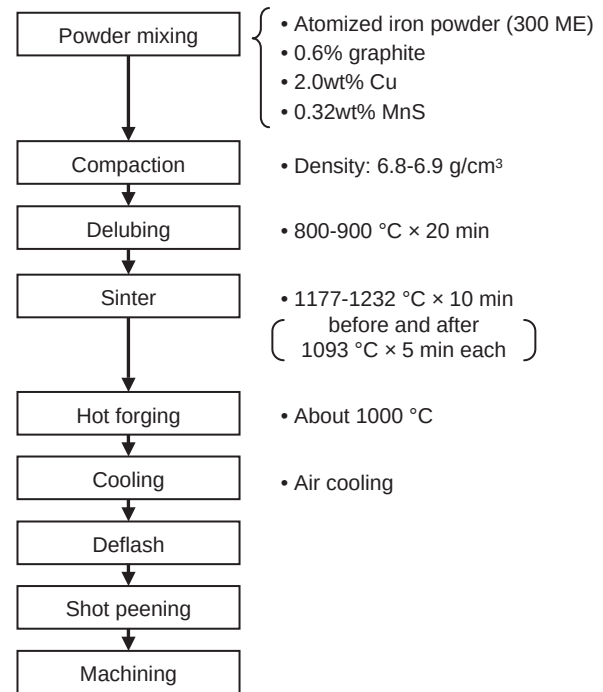


Fig. 6 Production process and condition of connecting rod

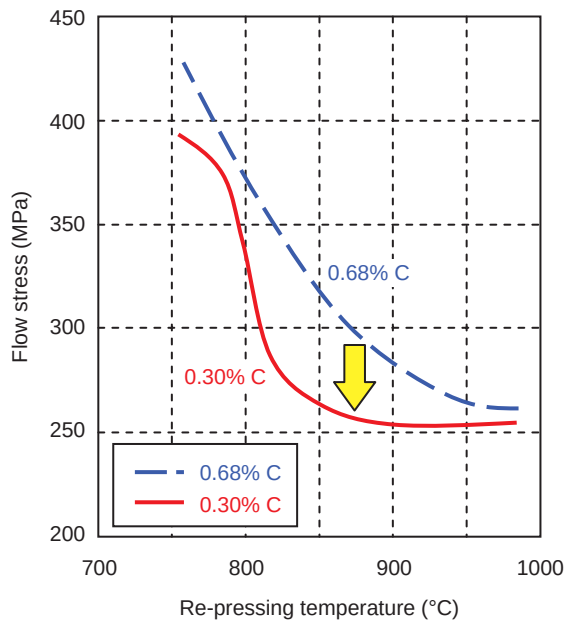


Fig. 5 Relation between flow stress and pressing temperature

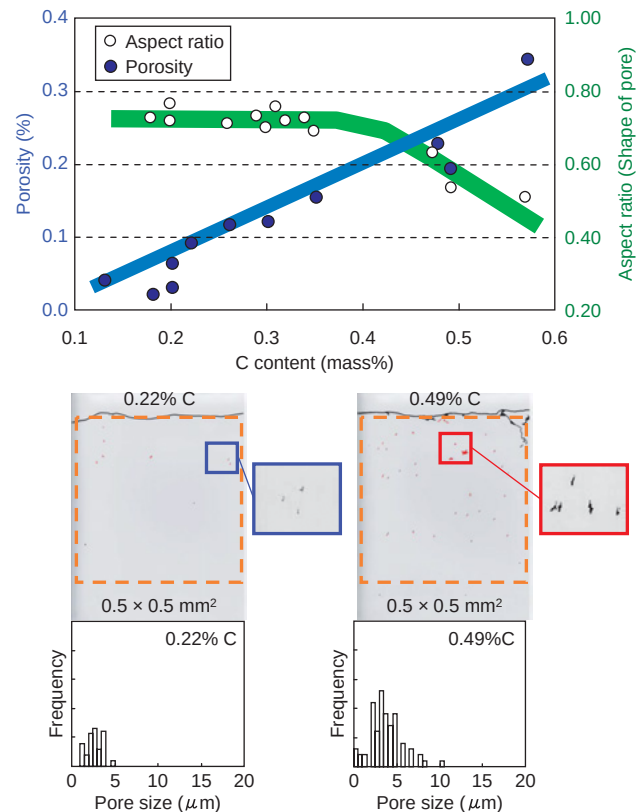


Fig. 7 Relation between C% and porosity, shape of pore (Photo: result of pore image analysis for C content)

C content was reduced to 0.35% or less.

Reducing the amount of porosity, pore size, and making the pores spherical can be presumed to reduce the concentration of stress on the pores. This reduces the potential for porosity near the surface of connecting rods to become a starting point for fatigue fractures, so it is necessary to aim for C content of 0.35% or less.

Figure 8 shows the relationship between the C content and the impact characteristics. Here, the tests were conducted at normal temperatures using a V-notched impact test piece as prescribed by JIS Z 2202. The impact value rises at a C content of 0.25% or less. Unlike a Charpy impact test piece, connecting rods have bolt holes for coupling with the crankshaft in the fracture split

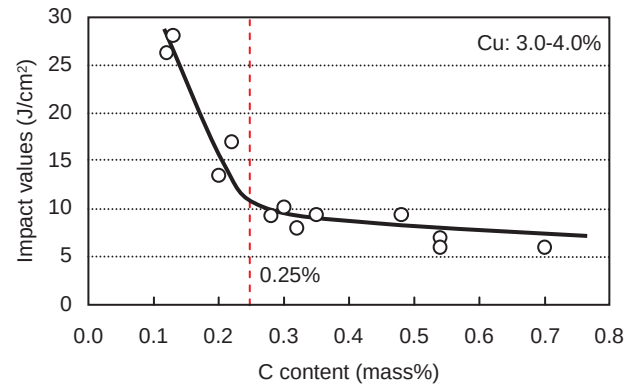


Fig. 8 Relation between impact value and C content

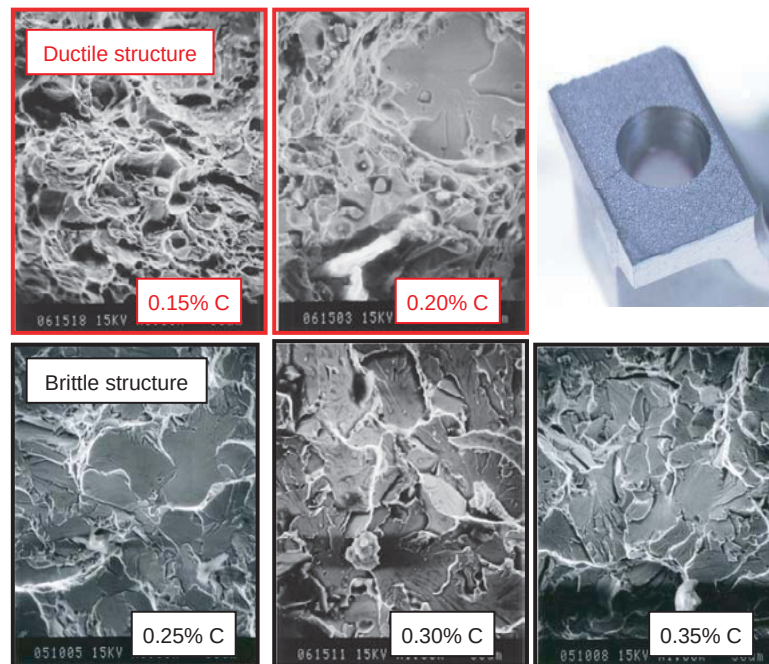


Fig. 9 SEM micrographs of fracture surface

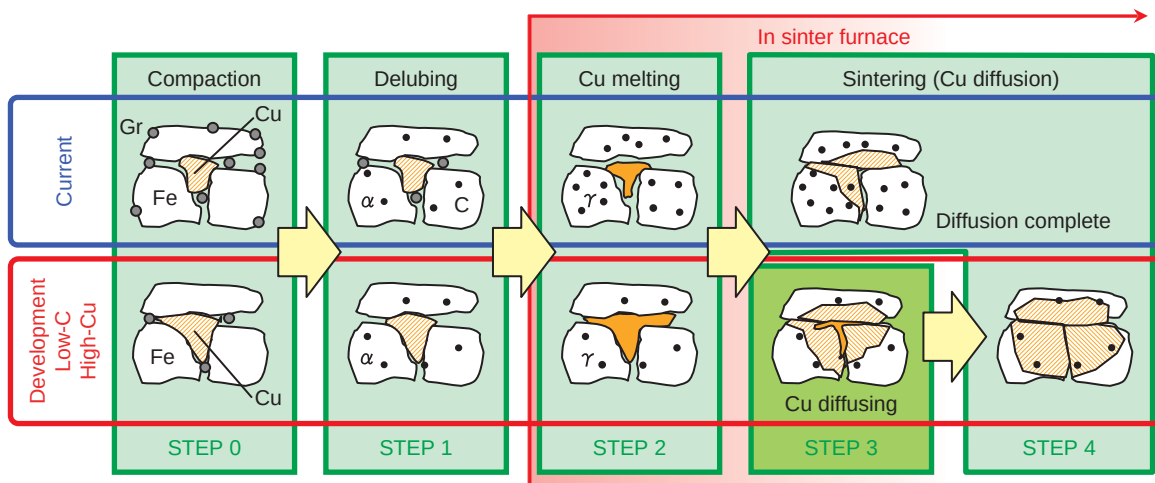


Fig. 10 Image of Cu melting and diffusion for high Cu rods in heat treatment process

portion, so an actual connecting rod was fracture-split and the surface properties were confirmed. Figure 9 shows an electron microscope image of the fractured surface of an actual connecting rod. Here, a V-notch approximately 1.0 mm deep was machined into the large end, which was the fracture starting point. The fracture-split portion exhibited the same surface properties over almost the entire surface. The fracture-split surface of connecting rods with a C content of 0.25% or more exhibited cleavage fracture surfaces, but dimples indicating ductile fracture surfaces appeared on the split surface at a C content of 0.2% or less. These dimples impede proper fit of the split surfaces when the connecting rod is reassembled after fracture splitting. These results indicate that reducing the C content by too much has an adverse effect on fracture splitting,

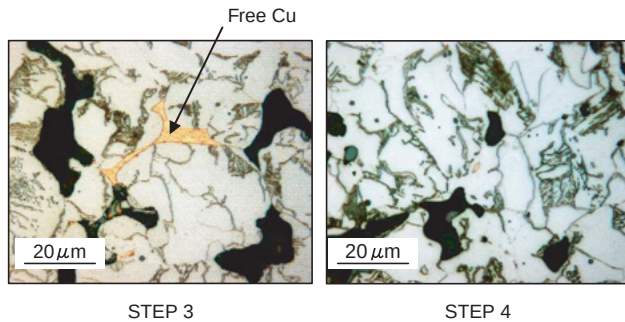


Fig. 11 Microstructure for high Cu rods in heat treatment process

so it is necessary to aim for C content of 0.25% or more in cases where fracture splitting is necessary.

Next, optimization of the Cu content was investigated. Figure 10 shows a concept drawing of Cu melting and diffusing. When the Cu content is increased the Cu melts inside the sintering oven (STEP 2) and then starts to diffuse in the same manner as the conventional materials, but the Cu diffusion is incomplete (STEP 3) even under conditions where diffusion was completed in the conventional materials. In this case, not only is it unable to obtain the full strengthening effects, but free Cu detracts from the strength. Therefore, it is necessary to completely diffuse the increased Cu (STEP 4). Figure 11 shows the actual structures with unmelted Cu remaining due to insufficient diffusion inside the sintering oven (STEP 3), and with the Cu completely diffused (STEP 4). The remaining unmelted Cu is confirmed to enter the gaps between the iron powder particles and interfere with adhesion between the iron powder particles. Therefore, a method was investigated of promoting diffusion to shift from STEP 3 to STEP 4 when increasing the Cu content.

When Cu diffusion is considered in terms of the one-dimensional diffusion distance, the diffusion distance is proportional to the diffusion coefficient and the time. In addition, the temperature dependence of the diffusion coefficient conforms to an Arrhenius equation as shown below, so the diffusion is proportional to temperature and time.

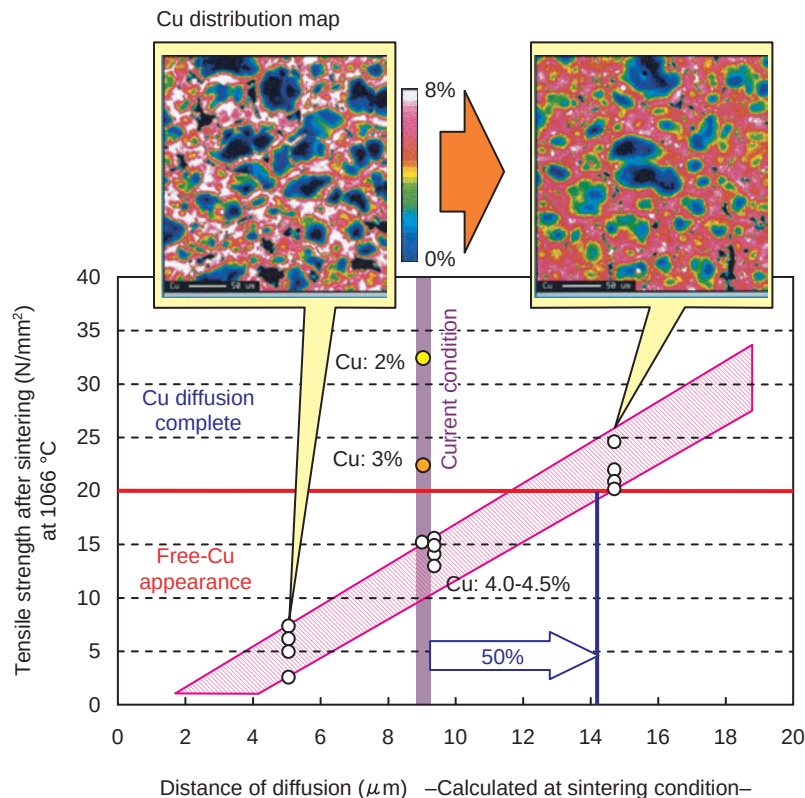


Fig. 12 Relation between high temperature strength and Cu diffusion

Diffusion distance: $d \propto \sqrt{Dt}$

Diffusion coefficient: $D = D_0 \exp\left(-\frac{Q}{RT}\right)$

Q: activation energy

R: gas constant

T: temperature

t: time

High temperature tensile strength tests were conducted using test pieces manufactured with different sintering temperature and time conditions in order to investigate the Cu diffusion conditions. These tests were performed at 1066°C, which is the connecting rod temperature immediately after removal from the sintering oven. Figure 12 arranges the first-order diffusion distances, calculated from the above diffusion equation according to the respective sintering conditions. In addition, the Cu density distribution within the test piece is also mapped to show the Cu solid solution diffusion status. These results show that in areas with low strength after sintering, the Cu is distributed in high density in the surface layers of the original powder particles. In contrast, in areas where sufficient strength is provided, the diffusion is uniform. Strength at high temperatures cannot be provided unless the Cu is sufficiently dispersed, so when increasing the Cu content it is necessary to set sintering conditions that diffuse the Cu uniformly throughout the particles.

In a pure Fe-Cu system, the Cu content in solid solution inside the austenite is said to be approximately 7.5 to 9% at a temperature of 1094°C⁽⁹⁾, and in a Fe-C-Cu system, the theoretical solid solution limit to the inside of the austenite is reported as approximately 6%⁽⁹⁾. In

addition, even in a powder-forged connecting rod with a dual-layer ferrite-pearlite structure, when the C content is reduced it is considered that the Cu solid solution limit tends to increase together with the ferrite ratio. Under the conventional conditions shown in Fig. 12, the Cu can be diffused evenly to the inside of the particles up to approximately 3%. However, when the Cu content is increased by 1.5 times to 4.5% under these conditions, Cu diffusion should also be promoted by approximately 1.5 times the conventional amount. Therefore, Fig. 13 shows the relationship between this sintering temperature and time and the calculated Cu diffusion distance. In the initial stages, there is much diffusion per unit time, and increasing the temperature further increases the diffusion

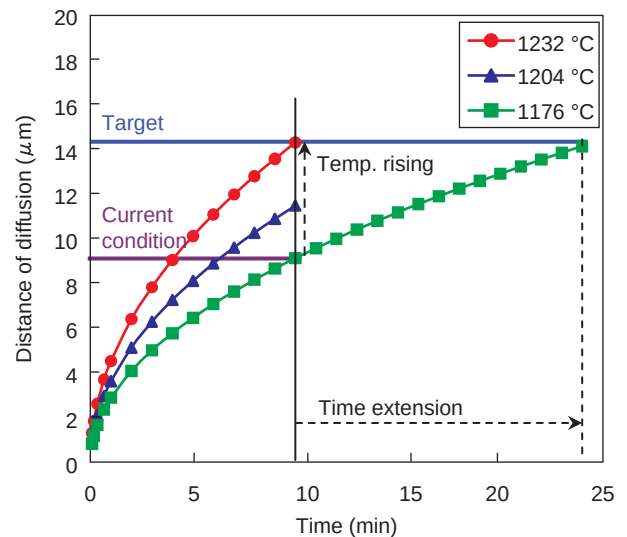


Fig. 13 Calculated results for Cu diffusion distance

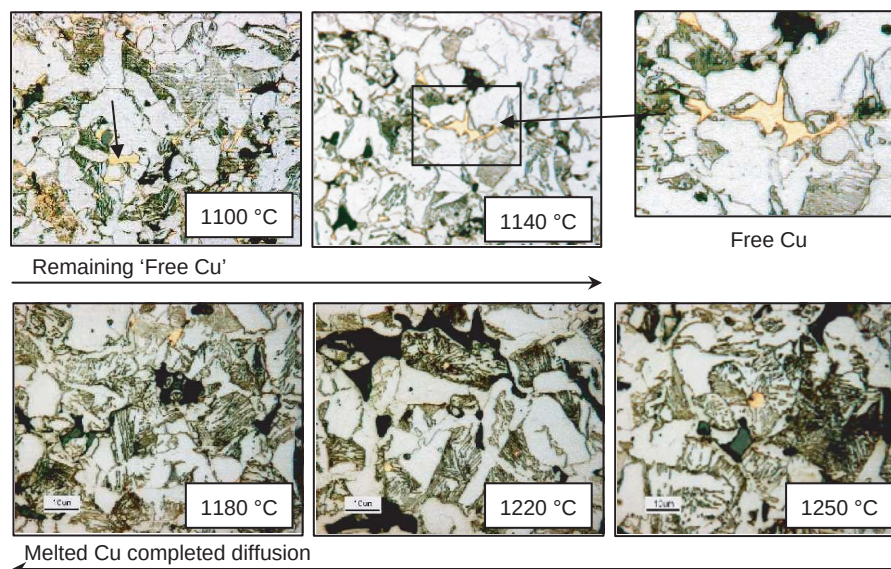


Fig. 14 Microstructure of test piece (0.35% C - 4.5% Cu) for sintering temperature (originally at 400X)

Table 1 Chemical composition for fatigue strength of connecting rod

	(mass%)		
	C	Cu	MnS
Development PF	0.26	3.59	0.32
	0.30	3.87	0.32
	0.35	4.27	0.32
	0.20	3.00	0.32
	0.13	3.42	0.46
	0.13	4.52	0.46
Current PF	0.39	1.64	0.30
	0.49	1.98	0.32
	0.54	2.14	0.30
High C/Cu	0.46	3.04	0.34
	0.51	2.93	0.33
	0.57	3.26	0.30

PF: Powder – forged rods

effects. After a certain amount of time has passed, the diffusion potential is reduced and the rate of diffusion also decreases. These calculated results indicate that increasing the sintering temperature and lengthening the sintering time can be considered as methods of promoting diffusion. However, the results also show that raising the temperature by 50 to 60°C and approximately doubling the time both provide roughly the same diffusion promoting effects. If the mass production conditions have room for raising the sintering temperature, this is considered to be a more effective method of promoting Cu diffusion than lengthening the sintering time. Therefore, in consideration of mass production performance, this study kept the sintering time constant and increased the Cu content by raising the sintering temperature. Taking into account the sintering oven performance and capability, the upper limit for the sintering temperature was set at approximately 1260°C.

The Cu content can be increased up to the solid solution limit within the target C content range of 0.25 to 0.35%, but it is considered that in this case, a long time will be needed for complete diffusion unless the sintering temperature is increased even further. Therefore, in consideration of mass production performance, the Cu content upper limit was set at 4.5%. Figure 14 shows the results of confirming the effects of the sintering temperature when using materials with a C content of 0.3% and Cu content of 4.5%. It was confirmed that there is no remaining unmelted free Cu at temperatures of 1180°C or higher, indicating that the Cu is completely in solid solution. These results confirmed that increasing the sintering temperature to 1180°C or more results in complete solid solution of approximately 4.5% Cu in a connecting rod with a C content of 0.3%.

From the above, the approach toward the component ratios of C and Cu, which are main connecting rod components, and the sintering conditions is as follows.

The C content should be reduced to 0.35% or less to minimize porosity and make the pores spherical, but it should also be 0.25% or more to obtain cleavage fracture surfaces during fracture splitting. Cu can be added up to the solid solution limit, but should be 4.5% in consideration of mass production performance. When using the same sintering time as the conventional method, the sintering temperature should be approximately 1180°C or more to completely diffuse the Cu. However, the upper limit is approximately 1260°C, in consideration of the mass production oven capability.

The relationship between hardness and fatigue strength was verified using actual connecting rods based on the above component ranges.

4. Connecting Rod Fatigue Strength

Fatigue tests were performed using actual connecting rods to evaluate the strength of the I-Beam of connecting rods with different main material component ratios. Table 1 shows the ratios of the main components C and Cu of the connecting rods used in the fatigue tests. In addition, fatigue tests were also performed on powder-forged connecting rods with a C content of 0.25% or less, which is unsuitable for fracture splitting. The C and Cu component ratios of these unsuitable connecting rods, a conventional ordinary powder-forged connecting rod, and a high hardness powder-forged connecting rod with both the C and Cu content increased are also shown in the table for comparison.

Figure 15 shows the fatigue test results for the connecting rods with various component ratios. The fatigue tests were performed in tension-compression mode ($R=-1$), and the fatigue limit of each connecting rod was obtained from the hardness around the fracture location and the S-N curve. These results show that when the C

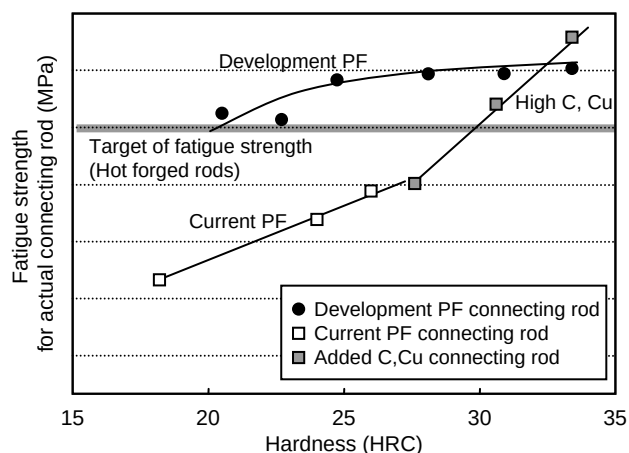


Fig. 15 Comparison of fatigue strength (tension and compression / $R = -1$) between developed connecting rods and current PF connecting rods

and Cu contents are simply increased in the conventional powder, the fatigue strength increases but at the same time the hardness also increases. To provide the target strength equal to that of a hot-forged connecting rod, the hardness rises to HRC30 or more, which impairs machinability. However, the newly developed powder-forged material with reduced C content and increased Cu content was confirmed to provide the target fatigue strength without corresponding hardening.

5. Effects of Increasing the Fatigue Strength

The powder-forged connecting rod material obtained by changing the material powder ratios and optimizing the manufacturing conditions achieved a fatigue strength guarantee value 30% or more than that of the conventional material while maintaining the same machinability. This achieved to reduce the weight by approximately 28 g per connecting rod, which, including the crankshaft balance adjustment, achieved a total weight reduction for the main moving components of approximately 290 g in the new ACCORD V6 engine.

In addition, this high fatigue strength powder-forged connecting rod provides the same fatigue strength as high-strength hot-forged non-tempered lightweight connecting rods (fracture splitting type). This means that they can be designed with the same weight, and results in flexible production, suited to each production base, regardless of the manufacturing method involved.

6. Conclusion

Technology was established to increase fatigue strength without increasing the hardness of powder-forged connecting rods produced locally in North America.

New powder-forged materials obtained using this technology were used to reduce the connecting rod weight without lowering the machinability. These results are summarized below.

- (1) Reducing the C content to reduce the pearlite, and increasing the Cu content to strengthen the ferrite solid solution is an effective means of increasing the fatigue strength while suppressing an increase in hardness.
- (2) Porosity occurring in the surface layers of the connecting rod during forging can become a starting point for fatigue fractures. Reducing the C content lowers the deformation resistance, enabling to reduce this porosity and make the pores spherical in shape, which effectively increases the fatigue strength.
- (3) The new powder-forged materials increase the fatigue strength by 30% or more without lowering machinability, compared to the conventional materials, and achieved to reduce the connecting rod weight.
- (4) The new material provides the same performance as hot-forged non-tempered high-strength lightweight connecting rods (fracture splitting type). This provides

interchangeability in high output, high load engines produced in both Japan and North America, and expands the local production range to which this new technology can be applied.

References

- (1) Matsubara, T., Sato, Y., Kimura, K., Kawase, N., Ito, S.: Development of Free Machining Titanium Alloy for Connecting Rods, HONDA R&D Technical Review, Vol. 3, p. 12-26
- (2) Matsubara, T., Sato, Y., Iida, Z., Taguchi, T.: Development of a High Fatigue Strength Free Machining Microalloyed Steel for Connecting Rods, HONDA R&D Technical Review, Vol. 4, p. 73-85
- (3) Iida, Z., Takada, K., Suzuki, S., Sato, C.: Development of Lightweight Connecting Rod, Honda R&D Technical Review, Vol. 17, No. 2, p. 115-121
- (4) Fukuda, S., Etou, H.: Development of Fracture Splitting Connecting Rod, JSAE Review, Vol. 23, No. 1, p. 101-104 (2002)
- (5) Yamaguchi, M., Ookuma, S., Miyazawa, T., Yamada, Y.: Development of Fracture-Splitting Connecting Rod, NISSAN Technical Review, No. 56, p. 21-25 (2005)
- (6) Ilia, E., O'Neill, M., Tutton, K., Lanni, G., Letourneau, S., Haehnel, M.: Benchmarking the Industry: Powder Forging Makes a Better Connecting Rod, SAE paper, No. 2005-01-0713, p. 1-13 (2005)
- (7) Ilia, E., O'Neill, M., Tutton, K.: Higher Fatigue Strength Materials for Powder Metal Forged Connecting Rods, SAE paper, No. 2002-010611, p. 1-7 (2002)
- (8) James, B. W., McDermott, M. J., Powell, R. A.: "Powder Forging" Metals Handbook, ASM International, Vol. 14, No. 9 (1988)
- (9) Nihon Gakujyutsu Shinkoukai Seikou Dai19iinkai: Tekkou to Goukingenso (Jyou), Seibundo Shinkousya, p. 353-355(1966) (in Japanese)

■ Author ■



Kentaro TAKADA



Ryosuke KOGURE



Teruo KOBAYASHI