

Development of High-strength Induction Hardened Crankshaft

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ABSTRACT

A high fatigue strength and wear resistant induction hardened crankshaft has been developed for diesel engines. Crankshafts for use in diesel engines must be engineered to tolerate the high loads generated by high in-cylinder pressures, and be capable of resisting wear caused by the carbon, which collects in the lubricating oil as a combustion by-product. Simultaneous hardening of the shaft and the fillet has been adopted in the newly developed crankshaft to achieve even higher strength while reducing the number of production processes, resulting in the development of a crankshaft with excellent fatigue strength, resistance to wear, and mass producibility. A special material was developed for the crankshaft to enable the curvature occurring during induction hardening of the fillet to be easily corrected. In addition, control of inclusions in materials has enabled the lead component, conventionally added to increase machinability, to be removed without sacrificing workability.

1. Introduction

The demand continues to grow for automobiles to place lower loads on the environment than ever before. There are high expectations placed on the diesel engine from the viewpoint of regulations on CO₂ emissions.

The diesel engine operates at higher cylinder pressures than the gasoline engine, causing high loads, particularly bending loads, on the crankshaft. Furthermore, the inclusion of combustion by-products (carbon) into the lubricating oil, a problem which does not occur in gasoline engines, requires high wear resistance in the reciprocating parts of the journal. This has necessitated development of materials and heat-treating technologies for more wear and stress resistant crankshafts.

2. Development Aims

Both selection of constituents and heat-treating processes are essential means for strengthening crankshafts against the high loads in diesel engines. Many methods for strengthening are in use⁽¹⁾.

Figure 1 shows an example of a conventional, mass-produced induction hardened crankshaft for passenger vehicles. Most induction hardened crankshafts receive induction hardening at the journals in order to improve wear resistance, and the fillets are roller-burnished in order to maintain high fatigue strength⁽¹⁾. Roller-burnishing processes are effective at strengthening fillets, but since fatigue strength is increased by residual compressive stresses, unless the material is quite hard, the residual stresses are low and the

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fatigue strength is not expected to be enhanced. This obliges the use of materials with poor workability. Another concern is that two production steps must be performed, heat treatment of the journal and roller-burnishing of the fillet, requiring more processing equipment. Therefore, a specification was created for induction hardening of the fillet shown in Fig. 1 with the double goals of establishing high fatigue strength while simplifying the sequence of operations on the production line, in the general process outlined in Fig. 2. Although further improved fatigue strength is obtained by applying induction hardening to the fillet in addition to the journals, there is another issue: the shaft is bent by the distortion induced by heat treatment during hardening. This distortion can be controlled by increasing the rigidity of the crankshaft, but this approach results in a weight increase. A light crankshaft can be made if it is possible to correct the shaft distortion during induction hardening. In order to accomplish this, it was therefore determined to develop a new crankshaft material, with due consideration to workability and induction hardenability, in addition to correction of shaft distortion, which is the major issue in induction hardening of the fillet. Simultaneously, a technology, which improves machinability, was employed

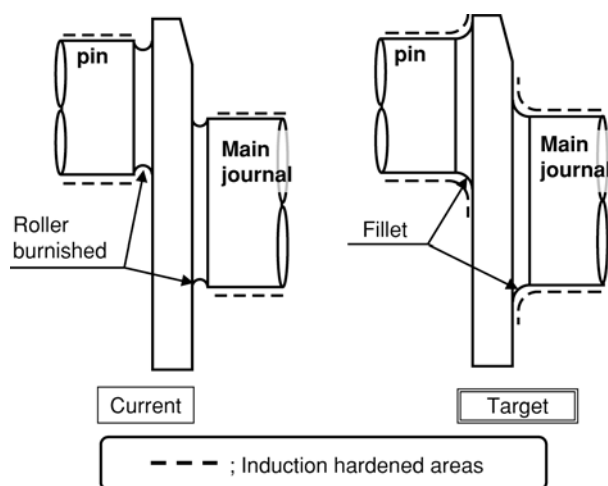


Fig. 1 Feature of the target crankshaft

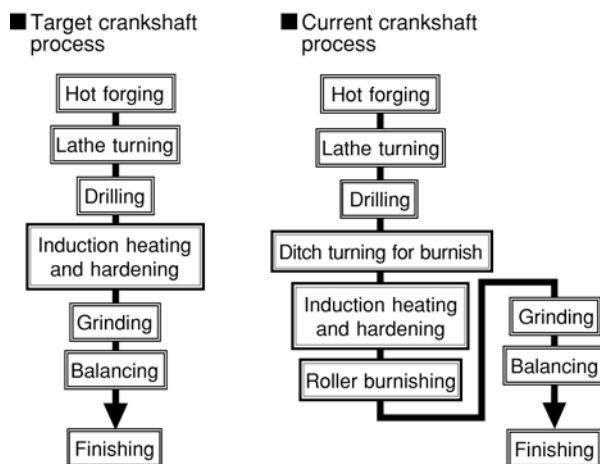


Fig. 2 Production process for induction hardened crankshaft

instead of adding lead, in order to decrease the use of hazardous materials, which are harmful to the environment.

3. Material Specifications

Vanadium-containing micro alloyed steel is one example of a crankshaft material suitable for induction hardening in mass production for diesel engines⁽²⁾. This material has a high degree of hardness after hot forging. It cannot be made on current crankshaft production lines, because tooling and processes would need to be optimized for its adoption. Therefore, the new material was developed with an eye to the considerations described in the following section.

3.1. Wear Resistance of Reciprocating Parts of the Shaft

Induction hardened test pieces were subjected to a wear test at the reciprocating parts with oil seals, using carbon-contaminated oil. The results of the test are shown in Fig. 3. The allowance of wear volume was determined to be 50 μm or less from the axial tracking characteristics of the oil seals. The trend in the minimum results in Fig. 3 was used to define a lower limit of HMV 580 for surface hardness. Also, as shown in Fig. 4, a correlation has been shown between surface hardness and the amount of C in the crankshaft material during induction hardening of the actual crankshaft. By this relation, a C content of 0.37 Wt% was set in order to reach the target surface hardness.

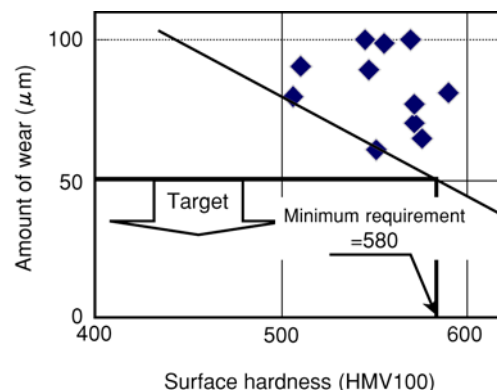


Fig. 3 Relation between surface hardness and amount of wear

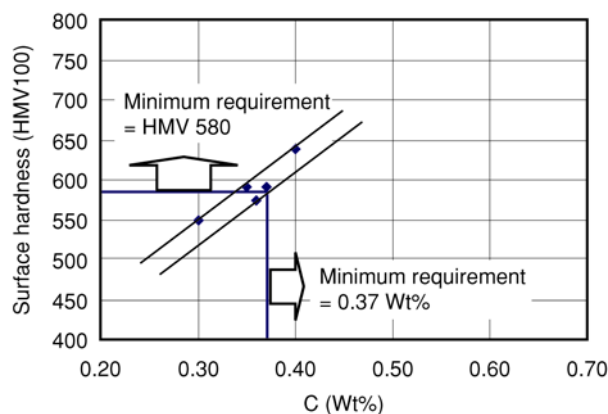


Fig. 4 Relation between amount of C and surface hardness

3.2. Producibility, Workability, Machinability

It has been reported that there is a correlation between carbon equivalents (Ceq) and material hardness after hot forging⁽³⁾.

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

Figure 5 shows the relation found in an actual crankshaft between the material Ceq and material hardness. An upper hardness limit of HRB 98 was set in deference to the processing conditions on the existing crankshaft production line, and a lower limit of HRB 85 was selected in order to maintain sufficient fatigue strength in the actual crankshaft; thus, a Ceq of 0.54 – 0.60 wt% was specified. Si, Mn and Cr are generally known to improve induction hardenability, so these were investigated for their abilities to improve fatigue strength while not raising material hardness. Si raises fatigue strength by raising the strength of ferrite in the ferrite-pearlite structure, though the material internal hardness is reported to be small⁽⁴⁾. In this development effort, the Si amount was set at 0.50 Wt% in consideration of Ceq range, and Mn was set at 0.60 Wt% to strike a balance.

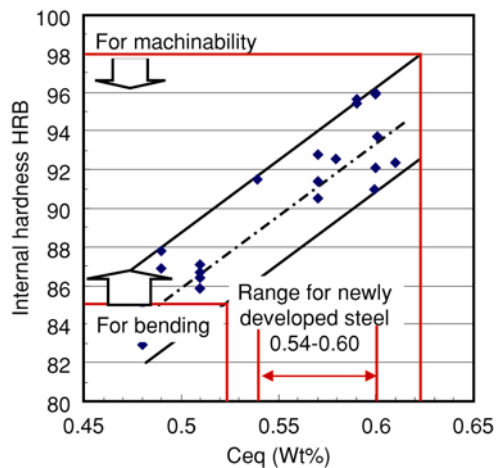


Fig. 5 Relation between Ceq and internal Hardness

3.3. Improvement of Induction Hardenability

Boron was added in order to improve and stabilize the induction hardenability. Addition of small quantities of B has been reported to raise induction hardenability without raising post-forged material hardness⁽⁵⁾. If N is present in the steel, BN is generated, reducing the solid-solution B; sufficient B was therefore ensured by adding Ti and pinning N in order to reduce solid-solution N.

3.4. Eliminating Lead

Finely dispersed sulfide inclusions are an effective replacement for lead in free-cutting steel⁽⁶⁾. They provide locations for crack onset in the material during machining, improving chip frangibility, thereby improving machinability.

The material constituents, determined by the considerations expressed so far, are listed in Table 1, and Fig. 6 provides microstructure of the material.

Table 1 Chemical composition of developed steel

C	Si	Mn	P	S	Cr	Ti	B	Pb	Ceq
0.39	0.50	0.60	<0.030	0.050	0.18	<0.08	Add.	–	0.57

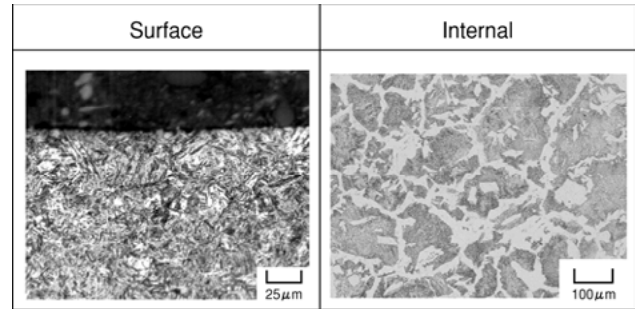


Fig. 6 Microstructure of crankshaft

4. Crankshaft Specifications

4.1. Approach to Crankshaft Strength

As shown in Fig. 7, crankshafts contain pins, journal fillets and lubrication supply openings (oil holes), which are important locations for considerations of strength. Fillets require extra strength to support the bending loads during operation, and oil holes require extra strength during support

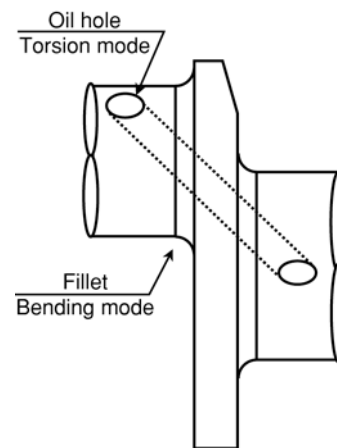


Fig. 7 Stress concentration point of crankshaft

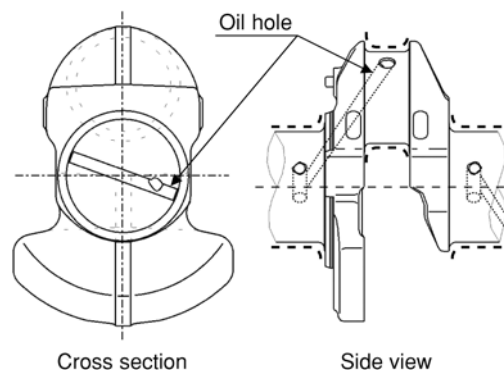


Fig. 8 Oil hole layout

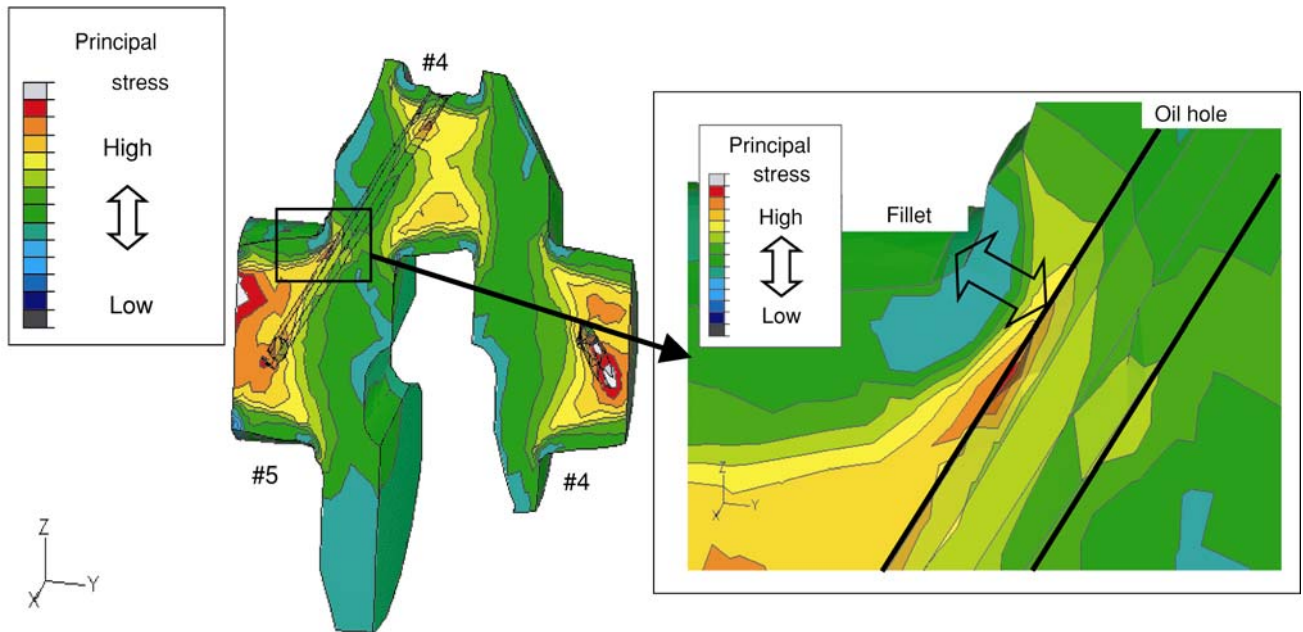


Fig. 9 Residual stress analysis around oil hole

of torsional loads.

It is known that high fatigue strength of a fillet can be obtained by increasing the effective depth of the hardened layer. Excessive depth means that excessive thermal energy is imparted to the crankshaft, however, which can cause it to bend or stretch. Therefore, an optimal depth of induction hardening was specified as appropriate for actual loads, in order to obtain an effective depth of the hardened layer with suitable fatigue strength. Residual stresses are also a key parameter for achieving fatigue strength. As shown in Fig. 2, the crankshaft under development is ground after the induction hardening in order to finish the shaft surfaces of reciprocating parts. Release of the residual stresses which evolved during induction hardening may occur due to the effect of the heat generated during the grinding process. Thus, the residual stress level was specified in order to meet a target fatigue strength after experimentally determining the relationship between fatigue strength and residual stresses.

The oil holes are close to the fillets, as shown in Fig. 8, so there is not much material thickness between them. Martensitic structures are created near the surface during induction hardening of the fillets, giving rise to residual compressive stresses. But the volume ratio accounted for by martensite drops with depth beneath the fillet, and the residual compressive stresses turn to tension. Voids like oil holes must be designed with caution, since they can become locations for initiation of cracking in a tensile stress field. Therefore it was determined to obtain the CAE-recommended optimal material thickness here. Figure 9 shows a contour diagram of the residual stress field from the oil hole design. Figure 10 presents a composite of these results and the relation between distance from the fillet, residual stress (σ_1) and the volumetric fraction of martensite (ψ_M). It is visible that the further from the fillet, the lower the residual stress; the material thickness between the fillet and the oil hole was therefore set at 6.3 mm in order to keep the

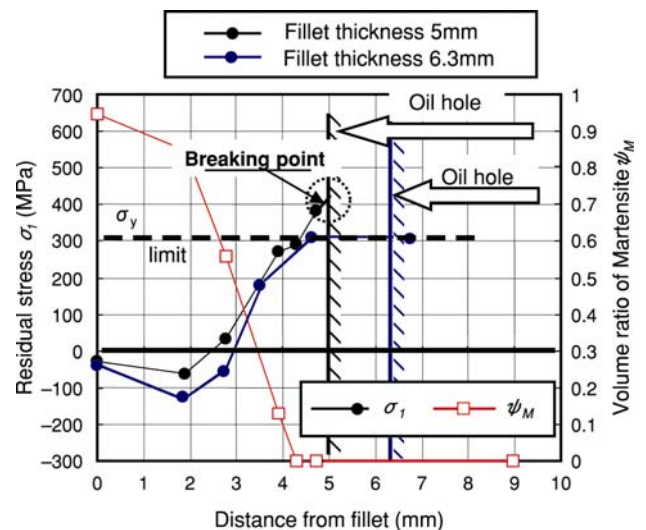


Fig. 10 Residual stress distribution around oil hole

stress lower than the material yield stress (σ_y). A test was also carried out in an actual crankshaft in order to verify that this had adequate fatigue strength.

4.2. Component Strength Characteristics

The specifications were set on the basis of the approach described above and the strength test results of components. Figure 11 displays a diagram of a crankshaft fillet fatigue test. The test employed actual crankshafts with altered effective depths of the hardened layer and residual stresses, and correlations between these parameters and fatigue strength were investigated. The relation between effective

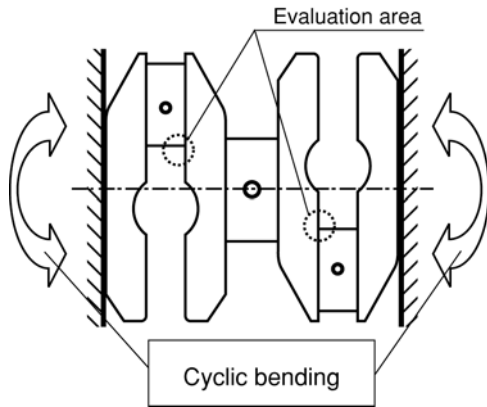


Fig. 11 Bending fatigue test for crankshaft

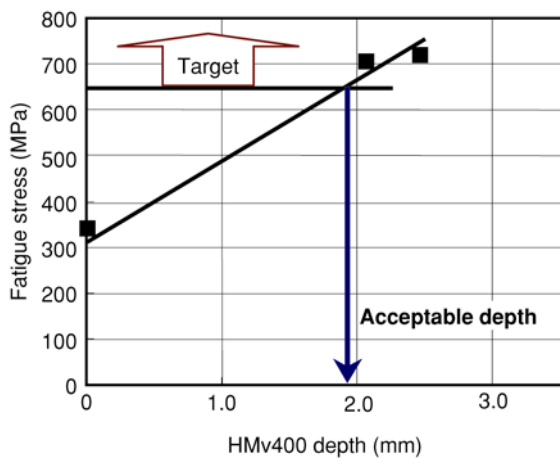


Fig. 12 Relation between depth of hardening and fatigue strength

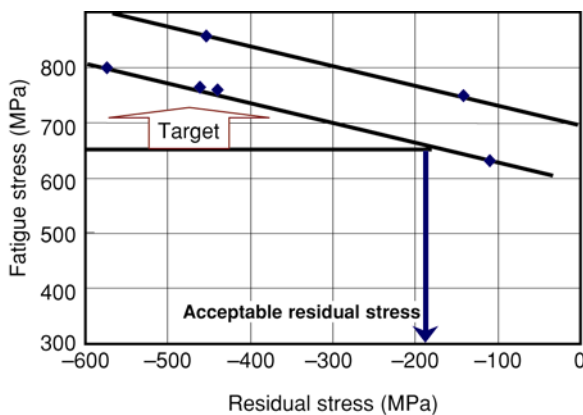


Fig. 13 Relation between residual stress and fatigue strength

depth of the hardened layer and 10^7 cycle fatigue limit is shown in Fig. 12 and that between residual stress and 10^7 cycle fatigue limit is shown in Fig. 13. This allowed setting of the effective depth of the hardened layer and residual stress level to obtain the target strength.

Figure 14 shows a diagram of a fatigue test for oil holes. Figure 15 provides the results from a torsional test of a crankshaft with the CAE-recommended thickness over fillets. The results presented here show that sufficient strengths were

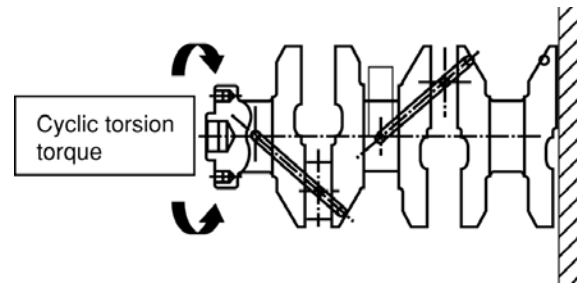


Fig. 14 Torsion fatigue test for crankshaft

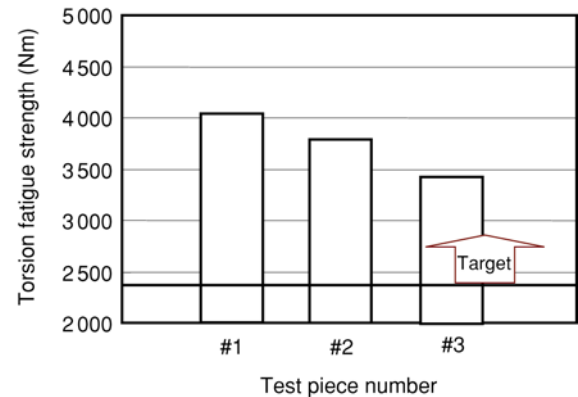


Fig. 15 Torsion fatigue test

obtained against the required strength.

4.3. Wear Resistance at Shaft-Metal Reciprocating Parts

Until the present, researchers have always relied on tests in actual engines to assess wear resistance at shaft-metal reciprocating parts, but this was a concern because it was not possible to make precise assessments of relations between material characteristics and wear. One of the goals of this development was to investigate unit testing methods allowing quantitative assessments. Figure 16 shows a schematic of a unit test apparatus. This apparatus would allow control of the lubricant temperature and sample cycle number. The lubricant contaminated by simulation equivalent to real diesel engine oil was used for the test. Figure 17 is a graph of the relation between test time at a given C concentration and

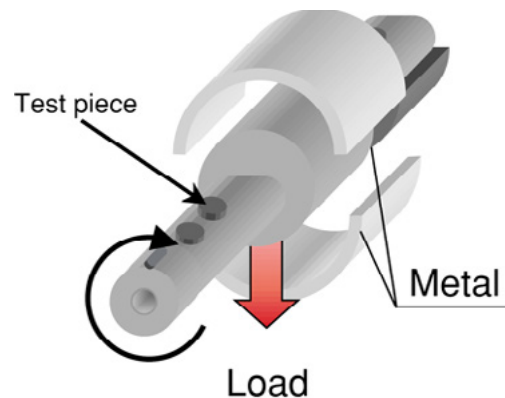


Fig. 16 Wear test of the shaft

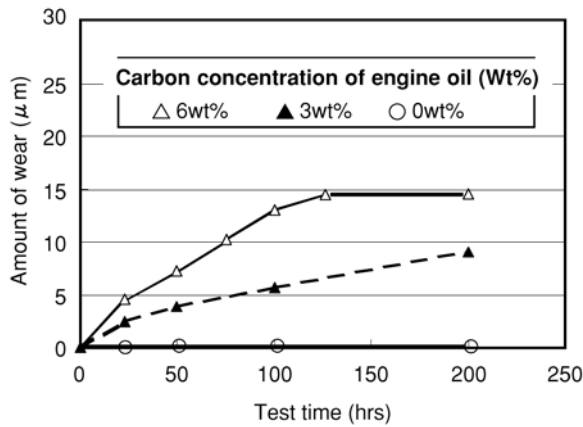


Fig. 17 Relation between test time and wear amount

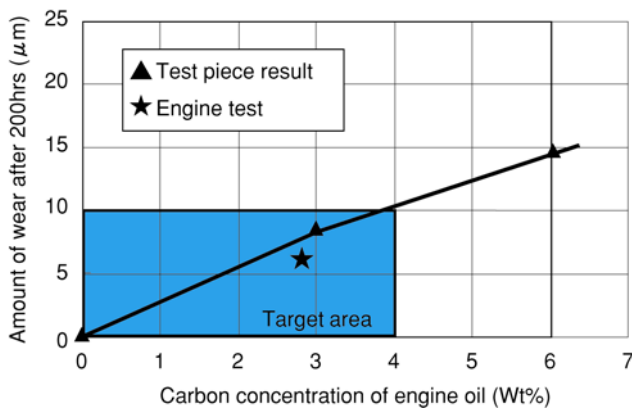


Fig. 18 Wear resistance test

amount of wear. Figure 18 summarizes some of the information in Fig. 17, the relation between carbon concentration in the oil and amount of wear after the 200-hour test. The result shows the amount of shaft wear in an actual engine is almost the same under the identical C concentration. This confirms that this unit evaluation method is valid for estimating the shaft wear in an actual engine in a very short time. This method allowed for the setting of the specifications for materials with superior wear resistance and for induction hardening.

5. Production Technologies

5.1. Correction of Shaft Distortion

The developed crankshaft is induction hardened at the fillets, so hardening-induced distortion was an issue. The following items were investigated as solutions:

- 1) Reducing bending distortion during induction hardening
- 2) Correction of bending distortion after induction hardening

For the first item, tests were carried out on control of hardening patterns on both sides of the fillet, the effect of the order of hardening of the pins and journals, and the characteristics of the distortion, using actual crankshafts. The conditions that resulted in the minimum distortion were selected. Next, the post-treatment correction of bending was investigated for the purpose of reducing axial runout.

Generally, excessive correction applied to shafts after surface hardening processes like induction hardening can lower fatigue strength. Attempts at bending correction of components with too-high interior hardness will also fail to elicit adequate revision of the shape, because the high yield strength is not exceeded. The authors anticipated that this component would respond to correction, however, since the hardness of the developed material had been specified with the need for correction in mind. Bending correction was carried out on crankshafts and they were then tested for fatigue strength. Fig. 19 shows the observed relation between plastic strain and ratio to maintain fatigue strength. This allowed estimation of the limiting plastic strain for obtaining fatigue strength; the maximum allowed correction for the crankshaft was specified on this basis.

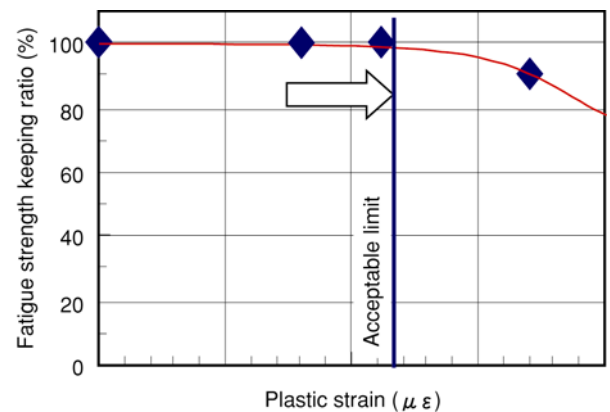


Fig. 19 Relation between plastic strain and fatigue strength

5.2. Machine Workability

As mentioned above, one of the goals of this development effort was to eliminate lead, a conventional additive to improve machinability. Because the crankshaft in this development represented the first application of lead-free material, the following issues were confirmed on the actual production line, and technical improvements were made to the processing conditions.

- 1) Tool slide parameters and RPM settings
- 2) Scrutiny of the tools used
- 3) Cutting oil parameters

Figure 20 shows the final results for miller tool life with relation to life in production of the current crankshaft. The lead-free crankshaft was adopted without sacrifice of current tool efficiency.

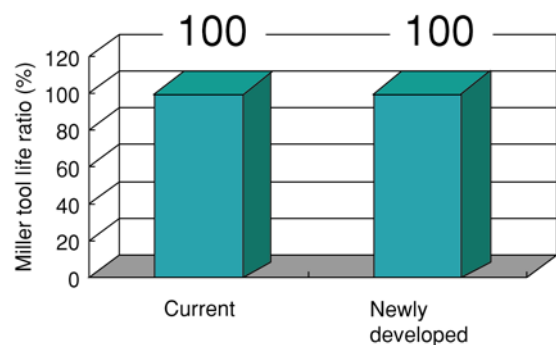


Fig. 20 Machinability result

6. Conclusion

As described above, an induction hardened crankshaft has been developed with superior strength and producibility.

- (1) A material was developed which offers satisfactory workability, hardenability and correctability in shaft components.
- (2) A lead-free steel was made possible by control of sulfide inclusions in the material.
- (3) Optimized oil hole design specifications were established using CAE.
- (4) By setting fillet hardening specifications, the roller burnishing process, which has been adopted for an induction hardened crankshaft in conventional passenger vehicles, was eliminated and the manufacturing process was simplified, while obtaining even higher strength.

This crankshaft is incorporated in the Accord with the Honda-developed diesel engine bound for sale in the European market this autumn.

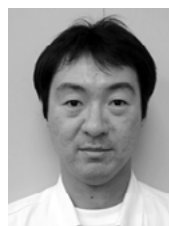
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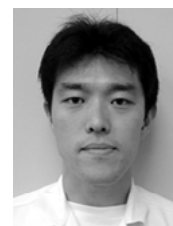
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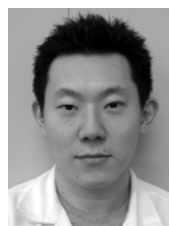
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