

Prediction Technology for Thermal Mechanical Fatigue Strength of Cylinder Head

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ABSTRACT

A method was established for predicting the thermal mechanical fatigue strength of a cylinder head without the need for verification by engine tests. The accuracy of thermal analysis was enhanced by revising the turbulent model and physical property values used in CFD calculations to calculate the thermal boundary conditions. Thermal mechanical fatigue analysis used a material model that takes into account the kinematic hardening rule and hardness overaging, which is dependent on temperature. The analysis accuracy was also increased by changing the bolt connection model from FEM node merging to multi-point constraint connection. Engine durability tests using an actual engine were performed to verify the accuracy of this CAE prediction technology, and the results confirmed that cracks occurred at the durability test cycle predicted by CAE. This research helped eliminate the former need for verification with measured temperatures, and enabled model-based prediction of thermal mechanical fatigue strength in the design phase.

1. Introduction

Automobile engines face increasing demands for higher power, better fuel economy, and lower emissions. This is creating the need to address higher exhaust gas temperatures due to the ending of fuel rich operation in order to protect exhaust parts, and increased thermal load due to higher specific power produced by turbocharged downsizing engines, etc.

The cylinder head consists of a combustion chamber and exhaust port, which are exposed to high temperature, high-pressure flames and combustion gases, a water jacket through which coolant flows, a cam chamber with valve system and oil passages that are exposed to engine oil, and an intake port that is a passage for fresh air. This means that even though the cylinder head is a single part, the thermal distribution in the operating condition exhibits large deviation, which produces thermal strain. The locations where thermal mechanical fatigue (TMF) strength due to high thermal load is an issue are the combustion chamber and exhaust port, which become hot during operation, and

the adjacent water jacket. It is a challenge to measure these locations with strain gauges, so CAE has been used to predict TMF.

TMF^{(1), (2)} accumulates due to repeated thermal strain produced by changes in both the thermal distribution and stiffness distribution stemming from the material properties and constraints. Factors producing thermal strain in the cylinder head can be divided by constraint type into the two types of internal constraint and external constraint, and thermal strain occurs due to the compound action of these constraints. Thermal strain due to internal constraint is produced by differences in thermal expansion due to deviation of the thermal distribution within a single part. For example, thermal strain is produced by relatively cooler surrounding areas constraining the hot combustion chamber. In contrast, thermal strain due to external constraint arises from constraint by other parts. For example, when the turbocharger undergoes thermal expansion, force is transmitted to the connections with the cylinder head via the bolts, which produces strain.

Evaluation of TMF strength calls for accurate prediction

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of thermal strain. However, the previous evaluation method had the following issues. First, it is necessary to perform temperature verification for CAE using the temperature measurement results in an actual engine using a cylinder head with approximately temperature measurement 100 points. This takes a period of around half a year from design to evaluation. Second, the CAE-based strain prediction accuracy was low in high-temperature, high-strain locations, and it is necessary to take into account more detailed material properties. Third, the turbocharger is high-temperature and high-stiffness and exhibits large thermal expansion, so high strain is produced around the bolt connections with the cylinder head. However, the contact model of the bolt connections did not match the actual situation, and the strain prediction accuracy was low. CAE verification previously used the temperature measurement results for the initial prototype, and if the TMF strength evaluation results did not satisfy the evaluation criteria in the condition with these issues remaining, the cylinder head had to be redesigned and durability tests repeated, which resulted in major development reworking. If the TMF strength evaluation results did not satisfy the evaluation criteria, the cylinder head had to be redesigned and durability tests repeated, which resulted in major development reworking.

2. Technological Elements of Evaluation Method

Figure 1 shows the system diagram for generation of thermal strain. Factors producing thermal strain can be divided into thermal distribution and stiffness distribution factors. Figure 2 shows the flow of CAE for TMF strength evaluation. First, the thermal boundary conditions of the exhaust port and water jacket are calculated by CFD, and then thermal analysis is performed. The calculated thermal distribution is used to perform TMF analysis, and the strain is extracted from the calculation results and used to evaluate the mechanical fatigue strength.

In order to address the previously mentioned issues for prediction of TMF strength, it is necessary to enhance the thermal boundary condition, material behavior, and constraint analysis accuracy. The key factors for calculating the thermal boundary conditions are the turbulent model used in CFD and the heat transfer coefficient calculation formula. The key factors for material behavior are the hardening rule and hardness overaging under a high temperature environment, and the key factor for constraint is the bolt connection model. This research performed the following contents with the goals of reducing redesign and durability test repetition and enabling evaluation of TMF strength in the design phase.

- (1) Develop a method for calculating the thermal boundary conditions in order to achieve accurate thermal analysis without the need for verification using an actual engine.
- (2) Develop a material model capable of reproducing

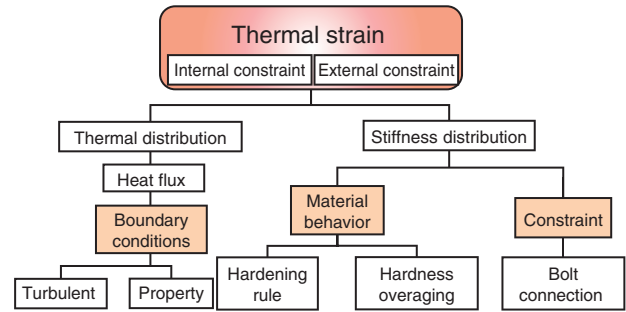


Fig. 1 Diagram of thermal strain factors

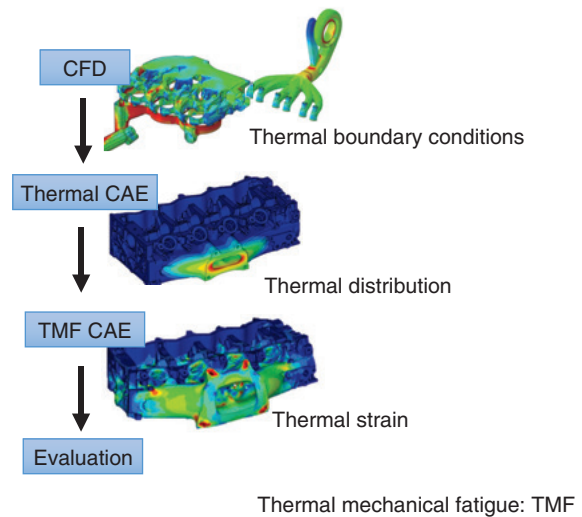


Fig. 2 Analysis flow of TMF evaluation

nonlinear properties of materials under high thermal loads.

- (3) Develop a connection model capable of reproducing the strain around bolt connections.

3. Development of Evaluation Method

3.1. Thermal Boundary Conditions

The methods used to calculate the thermal boundary conditions were revised to achieve a thermal analysis accuracy that would enable TMF strength evaluation in the design phase; that is to say, before verification using an actual engine is possible (Table 1). Here, the thermal boundary conditions are the heat transfer coefficient (HTC) from the fluid and the fluid temperature near the wall surface (hereafter, the boundary temperature). The CFD calculation method for the water jacket and exhaust port was revised, and CFD-based combustion analysis was newly performed for the combustion chamber. The target thermal analysis accuracy was $\pm 10^\circ\text{C}$.

Table 1 Thermal boundary conditions

		Previous method	New method
Water jacket and exhaust port	Turbulent model	Standard $k-\varepsilon$	Realizable $k-\varepsilon$
	Gas/LLC property	Constant	Variable with temperature
Combustion chamber	Boundary condition	Empirical value	Combustion CFD

3.1.1. Thermal boundary conditions of water jacket and exhaust port

The thermal boundary conditions of the water jacket and exhaust port are the HTC and the constant value boundary temperature obtained by CFD. The HTC of the water jacket was calculated by performing steady-flow analysis. The HTC of the exhaust port was obtained by performing unsteady-flow analysis for pulsating flow, using the average of the HTC at each crank angle.

Both the water jacket and the exhaust port are complex passages, so reproduction of separation and reattachment phenomena can be expected to enhance the HTC analysis accuracy. A more appropriate turbulent model was therefore investigated. The reproducibility of separation and reattachment was verified using the back-step flow model⁽³⁾,⁽⁴⁾ often referenced for accuracy verification of turbulent models [Fig. 3(a)]. The turbulent model was changed from the previous standard $k-\varepsilon$ model to a realizable $k-\varepsilon$ model⁽⁵⁾. This increased the separation and reattachment flow analysis accuracy, which enhanced the reproducibility of the pressure coefficient distribution on the wall surface [Fig. 3(b)].

Furthermore, in thermal analysis using the exhaust port HTC calculated by the previous method, the temperatures inside the exhaust port tend to be higher than measurements, so temperature adjustment was performed by multiplying with a coefficient of approximately 0.6 to 0.8. It is thought that because the physical property values of exhaust gas vary greatly at different temperatures, use of constant exhaust gas physical property values when calculating the HTC increased the HTC deviation. Thus, a new HTC calculation method was developed that uses physical property values that are functions of temperature.

Figure 4 shows the verification results of thermal analysis accuracy due to changing the turbulent model and revising the HTC calculation method. For comparison purposes, the exhaust port HTC uses the CFD calculation results without multiplication by a coefficient. Thermal analysis using thermal boundary conditions obtained by the new method achieved a prediction accuracy of $\pm 10^\circ\text{C}$ compared to measurements.

3.1.2. Calculation of thermal boundary conditions of combustion chamber by combustion analysis

The previous method reproduced the thermal distribution by segmenting the thermal boundary conditions of the combustion chamber based on a heuristic, assuming a constant boundary temperature, and weighting the HTC. However, this method calls for adjustment by weighting the HTC compared to measurement results, which presumes that temperature measurement test results are available. In addition, recent adoption of direct injection and turbocharging is resulting in increasingly complex combustion modes and combustion chamber shapes that make temperature verification by the previous method a challenge. Therefore, this research investigated a method capable of accurately calculating combustion chamber temperatures in the design phase.

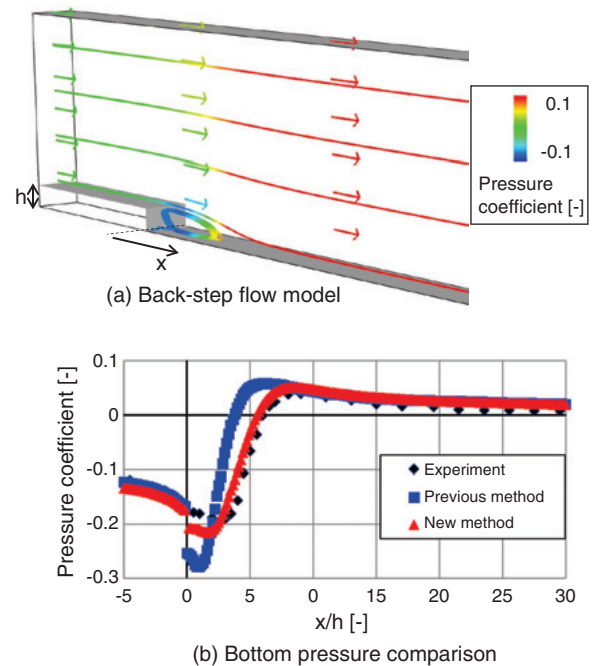


Fig. 3 Turbulent model verification in back-step flow

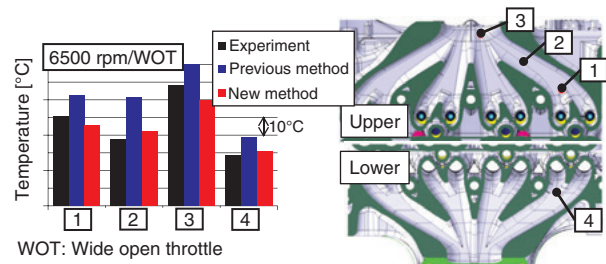


Fig. 4 Temperature comparison on exhaust port surface between experiment and CAE

CFD-based combustion analysis was used to understand the distribution of thermal boundary conditions in the combustion chamber. The boundary temperature and HTC at each crank angle were then extracted from the combustion analysis results and averaged to obtain the thermal boundary conditions. Figure 5 shows the thermal boundary conditions obtained by combustion analysis. The heat flux q from the flame to the combustion chamber is obtained by Eq. (1).

$$q = h \cdot \Delta T \text{ [W/m}^2\text{]} \quad (1)$$

h : HTC (heat transfer ratio) [W/m²K]

ΔT : Difference between combustion chamber wall surface temperature and boundary temperature [K]

The heat flux was previously expressed by weighting the HTC. However, the combustion analysis results show that both the boundary temperature and HTC have distributions, and it was determined that it would be challenging to express the heat flux with one or the other using a fixed value as in the previous method. Therefore, combustion analysis was performed to map both the boundary temperature and HTC onto the thermal analysis model.

The calculated temperatures were compared with engine test results to verify the accuracy of the new method (Fig. 6). Whereas the previous method based on a heuristic prior

to verification with actual engine temperature measurement results had error of up to 20°C compared to measurements, the new method achieved the target accuracy of $\pm 10^\circ\text{C}$.

3.2. Development of Material Model

The material model used in previous TMF analysis was a linear material model that used the Young's modulus, Poisson's ratio, and linear expansion coefficient at each temperature, and did not take into account plasticity or overaging. However, in order to evaluate the strength of high-temperature locations that are constrained by surrounding areas and undergo plastic deformation, such as the combustion chamber, it is necessary to accurately understand the nonlinear behavior of the material. The material model handled by CAE-based TMF evaluation uses a Young's modulus that takes into account temperature dependency, the stress-strain characteristics (S-S curve), and the linear expansion coefficient. Of these, the S-S curve is the key parameter for predicting the nonlinear behavior of the material. This research modeled the kinematic hardening rule⁽⁶⁾ and hardness overaging^{(7), (8)} in order to reproduce the nonlinear behavior of hot materials. In addition, the strength of the aging hardened alloy used in the cylinder head drops due to overaging as a result of constantly being at high temperature. However, rig tests showed that reduced energy loss due to shrinkage of the hysteresis loop resulted in a longer life, so in order to perform stricter strength evaluation, it was decided to not take creep into account.

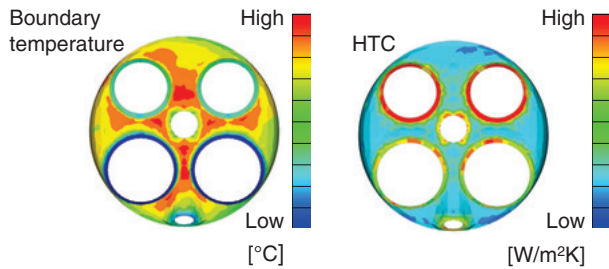


Fig. 5 Boundary conditions calculated by CFD

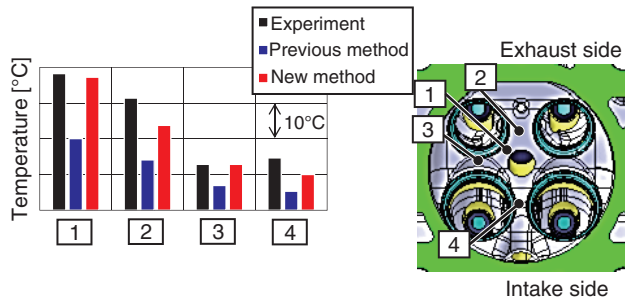


Fig. 6 Temperature comparison on combustion chamber surface between experiment and CAE

3.2.1. Application of kinematic hardening rule

The S-S curve obtained by repeating the thermal cycle varies according to the hardening rule. Hardening rules include the isotropic hardening rule and the kinematic hardening rule, and this research compared both rules. A TMF test was used to verify the CAE accuracy with regards to the S-S curve when a thermal load is repeatedly applied. This test uses a mechanical load and thermal cycle to apply a compound load to a material unit test piece, and has been used to evaluate the TMF resistance of various parts. Figure 7 shows an outline of the test. A model was created by carving out only the evaluation location as shown in Fig. 7(b) in order to determine the correlation between CAE and measurements. The test mode [Fig. 7(c)] repeated heating and cooling between 50°C and 250°C under load conditions that produce compressive strain during the heating period. Figure 8 shows the results of comparing the hysteresis loops measured during the test and the hysteresis loops obtained by CAE-based analysis for an input mechanical strain of $\pm 0.3\%$. These results show that compared to the nonlinear behavior calculated by the isotropic hardening rule shown in Fig. 8(a), use of the kinematic hardening rule shown in Fig. 8(b) more closely matches the TMF test results. As a result of taking into account the kinematic hardening rule, the Bauschinger effect⁽⁹⁾ could be simulated from the 1st cycle of the hysteresis loop, and the maximum stress of the 3rd cycle had error of 3% or less compared

to TMF test results. In contrast, when using the isotropic hardening rule, the maximum stress of the 3rd cycle had error of up to 30% compared to TMF test results. Therefore, the kinematic hardening rule was used.

3.2.2. Consideration of hardness overaging

The aluminum alloy used in the cylinder head is strengthened by heat treatment, so extended exposure to a high-temperature environment produces hardness overaging, which reduces the material strength and also changes the S-S curve. Figure 9 shows the hardness overaging characteristics of the cylinder head material depending on the time exposed to each temperature environment. In

particular, as the combustion chamber and other parts are exposed to high temperatures during engine operation, CAE-based strength evaluation should take into account hardness overaging. Hardness overaging is a phenomenon that occurs continuously over time, so it is a challenge to express by elasto-plastic analysis. This research divided the degree of overaging into the four levels of A (HRB 60 or more), B (HRB 40 to 60), C (HRB 20 to 40), and D (HRB 20 or less) for use as the degree of hardness overaging, and created an S-S curve for each degree of overaging as shown in Fig. 10. Figure 10(a) shows the S-S curve for each hardness of HRB 70, 50, 30, and 10. These four hardness levels were respectively assigned as the typical hardness for each degree of overaging A to D. The S-S curve for each hardness was measured at various temperatures, and a temperature-specific S-S curve for each degree of hardness overaging was created as shown in Fig. 10(b) and applied to thermal fatigue analysis.

The degree of overaging changes according to the temperature and time, so the degree of overaging of the analysis object varies according to the engine operating conditions. The temperature is obtained by thermal analysis,

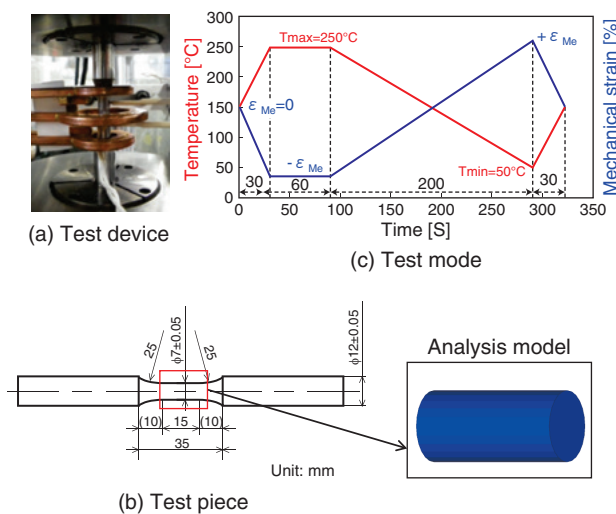


Fig. 7 TMF test outline and analysis model

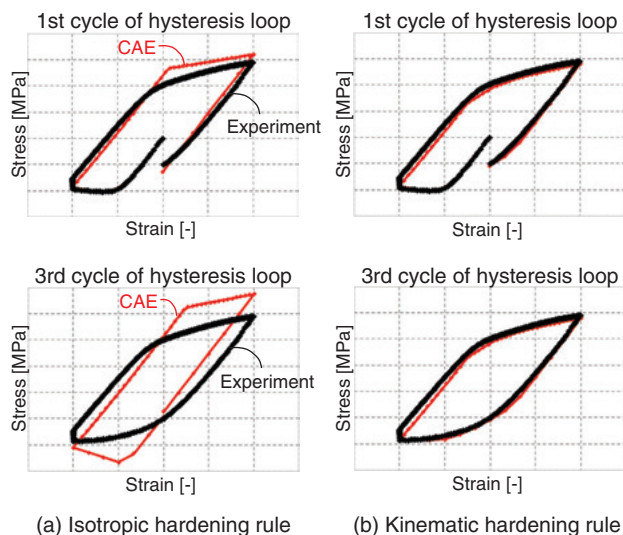


Fig. 8 Hysteresis loop due to hardening rule

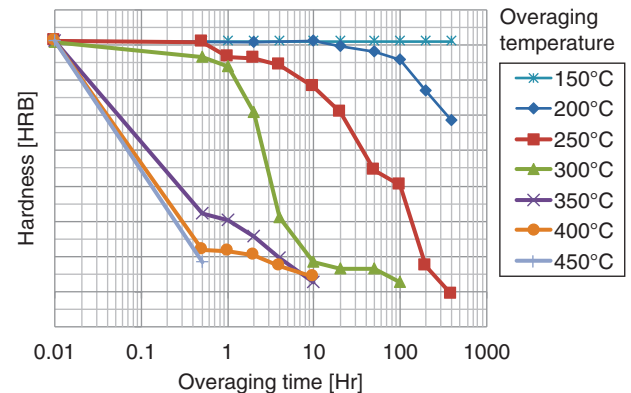


Fig. 9 Hardness overaging characteristics of aluminum alloy

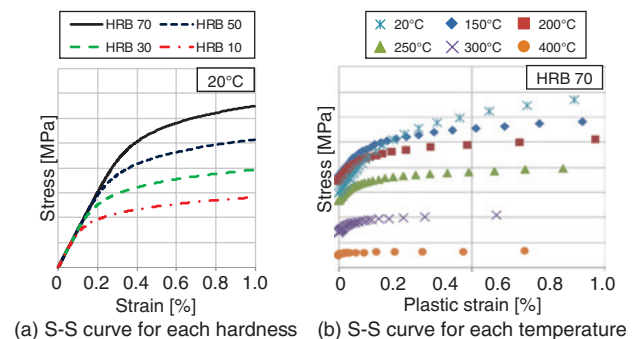


Fig. 10 Creation of S-S curve for each degree of overaging

and the overaging time is determined by the assumed operating mode, so the degree of overaging of each part of the analysis object can be understood from these factors. Strength analysis that takes into account thermal overaging of the material can be realized by performing elasto-plastic analysis separately using the S-S curves for each degree of overaging of each part.

3.3. Connection Model

It has been challenging to predict the strain around the bolts that fix the turbocharger on the cylinder head using conventional CAE. This is thought to be an issue when modeling the bolts that transfer the external constraint by the turbocharger to the cylinder head.

Bolt bending due to thermal expansion of the turbocharger has a large impact on the turbocharger connecting areas. The previous thread connection model expressed the FEM model of the connecting areas between the bolt and the internal threads by merging nodes [Fig. 11(a)]. However, in connecting areas with merged nodes, the model was unable to reproduce the behavior where the bolt separates from the internal thread when bending force is applied to the bolt, so the impact of external constraint could not be properly expressed. Therefore, the multi-point constraint (MPC) shown in Fig. 11(b) was used to track the bolt in the thrust direction, and the force transmission due to the bolt axial force and bending was reproduced by defining contact in the radial direction. A verification test was performed using a test piece that simulates the area around the cylinder head exhaust flange to verify the plausibility of the bolt connection model (Fig. 12). This test fixed an aluminum test piece that simulates the cylinder head to a surface plate, connected a steel plate that simulates the exhaust flange with a bolt, and applied a load to the steel plate. Fifteen strain gauges were installed continuously around the internal threads, and the strain distribution around the bolt connecting area was measured. A load of 20 kN was applied in the vertical direction using a Shimadzu Autograph precision universal tester. The rig test results and CAE results are shown in the lower part of Fig. 12, and confirmed that the analysis accuracy in all areas was enhanced compared to the previous method.

Next, an actual engine was used to verify the analysis accuracy of the thermal strain produced by the external

constraint of the exhaust system around the bolt connecting area. This test used a single-cylinder cylinder head (Fig. 13). The connection model using MPC provided better strain analysis accuracy compared to the previous bolt connection model with merged nodes, and achieved an accuracy of $\pm 10\%$ compared to an actual engine.

These enhancements in analysis accuracy were applied to analysis of cylinder head TMF strength, and the results reconfirmed the combustion chamber as the location with the greatest thermal strain.

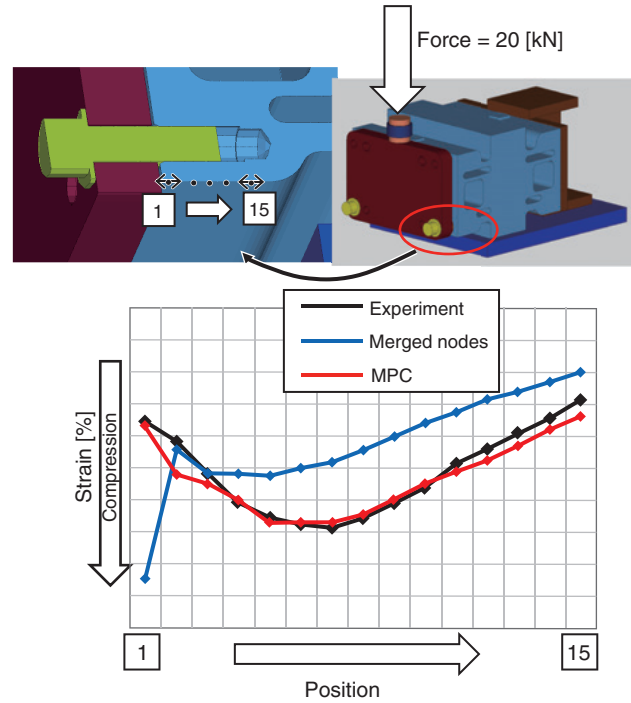


Fig. 12 Advanced rigid body connection model

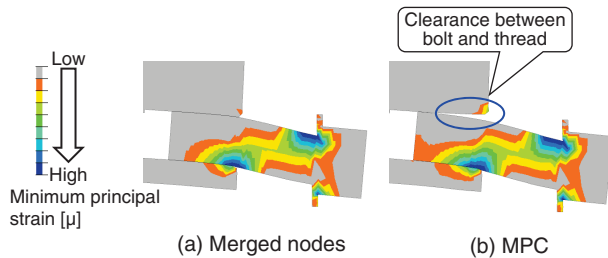


Fig. 11 Rigid body connection model

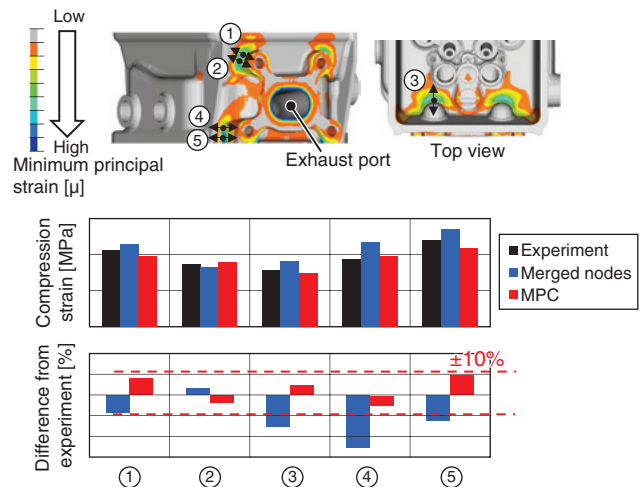


Fig. 13 Verification on thread connecting area with exhaust port

4. Comparison of Prediction Technology and Test Results

A concentrated durability test using an actual engine was performed focusing on the combustion chamber, which is the cylinder head location with the highest thermal strain, in order to confirm the accuracy of TMF evaluation using the new method. Table 2 shows the engine specifications used in this test. This durability test increased the thermal strain by adjusting the boost pressure in the WOT condition to increase the power and by controlling the coolant flow rate. In addition, the durability test mode was set by calculating the holding time during which the thermal strain is generally saturated from the results of temperature measurement tests during mode operation (Fig. 14).

Figure 15 shows the TMF analysis results in this durability test mode plotted on an S-N diagram. The change from the previous linear material model (blue plots in Fig. 15) to a nonlinear material model (red plots in Fig.

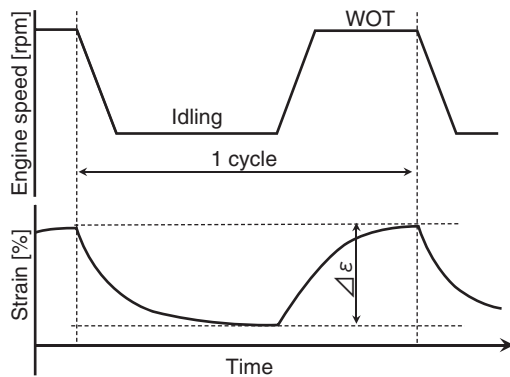


Fig. 14 Durability test cycle

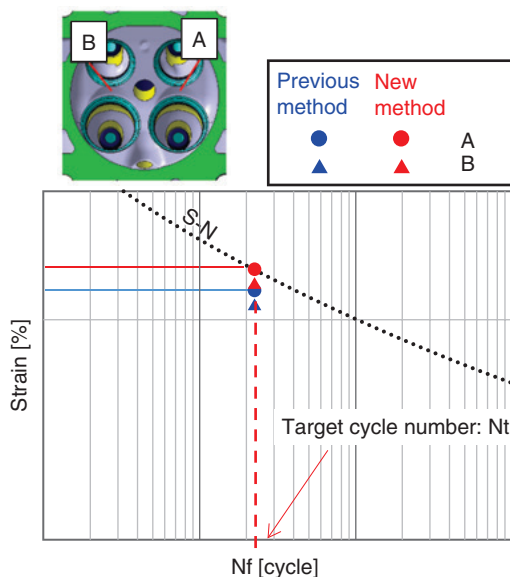


Fig. 15 Effect of new method on S-N diagram

Table 2 Engine specifications

Engine type	L4 DOHC VTEC Turbo
Bore × Stroke [mm]	73.0 × 89.4
Displacement [cm ³]	1496
Compression ratio [-]	10.6
Maximum power [kW/rpm]	110/5500
Maximum torque [Nm/rpm]	203/1600-5000
Fuel type	Gasoline (RON91)

15) resulted in higher calculated thermal strain. This is because the thermal strain analysis accuracy was enhanced by reproducing the kinematic hardening rule and hardness overaging due exposure to high temperature and high strain.

A durability test was performed with the number of durability test cycles N_t determined so that cracks occurred only at location A, which has higher thermal strain according to the S-N diagram. Figure 16 shows the durability test results. The results confirmed that cracks occurred only at location A and not at location B.

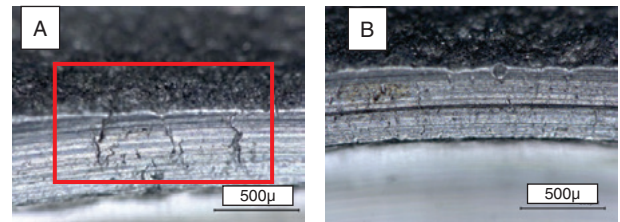


Fig. 16 Combustion chamber after durability test

5. Conclusion

A method was established that enables model-based prediction of the cylinder head TMF strength in the design phase. The developed technologies are summarized below.

- (1) Technology was developed that can predict cylinder head temperatures with an accuracy of $\pm 10^\circ\text{C}$, without verification using an actual engine. This was achieved by revising the CFD analysis method for the water jacket and exhaust port, and using combustion analysis to obtain the thermal boundary conditions.
- (2) A material model was developed that takes into account the hardening rule and hardness overaging, which enabled reproduction of material behavior up to high heat loads.
- (3) The bolt connection model was revised, and a model was developed that accurately reproduces the strain distribution of an actual engine.

References

- (1) Udoguchi, T.: Thermal Cycle Fatigue, Journal of the Japan Welding Society, Vol. 37, No. 6, p. 573-585, (1968) (in Japanese)
- (2) Toda, H., Kobayashi, M.: Thermal fatigue fracture of materials, Journal of Japan Institute of Light Metals, Vol. 59, No. 6, p. 312-319, (2009) (in Japanese)
- (3) https://turbmodels.larc.nasa.gov/backstep_val.html
- (4) Lee, C. Y., Park, S. H., Cho, S., Lee, I.: Delayed-Detached Eddy Simulation for Optical Path Control on Backward-Facing Step Flow, Seventh International Conference on Computational Fluid Dynamics, ICCFD7-2701, (2012)
- (5) Shih, T-H., Liou, W. W., Shabbir, A., Yang, Z., Zhu, J.: A New k- ϵ Eddy Viscosity Model for High Reynolds Number Turbulent Flows – Model Development and Validation, Computers & Fluids, Vol. 24, Issue 3, p. 227-238, (1995)
- (6) Lee, M. G., Kim, D., Chung, K., Youn, J. R., Kang, T. J.: Combined Isotropic-Kinematic Hardening Laws with Anisotropic Back-stress Evolution for Orthotropic Fiber-Reinforced Composites, Polymers & Polymer Composites, Vol.12, No.3, (2004)
- (7) Toda, H., Fukunaga, T., Kobayashi, M., Uesugi, K., Kobayashi, T., Yamada, T., Ooba, Y., Kakizaki, M.: Thermo-mechanical fatigue property of a surface-hardened AC4CH cast aluminum alloy, Journal of Japan Institute of Light Metals, Vol. 58, No. 6, p. 236-241, (2008) (in Japanese)
- (8) Moizumi, K., Tezuka, H., Sato, T.: Influence of precipitation hardening and eutectic Si microstructures on thermal fatigue life of Al-Si-Mg-Cu based cast alloys, Journal of Japan Institute of Light Metals, Vol. 54, No. 6, p. 205-210, (2004) (in Japanese)
- (9) White, C. S.: A Combined Isotropic-Kinematic Hardening Model for Large Deformation Metal Plasticity, Final Report, MTL TR 88-46, U.S. Army Material Technology Laboratory, (1988)

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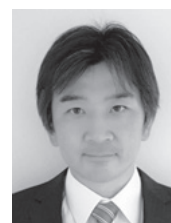
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