

Prediction Method of Low-cycle Fatigue Breakdown in HSDI Diesel Cylinder Head

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ABSTRACT

This paper introduces a method of predicting low-cycle fatigue breakdown that takes as its focus the area around the glow plug hole of the diesel engine cylinder head, where cracks frequently occur during operating modes in which hot and cold cycles are repeated. Because an understanding of the strain amplitude and temperature of the areas in which cracks originate is necessary in predicting fatigue breakdown, strain analyses were conducted using CAE, and at the same time a method of calculating temperature from hardness measurements was used to determine local temperatures. This made it possible to study the local conditions of the cylinder head combustion chamber, which had previously represented a challenge. In addition, a hot-and-cold cycle endurance test using a prototype engine demonstrated the validity of predictions of low-cycle fatigue breakdown using the new method. The project also proposes the incorporation of the method in the design process in order to employ it as a tool for the review of specifications in new engine development.

1. Introduction

The occurrence of cracks between the valve seats of the cylinder head combustion chamber (Fig. 1) due to hot-and-cold cycles has been a major issue in diesel engine development up to the present. This type of cracking is considered to be a thermal fatigue phenomenon⁽¹⁾. When cyclic loads are applied to the combustion chamber during the hot-and-cold cycle, plastic deformation occurs repeatedly, becoming the origin of the cracks.

In this type of cracking due to low-cycle repetition, a method of predicting fatigue life using the strain amplitude as an index is available, as shown by the Manson-Coffin equation⁽²⁾. Because the strength characteristic of materials varies with temperature, it is necessary to measure the temperature of the area under analysis in addition to its strain amplitude in order to predict the fatigue life of the cylinder head combustion chamber.

However, the measurement of the strain amplitude while the engine is in operation is highly technologically challenging. Up to the present, methods such as the estimation of the strain amplitude from the comparatively more easily measured temperature, based on the relationship between strain amplitude and temperature in a limited operating area, have been attempted (Fig. 2). Such

estimates are, however, not always sufficiently accurate, and it has not been possible to accurately predict fatigue life. Because of this, there has been no option but to use endurance tests involving actual engines as the main means when attempting to verify the durability and reliability of engines, resulting in an increase in the number of engine prototypes constructed.

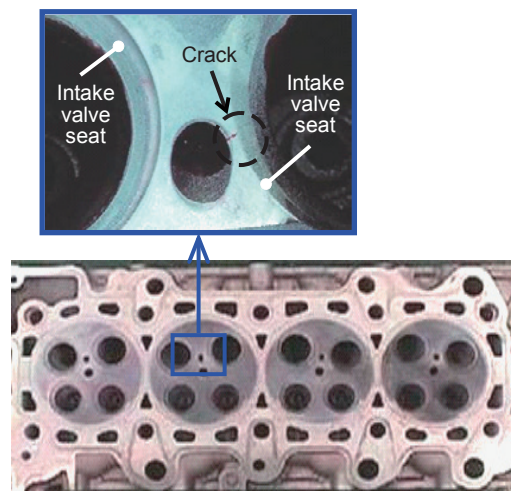


Fig. 1 Crack found beside glow plug hole

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The research discussed in this paper, therefore, attempted to formulate a method of accurately measuring and analyzing the temperature and strain amplitude of the areas in which cracks originate, in addition to attempting to predict the occurrence of cracks during the hot-and-cold cycle by studying the conditions of strain amplitude and temperature in each part of the combustion chamber and comparing this with the fatigue limit diagram of the heat cycle for the cylinder head material.

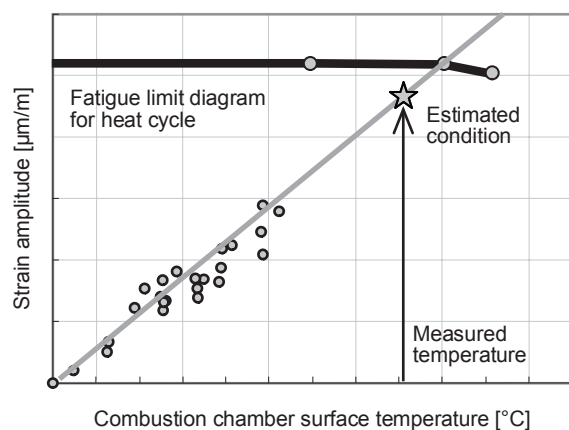


Fig. 2 Estimation of combustion chamber surface condition based on measured temperature

2. Method of Prediction of Low-cycle Fatigue Breakdown

2.1. Subject of Analysis

Hot-and-cold cycle endurance tests were conducted using prototype engine A in order to develop and verify a method of prediction of low-cycle fatigue breakdown in the cylinder head combustion chamber. Figure 3 shows an overview of hot-and-cold cycle test mode 1, which was used in the present research. This endurance test mode was selected because past experience of the development of diesel engines has indicated that of several test modes available, it is severe and thus appropriate for evaluation of cracking in the cylinder head combustion chamber. For the present research, this test mode was repeated approximately 104 times. The status of cracking in each part of the combustion chamber was varied by varying the temperature of the surface of the combustion chamber, giving four separate endurance test cases in which the cooling conditions and the combustion conditions were changed. Table 1 shows the endurance test conditions and the state of the cylinder head combustion chambers following completion of the tests. The temperatures beside the glow plug holes and the temperatures between the exhaust valves as shown in Table 1 are the highest surface temperatures reached during the endurance test modes, and were measured on flat areas of the surface using thermocouples.

In Case 1, cracks occurred between the intake valve seats (beside the glow plug hole) (“a” in Table 1), between the exhaust valve seats (“b” in Table 1), and between the intake and exhaust valve seats (“c” in Table 1) on the surface of the cylinder head combustion chamber. In Case 2, cracks occurred beside the glow plug hole and between the intake and exhaust valve seats, and in Case 3, cracks occurred beside the glow plug hole. No cracks occurred in Case 4.

Figure 4 shows the results of observation of the fracture face of a crack beside the glow plug hole. Generally, the glow plug hole is a hole drilled in the surface of the cylinder head combustion chamber by machining; the surface of the cylinder head combustion chamber is also formed by machining. Because of this, the glow plug hole has a right-angled or obtuse-angled edge. Observation of fracture faces showed that cracks originated on the edge of the glow plug hole rather than on the flat sections of the surface of the combustion chamber. The project therefore worked towards prediction of low-cycle fatigue breakdown with this area as the subject of analysis.

2.2. Method of Analysis of Strain Amplitude

When a strain gauge is used to measure strain, because it is not possible to directly attach the gauge to the edge of the glow plug hole, local measurements of strain cannot be taken. In addition, the limits of the heat resistance of the strain gauge prevent measurements from being taken

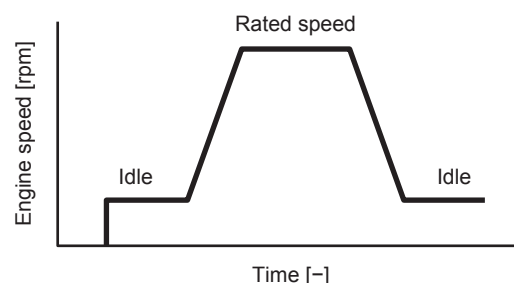


Fig. 3 Hot and cold cycle test mode 1

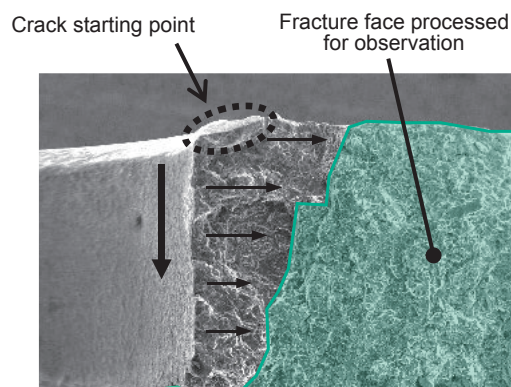
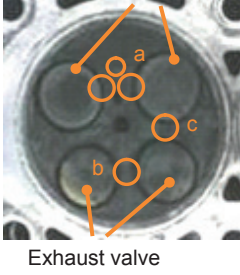
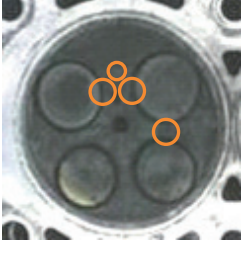


Fig. 4 SEM image of broken-out section of crack beside glow plug hole

Table 1 Hot and cold cycle endurance test conditions and resulting cracks

Prototype engine A					 Indicates location of crack observed after test
Case No.	1	2	3	4	
Occurrence of cracks					
Engine load	Full load	Full load	Full load	Full load	
Coolant temperature [°C]	96	97	80	82	
Coolant flow rate	Base	Base +75%	Base +26%	Base +39%	
Nozzle cone angle	Base	Base	Base	Base -3 deg	
Temperature beside glow plug hole [°C]	282	253	226	225	
Temperature between exhaust valve seats [°C]	298	256	236	230	

in high-temperature environments at high engine output. A strain analysis was therefore conducted using computer-aided engineering (CAE).

The generation of strain due to inhomogeneous temperature distribution in the combustion chamber and the concentration of that strain is thought to be the origin of cracking in the cylinder head combustion chamber during hot-and-cold cycle endurance tests. Figure 5 shows the average temperature distribution in the combustion chamber during the cycle. The temperature is high at the center of the combustion chamber, in particular at the injector hole. The high temperature at the center of the combustion chamber results in thermal expansion towards the external circumference of the chamber. By contrast, the

rate of thermal expansion of the external circumference of the combustion chamber is lower than that of the center, because its temperature is comparatively low. This difference in the rate of thermal expansion due to inhomogeneous distribution of temperature results in compressive strain in the radial direction in the combustion chamber. It is thought that this compressive strain concentrates in areas with a low cross-sectional area, such as beside the glow plug hole and between the valve seats, and that these areas of concentrated strain become the origin points of cracks with repeated hot-and-cold cycles.

The flow of the analysis was therefore established as follows: first the temperature distribution was determined by means of a thermal analysis, then a strain analysis was conducted on the basis of the temperature distribution. The analysis followed the order (1) to (5) described below (Fig. 6):

- (1) A finite element method (FEM) model of the cylinder head was formulated (Fig. 7).
- (2) Heat transfer coefficients determined using computational fluid dynamics (CFD) analysis were mapped onto the surfaces of the water jacket in the FEM model, and thermal boundary conditions were imparted. VECTIS (a three-dimensional fluid dynamics program) was used as the analytic solver.
- (3) Thermal boundary conditions were imparted to the combustion chamber and other cylinder head surfaces. The area was segmented and figures for gas temperature and heat transfer coefficient were set in such a way

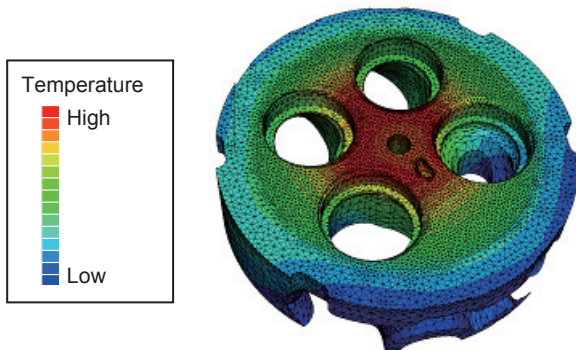


Fig. 5 Temperature distribution of combustion chamber surface

that the analysis results would agree with the results of thermocouple measurements of the combustion chamber surface temperature under the same operating conditions as an actual endurance test. The thermal boundary conditions were set in response to the higher and lower temperatures occurring during the endurance test mode, occurring at rated output and during idling, respectively. Here, measurements should be taken at multiple points

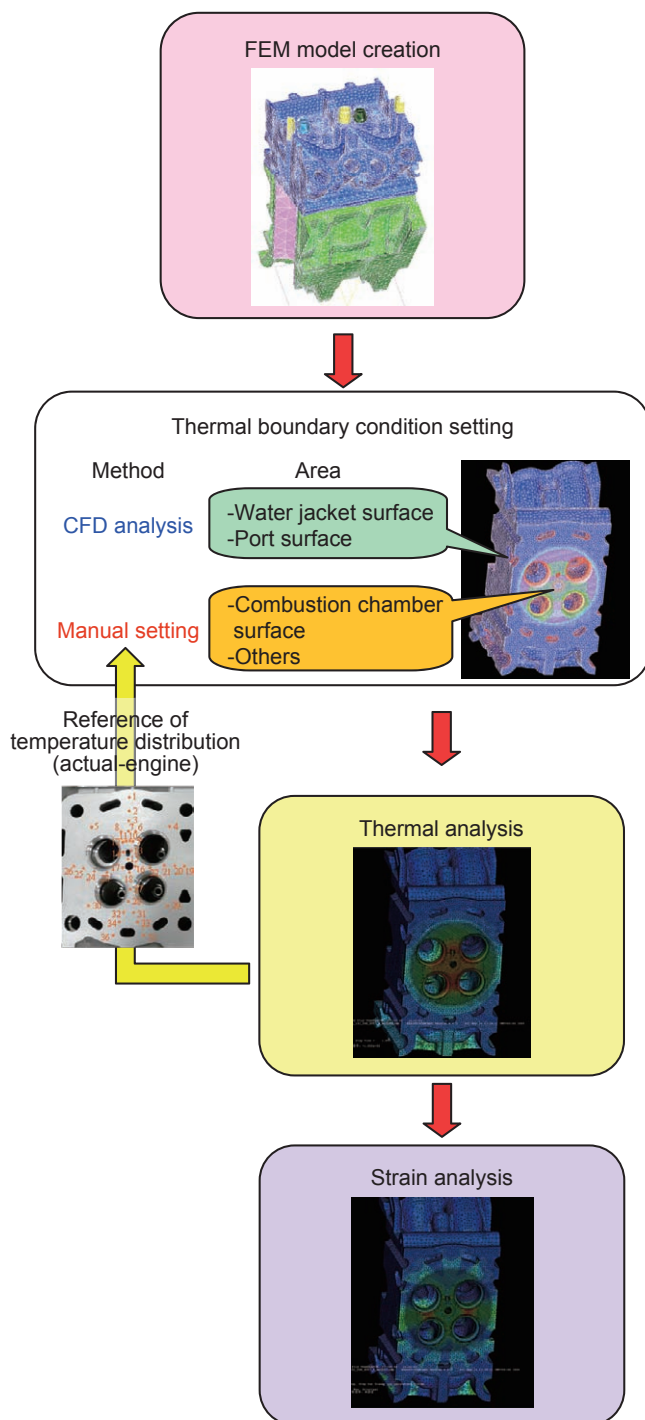


Fig. 6 Flow diagram of strain analysis

in order to determine the temperature distribution of the combustion chamber using thermocouples.

- (4) A thermal analysis was conducted using ABAQUS (a general purpose nonlinear finite element analysis program).
- (5) The strain amplitude during hot-and-cold cycles was analyzed based on the determined temperature distribution. ABAQUS was used as the analytic solver, as in the case of the temperature analysis.

There are also examples in which a combustion analysis using CFD has been conducted as the stage of imparting thermal boundary conditions to the surface of the combustion chamber^{(3), (4)}. Figure 8 shows the flow of the analysis in this case. However, accurately modeling the actual state of combustion using CFD necessitates numerous processes – an in-port pulsation analysis, an in-cylinder flow analysis, a spray analysis, and a combustion analysis – and a high level of analytic accuracy is necessary for each of these processes. Spray and combustion analyses in particular involve a large expenditure of time for the coordination and verification of multiple parameters. In addition, it is necessary to compare the results of a combustion analysis with the results of temperature measurements taken in an actual engine as one means of verification of the accuracy of the analysis. Taking into consideration the main purpose of the analysis in predicting low-cycle fatigue breakdown and the reduction of computation time, the method shown as (3) above was devised in the case of the present project. Figure 9 shows an example of the setting of thermal boundary conditions for the combustion chamber for the high-temperature state of the endurance test mode using this method. Figure 10 compares the temperature of the surface of the combustion chamber at this state as measured using thermocouples and as determined by a CAE thermal analysis.

The relationship between temperature and strain amplitude determined in Step (5) using CAE was compared with actual measurements taken using thermocouples and strain gauges. The area compared was the flat section beside the glow plug hole, as shown in Fig. 11. Figure 12 shows the results of the comparison.

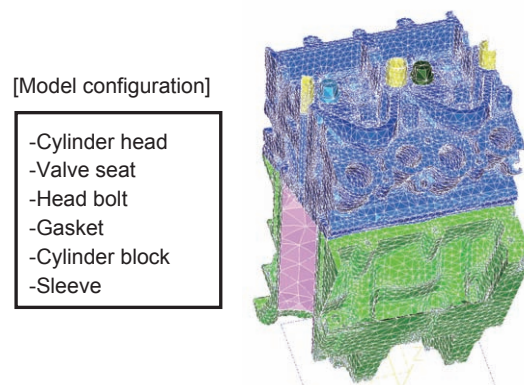


Fig. 7 FEM model configuration

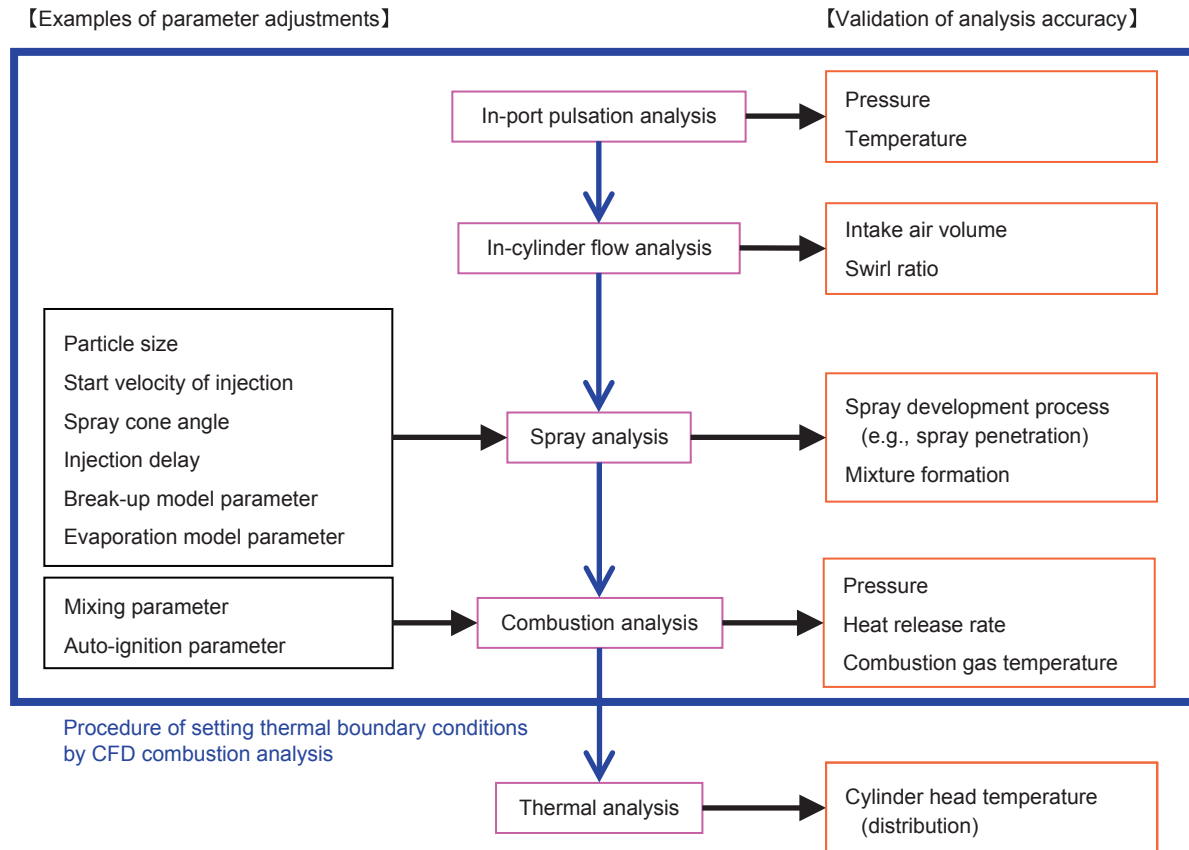


Fig. 8 Procedure of CFD combustion analysis and examples of parameters and validation at each step

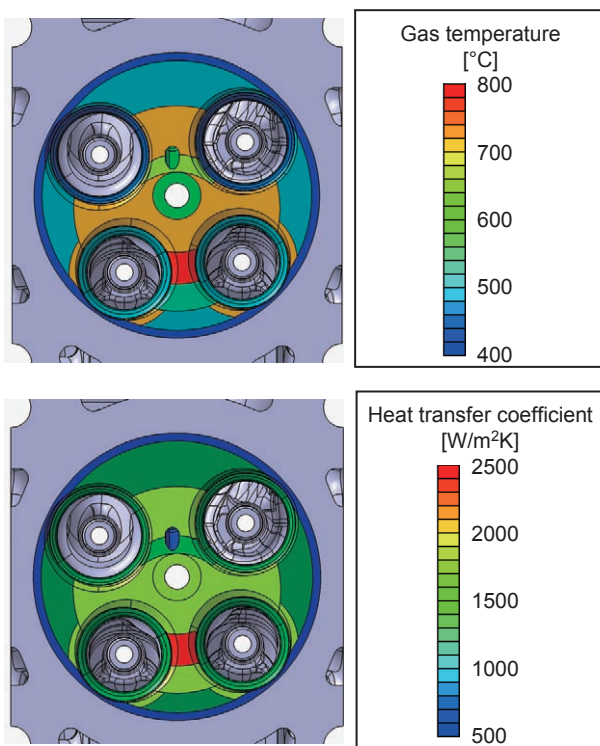


Fig. 9 Combustion chamber thermal boundary conditions (high-temperature state of endurance test)

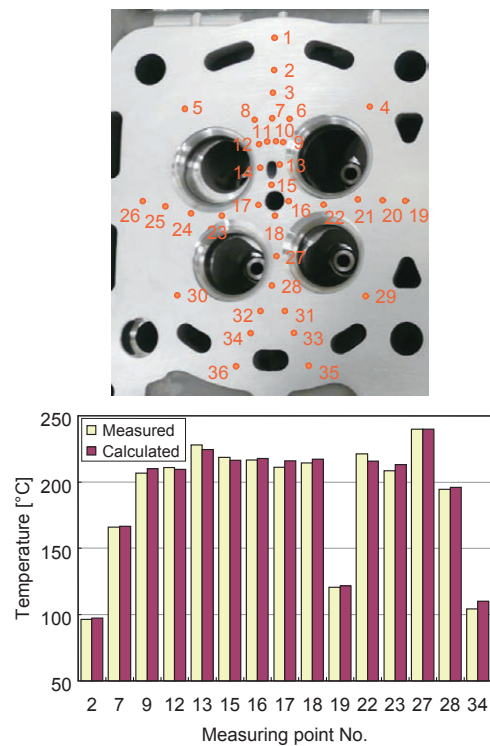


Fig. 10 Measured and calculated values of combustion chamber surface temperature (high-temperature state of endurance test)

The temperatures shown on the horizontal axis are the highest temperatures reached in the flat area during the endurance tests. The CAE results correspond well with the approximation curve for the strain amplitude against temperature as determined from actual measurements. In addition, study of the points at which the maximum strain amplitude was generated in the CAE results showed that they corresponded to the specific points at which cracks originated during actual endurance tests (Fig. 13).

2.3. Method of Analysis of Local Temperature

Next, a detailed analysis of the surface temperature beside the glow plug hole was attempted. Thermocouples are generally employed as the method of measuring the surface temperature of combustion chambers. However, as in the case of strain gauges, it is not possible to directly embed thermocouples in the edge of the glow plug hole. The conventionally used method has therefore been to take temperature measurements using thermocouples on the adjacent flat area to the edge, and to use these temperatures as representative of the temperature of a given area which includes the edge.

In the present project, in addition to temperature measurements using thermocouples, the local temperature

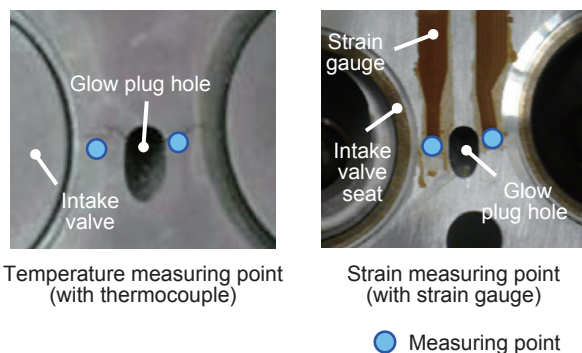


Fig. 11 Temperature and strain measuring points beside glow plug hole

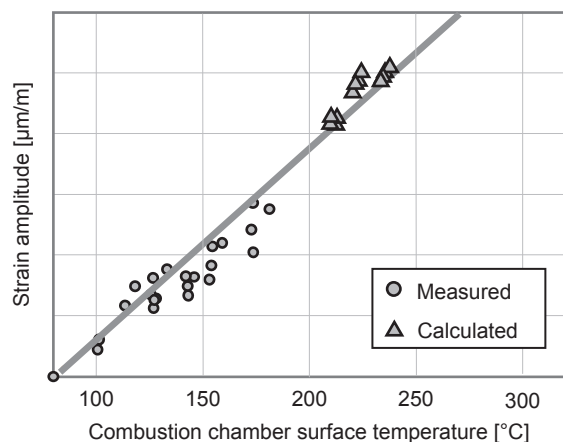


Fig. 12 Measured and calculated strain amplitudes and temperature beside glow plug hole

of peripheral areas including the glow plug hole edge was determined by means of a method of converting to temperature from measurements of the hardness of the surface of the combustion chamber, using the overaging characteristic of the material (termed “the hardness method” below). The order of the analysis is described in (1) to (4) below.

- (1) Temperature measurements of the surface of the combustion chamber were taken under the same conditions as the endurance test, using thermocouples.
- (2) The hardness of the surface at the same points at which temperature measurements were taken was measured using the Vicker’s method⁽⁵⁾.
- (3) The correlation function between the temperature measurements taken using the thermocouples and the hardness measurements was determined. The temperatures employed were the highest temperatures reached during the endurance test modes.
- (4) The hardness of arbitrary points was measured, and the local temperature was calculated using the correlation function determined in Step (3).

Figures 14(a), (b), and (c) respectively show examples of temperature measurements, hardness measurements, and the correlation function obtained from them. The relationship between surface hardness and the temperature reached following hot-and-cold cycle endurance tests can be approximated as a line. By this means, the temperature of the edge can be found from the hardness of the edge.

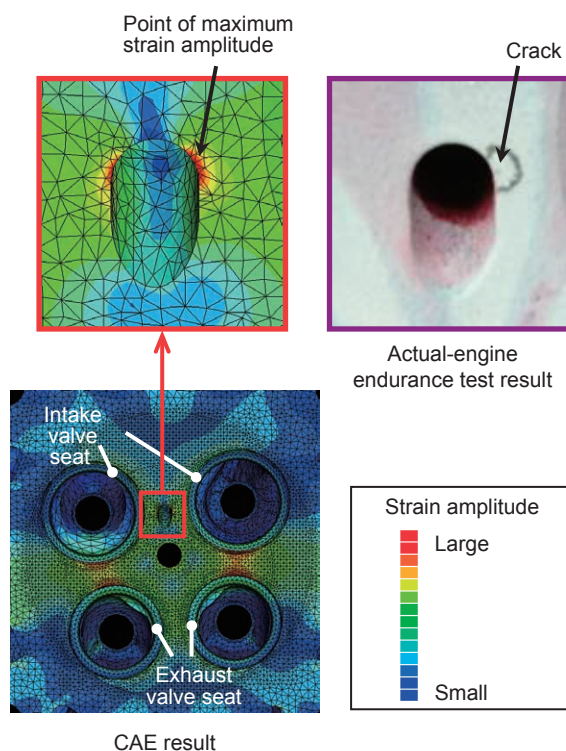


Fig. 13 Strain amplitudes in hot and cold cycle endurance test

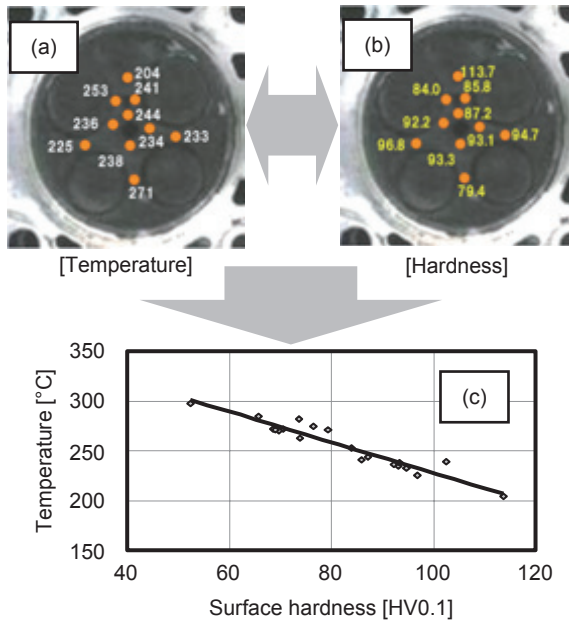


Fig. 14 Relationship between temperature and hardness of combustion chamber surface

Case No.	2
Crack occurrence	Yes
Flat area temperature	253 °C
Edge temperature	278 °C
Flat area temperature measuring point (with thermocouple)	

[Hardness measuring position]
Hardness was measured along lines L1 and L2 from the edge as the origin.
(crack starting point to propagation area)

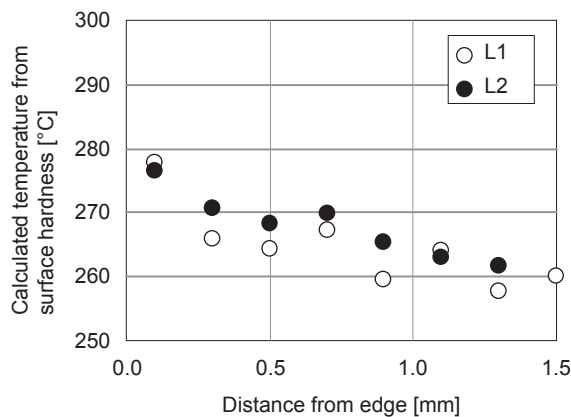


Fig. 15 Edge temperature calculation from measured hardness

Figure 15 shows temperatures beside the glow plug hole for the hot-and-cold cycle endurance test in Case 2, determined using this method. The edge temperature determined using the hardness method was 278°C, 25 °C higher than the temperature measured in the flat area using a thermocouple. The new method showed that a large temperature gradient (following lines L1 or L2 in the figure) existed within even a mere 1.5-mm range, and local high temperatures occurred in the edge, the origin point of cracks.

Figure 16 shows a comparison of temperatures beside the glow plug hole for Cases 3 and 4. While there was virtually no difference between the cases in terms of the temperatures of the flat areas as measured using thermocouples (226°C and 225°C), there was a difference from the perspective of occurrence of cracks. In Case 4, the temperature distribution of the combustion chamber was deliberately varied locally by varying the state of combustion through changes in the injector nozzle cone angle. Accordingly, when the temperature of the edge of the glow plug hole was determined using the hardness method, it was found that a 20°C temperature difference

Case No.	3	4
Crack occurrence	Yes	No
Nozzle cone angle	Base	Base -3 deg
Flat area temperature	226 °C	225 °C
Edge temperature	255 °C	235 °C
Flat area temperature measuring point (with thermocouple)		

[Hardness measuring position]
Hardness was measured along lines L3 and L4 from the edge as the origin.
(crack starting point to propagation area)

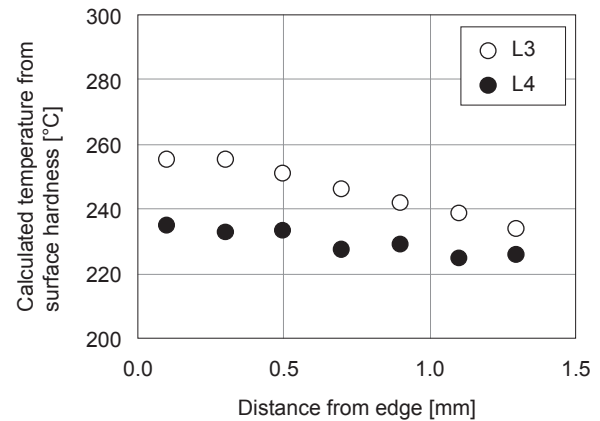


Fig. 16 Influence of nozzle cone angle on edge temperature

existed, with the edge reaching 255°C in Case 3, in which cracking occurred, but only 235°C in Case 4, in which no cracking occurred. It is conjectured that this localized difference in temperature was related to the significant difference between the cases in the occurrence of cracking. As this indicates, determining the temperature of the edge, where cracks originate, is an important factor in predicting fatigue breakdown. It was also shown that the calculation of temperature based on hardness measurements was an effective method of doing so.

2.4. Fatigue Limit for Heat Cycle of Cylinder Head Materials

In order to predict fatigue breakdown based on the strain amplitudes and temperatures determined as described in Sections 2.2 and 2.3, a criterion based on the strength characteristic of the cylinder head material was necessary. Unit tests were therefore conducted on the material used for the cylinder head, and an attempt was made to use the obtained limit strain amplitude as a criterion of fatigue breakdown.

The limit strain amplitude was determined in steps (1) to (5) below (Fig. 17):

(1) AC2B-T6^{(6), (7)} was used as the material for the test pieces. Table 2 shows the chemical composition of

Table 2 Chemical compositions of AC2B alloy [wt%]

Si	Cu	Mg	Zn	Fe	Mn	Ni	Al
6.3	3.2	0.17	0.01	0.13	<0.01	<0.01	Balance

the material. With regard to heat treatment conditions, following heating at 500°C for four hours, the material was quenched in water, after which it was subjected to aging treatment at 200°C for four hours. The test piece was a round bar with an external diameter of 7 mm, and a distance of 12 mm was used between reference points.

- (2) With the local conditions in which cracks would occur in mind, endurance tests were conducted, imparting a temperature and strain cycle in which compressive strain occurred repeatedly at high temperatures and tensile strain occurred repeatedly at low temperatures (out-of-phase heat fatigue cycle) to the test piece. For strain control, an extensometer was used to set conditions such that the total amplitude of mechanical strain was a range from 0.6 to 1.6%. An induction heater was used for heating, and natural convection for cooling. The temperature cycles were 50 to 200°C, 50 to 250°C, and 50 to 280°C.
- (3) Cycle to fatigue failure was plotted against the strain amplitudes determined from the tests, and the limit

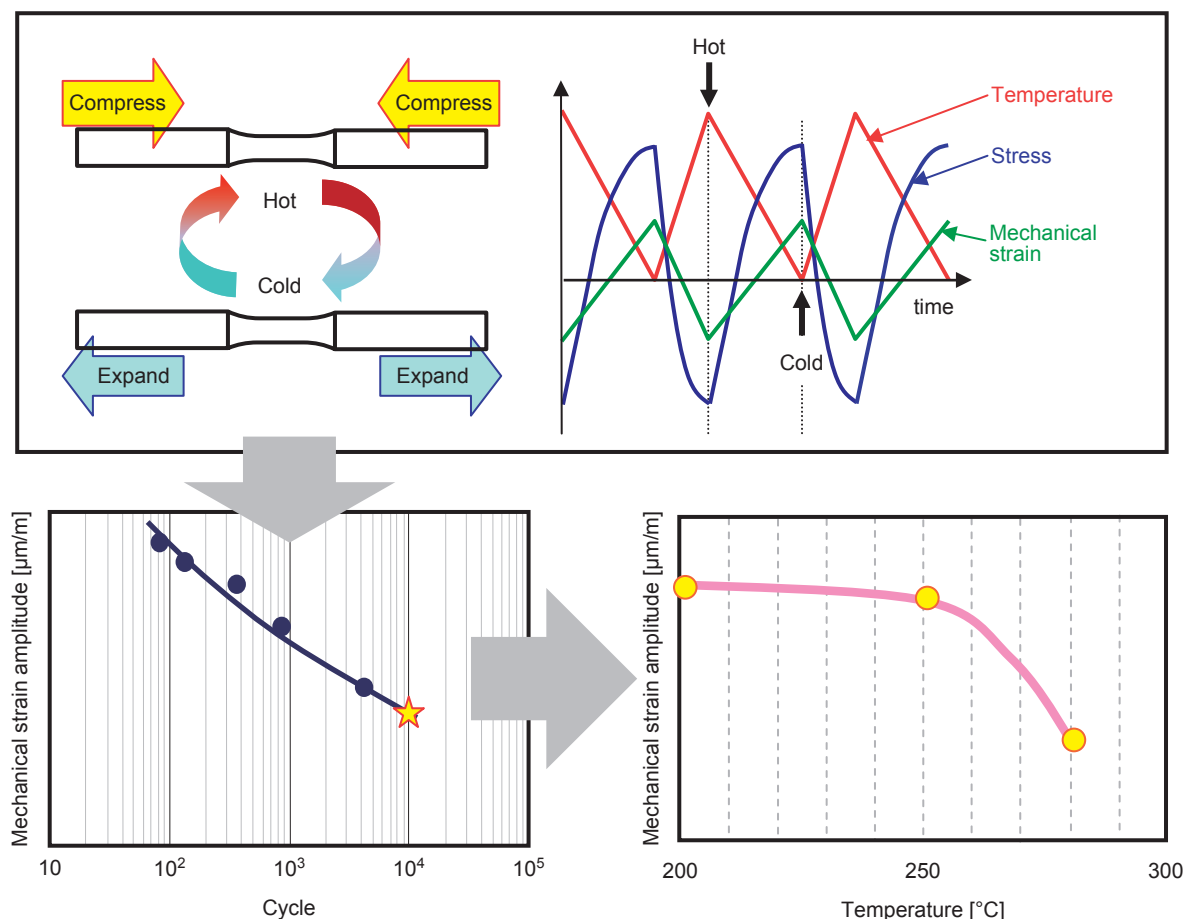


Fig. 17 Steps taken to obtain material fatigue limit diagram for heat cycle

strain amplitude (failure probability: 50% (B50)) for 104 cycles was obtained.

- (4) The limit strain amplitude discussed above was found for each temperature cycle.
- (5) The limit strain amplitude for the highest temperature reached during each temperature cycle was plotted on a strain amplitude-temperature graph, and the fatigue limit diagram for the heat cycle was determined for the cylinder head material.

3. Results of Combustion Chamber Analysis and Verification of Effectiveness of Technology for Prediction of Low-cycle Fatigue Breakdown

The strain amplitude and temperature of the surface of the combustion chamber during a hot-and-cold cycle endurance test were determined using the method described above, and compared with a fatigue limit diagram for the heat cycle. The results are shown in Fig. 18. The graph shows only results for edges where the possibility of cracking is high. Circles mark areas in which cracks did not occur, while crosses mark areas in which cracks occurred. As evidenced from the graph, the occurrence of cracking during a hot-and-cold cycle endurance test can be studied on the basis of the relationship between strain amplitude and temperature and the fatigue limit diagram for the heat cycle obtained using this method.

Focusing on the margin of each section of the combustion chamber in relation to the fatigue limit diagram, it is greatest in the case of the edge between the exhaust valve seats, followed by the edge between the intake and exhaust valve seats, and the edge of the glow plug hole.

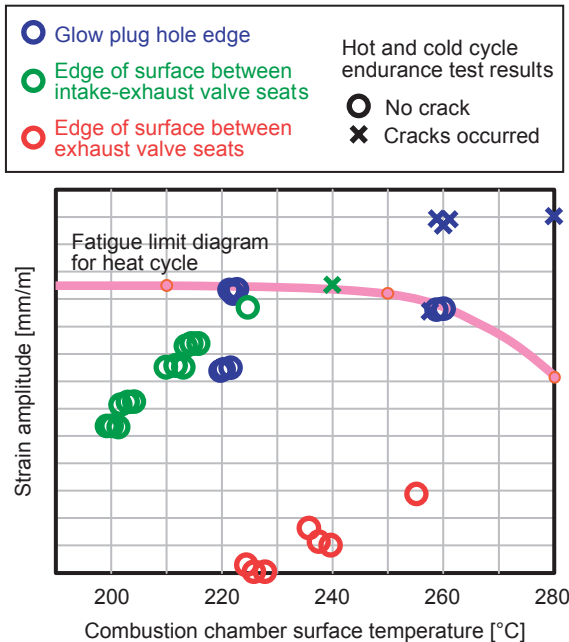


Fig. 18 Strain amplitudes and temperature of prototype engine A

Table 3 Prototype engines A and B - changes in specifications

	Prototype engine A	Prototype engine B
Engine output	Base	Base +10%
Fuel injection timing	Base	Base +2 deg advance
Valve skew angle	Provided	None
Coolant flow direction in cylinder head	Longitudinal flow	Cross flow
Coolant flow rate	Base	Base +17%

This accords with the tendency displayed when the number of points of occurrence of cracking was gradually reduced in a series of hot-and-cold cycle endurance tests (Table 1).

In order to verify the effectiveness of the new method of predicting low-cycle fatigue breakdown, it was incorporated in the cylinder head design process, and new engine specifications and geometries were designed to maintain the conditions of the surface of the combustion chamber during hot-and-cold cycle endurance tests within the range determined by the fatigue limit diagram. Prototype engine B was constructed on this basis. Table 3 shows the main points of difference between engine A and engine B. As was the case previously, an endurance test was conducted using hot-and-cold cycle test mode 1 and the occurrence of cracking was studied. Figure 19 shows the conditions of strain amplitude and temperature and the occurrence of cracking, focusing only on the edges for which the potential for cracking is high.

As in the case of prototype engine A, the area in which

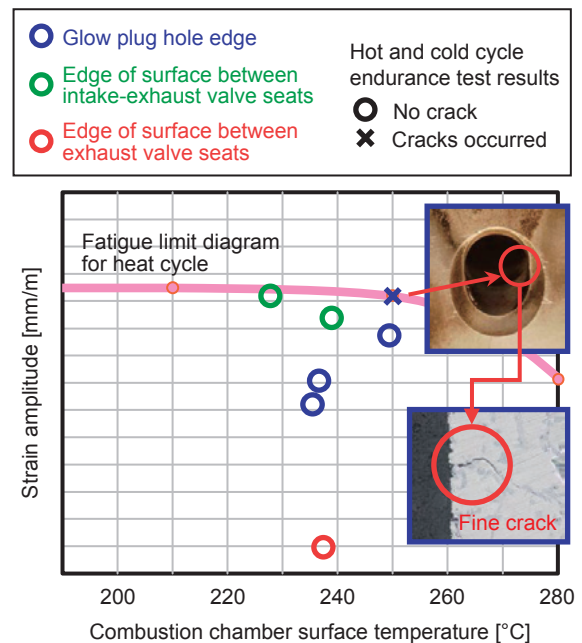


Fig. 19 Strain amplitudes and temperature of prototype engine B

the potential for cracking was highest in prototype engine B was the edge of the glow plug hole. This area was almost entirely on the curve of the fatigue limit diagram. When the area was studied in detail using an optical microscope following the completion of the hot-and-cold cycle endurance test, a microscopic crack of approximately 50 μm was discovered.

The results discussed above show that the new method is effective in the prediction of low-cycle fatigue breakdown during hot-and-cold cycle endurance tests, even for engines of differing specifications.

4. Proposal for Cylinder Head Design Process using New Method

A method of incorporating the new method in the new engine design process is proposed (Fig. 20). The magnitude of the strain amplitude in the cylinder head combustion chamber and the inhomogeneous combustion chamber temperature distribution that produces it originate in the shape of the combustion chamber, in particular the valve layout, the combustion conditions, and the cooling

conditions of the cylinder head. Because these factors not only affect the durability of the cylinder head, but impact on a wide range of areas including engine power, it would be desirable to establish appropriate parameters at the initial stage of engine development. It would therefore be effective to front-load the prediction of low-cycle fatigue breakdown at the stage of formulation of engine specifications by incorporating the new method in the development process.

The rapid prototyping engine in Fig. 20 is designed to test estimations of the temperature increase of the edges, and estimations of gas temperature and heat transfer coefficient. Because of this, the engine need only be constructed with the minimum shape and specifications to fulfill this purpose. It would be desirable if such an engine could be designed and developed in a short period of time.

The future goal of the authors is to introduce the CFD combustion analysis shown in Fig. 8 into the CAE strain analysis flow shown in Fig. 6, and to incorporate this in the design process. However, taking into consideration the level of analytic accuracy of CFD and the time necessary for the calculation of full combustion models, the process proposed in this paper can, at present, be deemed the more feasible.

5. Conclusion

An attempt was made to develop a method of prediction of low-cycle fatigue breakdown in cylinder head combustion chambers. The following results were obtained:

- (1) Cracks originate in edges; because both the strain amplitude and the temperature of the edges differ from those of adjacent flat areas, understanding the local conditions of these parameters is necessary for the prediction of cracking.
- (2) Taking the area around the glow plug hole as the subject of analysis, it was shown that valid figures for strain amplitude and temperature could be obtained, respectively, by CAE strain analyses and the hardness method.
- (3) Fatigue limit diagrams for heat cycles, plotted using limit strain amplitudes that were obtained from unit heat fatigue tests on materials, were compared with the conditions of strain amplitude and temperature obtained from CAE and the hardness method. By this means, it was made possible to accurately predict low-cycle fatigue breakdown in cylinder head combustion chambers during hot-and-cold cycle endurance tests.
- (4) It would be desirable to front-load a method of prediction of low-cycle fatigue breakdown in the new engine development process, and it was possible to incorporate the new method in the design process within the time constraints demanded in engine development.

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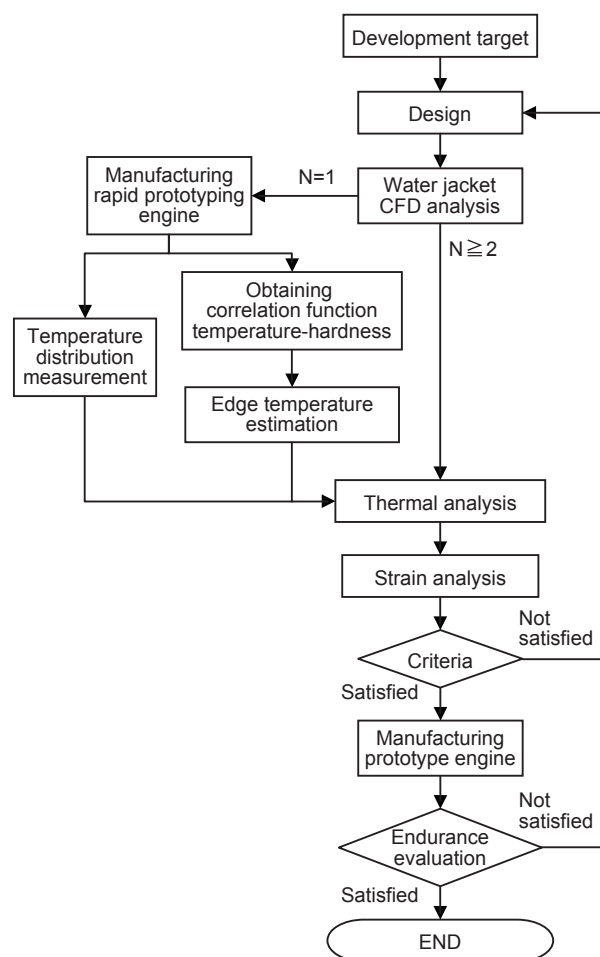


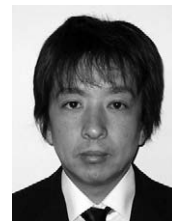
Fig. 20 Proposal of low-cycle fatigue evaluation in design process

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