

Establishment of Prediction Technology of Fatigue Strength in Roots of Internal Thread for Crankcase Assembly and Application in Product Development

Hiroshi KURIBARA*

Junya SAITO*

Hideki SAITO*

Daisuke SEKIYA*

ABSTRACT

Aluminum alloy crankcases are generally used in motorcycle engines. Fatigue fractures sometimes occur in the roots of the internal threads of the cylinder head fastening bolts and the crankshaft main bearing fastening bolts in durability tests in the prototype stage. Conventionally, theoretical evaluation of absolute values of fatigue strength in the roots of the internal threads was a challenge, so evaluation of fatigue strength had to rely on durability tests using actual engines.

This study developed technology that uses FEM analysis to theoretically evaluate the fatigue strength of the entire crankcase, including the internal thread portions of the main bolts. This technology performs parallel calculation processing on a large-scale FEM model that takes into account the forms and contact characteristics of the external and internal threads, and was found to be practical in terms of both calculation accuracy and calculation time. Examples of applying this new method to product design showed that fatigue strength in the roots of the internal threads for crankcase assembly can be enhanced without increasing the weight, by modifying the form around the bolt fastening area and the form of the bolt tip.

1. Introduction

Aluminum alloy crankcases are used in motorcycles mainly from the viewpoint of weight reduction. However, a characteristic issue for these engines is fatigue fracture starting from the roots of the internal threads of the fastening areas of bolts subject to high axial force, such as the cylinder head stud bolts and the crankshaft main bearing fastening bolts. When both the external and internal threads are made of steel, fastening area fractures generally occur starting from the underhead fillet of the bolt flange or the roots of the external thread that is not engaged with the internal thread. However, when fastening a steel external thread to an internal thread made of aluminum, which has lower material strength than steel, fractures may originate on the internal thread side. Figure 1 shows the location of a fracture starting from the roots of the internal thread that occurs in durability tests in the prototype stage. The starting point is in the roots of the internal thread where the engaging with the external thread ends, and the fracture surface occurs as a fatigue fracture surface.

Demands to reduce the environmental load and product development costs by reducing durability tests are increasing the importance of technology that can

evaluate performance in the product development process. Crankcases have complex shapes, and design requires a high degree of balance between weight reduction and durability. Therefore, evaluation of fatigue strength using FEM analysis in the initial design stages is a useful and important method.

However, in conventional evaluation of the fatigue strength of bolt fastening areas, the roots of the internal threads for crankcase assembly had to be excluded from the evaluation subject due to their detailed form and complex contact modes. Therefore, the strength of these areas was evaluated by durability tests using actual engines. Many studies have analyzed the stress in the bolt fastening

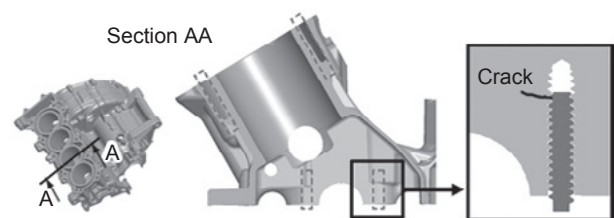


Fig. 1 Location of starting point of fatigue fracture at internal thread

* Motorcycle R&D Center

areas⁽¹⁾⁻⁽³⁾, but practical studies that aim to evaluate the fatigue strength of the overall product form are rare. This study developed technology for evaluating the fatigue strength of the entire crankcase, including around and inside the bolt fastening areas.

2. Development of Technology for Evaluating Fatigue Strength of the Crankcase including Bolt Fastening Areas, and Verification of Validity

Three processes were used to develop the technology as follows.

Step 1: Construction of an FEM model for stress analysis of the bolt fastening area

Test pieces focusing on the bolt fastening area were used to measure the strain at the roots of the internal thread and the external surface of the bolt fastening area, and the stress was analyzed using a FEM model that simulates strain tests using test pieces. The correlation between the strain and stress was then investigated to construct an accurate modeling method for stress analysis of the bolt fastening area.

Step 2: Construction of an FEM model for stress analysis of the entire crankcase

A stress analysis model for the entire crankcase was constructed that incorporates the bolt fastening area analysis model constructed in Step 1. The strain was measured using an actual engine, and the validity of the model to reproduce the stress distribution of the entire crankcase was verified.

Step 3: Construction of a method for calculating the fatigue safety factor

A method was constructed for calculating the fatigue safety factor of the entire crankcase, including the bolt fastening areas, based on the material strengths and the history of stress generated in the engine assembly process and during operation.

2.1. Construction of a Model for Stress Analysis around the Bolt Fastening Area

2.1.1. Construction of a model for stress analysis at the roots of the internal thread

Following construction of an FEM model that takes into account the detailed characteristics of the bolt fastening area, equivalent measurements were performed using an actual test piece, and the validity of the model proposed by this study was evaluated by comparing the respective results. Figure 2 shows an overview of the FEM model. M6 to M12 bolts are often used as the main bolts in motorcycle engines, but it is a challenge to accurately measure the strain, so the nominal bolt diameter was set at $\phi 64$. In addition, actual bolts have a spiral thread form, but with regards to fractures occurring at the roots of the internal thread, it was assumed that the effects of the load in the lead direction generated by contact at the bolt lead angle are small enough to be ignored. Therefore, this study used a

model with an axisymmetric form for the thread form. The bolts are made of steel and have a single external thread, the internal thread side forms seven valleys inside an aluminum block, and the external thread is inserted and places an axial force load on the fourth valley from the top. A limit-sliding model was used for the location where the parts contact each other to reproduce the load and slipping behavior between the external and internal thread contact surfaces. Measurement values obtained from actual test pieces were used for the forms and material characteristics of each part.

Figure 3 shows the test piece form and the strain measurement sequence used to measure the strain at the roots of the internal thread. First, strain gauges were attached to the roots of the internal thread with the test piece in the divided condition. Next, the two base bodies were bolted together with the external thread bolt inserted to the internal thread portion. Finally, a nut was fastened to the thread cut in the upper portion of the external thread bolt, and the axial force and strain at the roots of the internal thread were measured. Figure 4 shows the positions for evaluating the strain at the roots of the internal thread. Stress evaluation points were set in three locations at different angles in the circumferential direction, in each of three roots consisting of the root that holds the bolt external

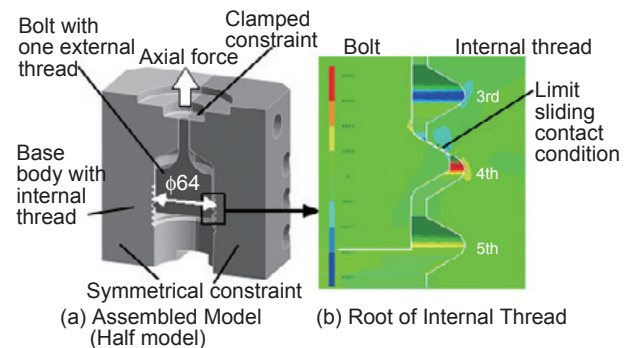


Fig. 2 FEM model for strain analysis at root of internal thread

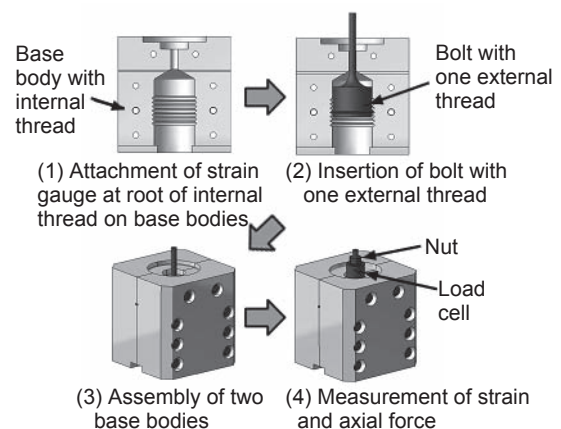


Fig. 3 Measurement sequence for strain at root of internal thread

thread and the roots immediately above and below in the axial direction. Both the measurements and FEM analysis obtained the strain in the direction of the bolt axis along the root fillet.

Figure 5 compares the strain values at the roots of the internal thread obtained by FEM model analysis and actual measurements. The measurement results show that both the stress distribution and quantitative values match closely for the internal thread root that engages with the bolt external thread and for the internal thread roots immediately above and below the meshed root, thus confirming the validity of the model proposed by this study.

2.1.2. Verification of stress analysis accuracy at the external surface of the bolt fastening area

When evaluating the fatigue strength of the crankcase, it is necessary to accurately reproduce the stress conditions not only at the roots of the internal threads of bolts subject to high axial force, but also in surrounding areas. Therefore, the correlation between measurements and simulations was verified for the strain at the external surface of the bolt fastening area. Figure 6 shows the test piece used to measure the strain at the external surface of the bolt fastening area. The test piece has three columns, with an internal thread formed on the center cylindrical column. Strain gauges are attached to the surface of the center column at intervals matching the thread pitch in the axial direction. The strain at the external surface of the bolt fastening area is measured by inserting a spacer to this test

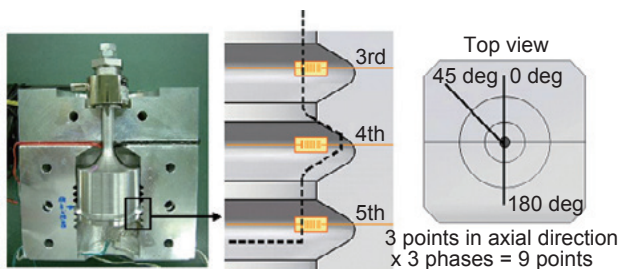


Fig. 4 Measurement point for strain at root of internal thread

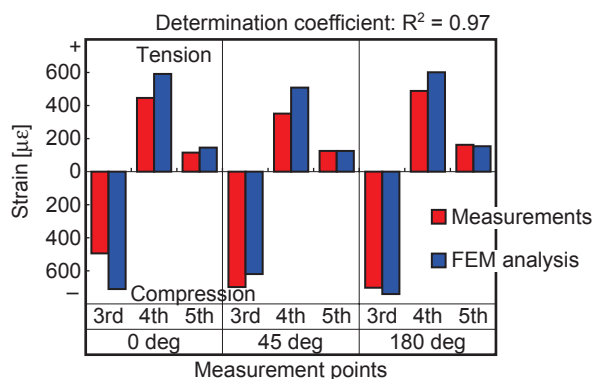


Fig. 5 Strain at root of internal thread: Measurements vs. FEM analysis

piece and applying axial force. Figure 7 shows an overview of the FEM model used to simulate experiments using this test piece. The modeling method was the same as that used to create the stress analysis model for the roots of the internal thread.

Figure 8 compares the strain values at the external surface of the bolt fastening area obtained by measurements

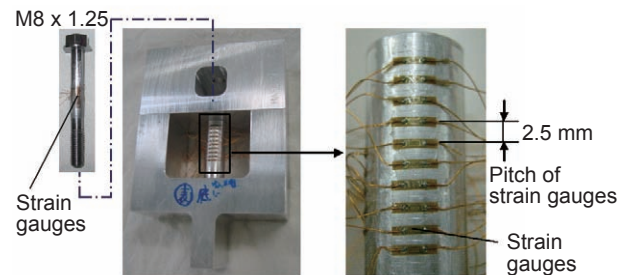


Fig. 6 Test piece for measurement of strain at external surface of bolt fastening area

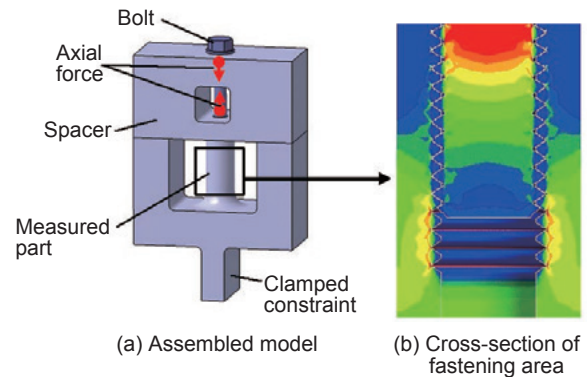


Fig. 7 FEM model for strain analysis at external surface of bolt fastening area

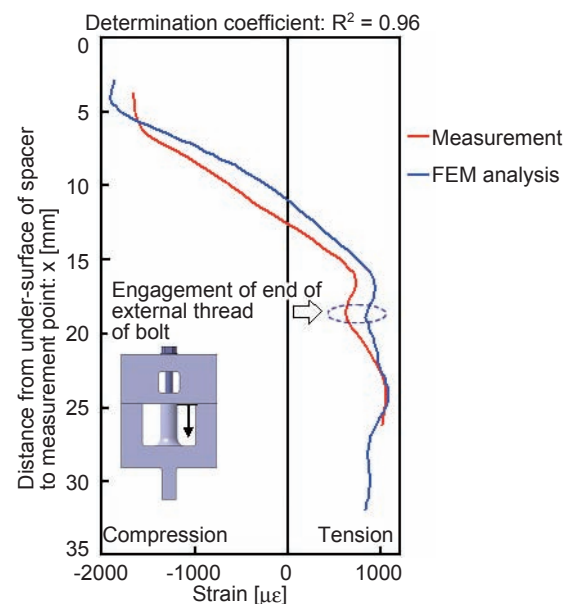


Fig. 8 Strain at external surface of bolt fastening area: Measurements & FEM analysis results

and by FEM model analysis. The measurement and simulation results match closely for both the strain at the roots of the internal thread and the strain distribution at the external surface of the bolt fastening area, thus confirming the validity of the model proposed by this study.

2.2. Construction of a Stress Analysis Model for the Entire Crankcase

A stress analysis model of the entire crankcase was constructed that incorporates the bolt fastening area model described in section 2.1. into the internal thread portions of the crankcase stud bolt fastening areas. Figure 9 shows an overview of the model and the flow of analysis using a single-cylinder engine as an example.

The main types of strain generated in the crankcase during engine operation are: (1) residual strain generated by the casting, heat treatment, and machining processes; (2) strain generated in the engine assembly process; (3) strain generated by the cylinder pressure load and the bearing reaction forces of the crankshaft, transmission and other parts; (4) strain generated around the engine mounts from supporting the inertial motion of the engine; and (5) strain rooted in non-uniformity of the temperature distribution and differences in the coefficients of thermal expansion of different components. This study focused on strains (2) and (3), which have a particularly large effect on the stress mode at the roots of the internal thread. The loads taken into account were the stud bolt axial force, cylinder pressure, piston thrust force, the crankshaft main bearing and transmission bearing loads, and the uniaxial primary balancer bearing load.

In addition to the crankcase that is the evaluation subject, the parts needed to transfer and receive the loads (2) and (3) above were also selected and assembled into the FEM model. In addition, the stress-strain curve calculated from tensile tests using test pieces cut from actual parts was used for the crankcase material characteristics.

As shown in Fig. 9, the measurement values for the

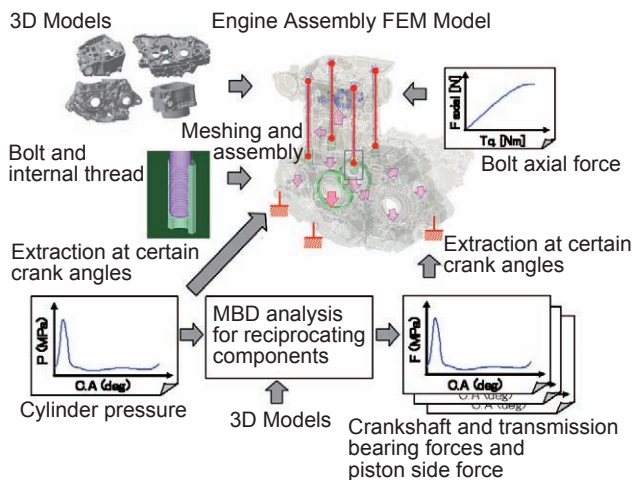


Fig. 9 Stress analysis model for entire crankcase

cylinder head fastening bolt axial force and the cylinder pressure were used for the quantitative load condition values. Calculation values obtained by flexible multibody dynamics⁽⁴⁾ were used for the crankshaft, transmission shaft and balancer shaft bearing loads.

FEM models of engine assemblies that include detailed thread forms have large numbers of elements, and require calculations that take into account the nonlinearity of contact and materials, so the calculation scale becomes quite large. Therefore, a parallel calculation solver was used as the solver to enable calculations to be performed in a short time for even these types of large-scale models. Table 1 gives an overview of the analysis scale for the engine assembly model. Even though the calculation scale is large, analysis can be performed in a time period that enables repeated investigation of specifications in the design stage.

The strain values generated on the crankcase during engine assembly and operation were measured to evaluate the validity of the analysis model. Figure 10 shows a photograph of the engine used for measurement. Six locations were selected as the strain measurement points, in reference to the strain distribution map obtained by FEM analysis. Figure 11 shows the locations where the strain

Table 1 Scale of FEM stress analysis model for entire crankcase

Number of elements	10 million elements
Number of contact elements	1 million elements
Minimum mesh size	25 μm
Number of CPUs used in calculation	50 CPUs
Calculation time/One boundary condition	5 hours

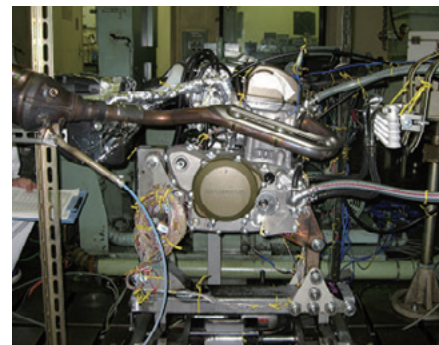


Fig. 10 Engine used to measure strain when assembled and under operating conditions

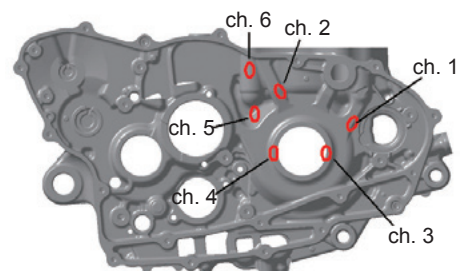


Fig. 11 Locations for attachment of strain gauges

gauges were attached. The strain gauges were attached in the directions in which the maximum principal strain and minimum principal strain are generated.

Figure 12 shows the correlation between the strain calculation results and strain measurement results at each point, at a crank angle of 16 degrees which results in the maximum cylinder pressure, during steady-state operation at wide open throttle and an engine speed of 6000 rpm. The strain values shown in this figure are the sum of the strain generated by the effects of axial force and the strain generated during engine operation due to the effects of the cylinder pressure load and each bearing load. The mean of the strain measurement results for ten cycles was used for the measured strain data, to minimize the effects of cycle fluctuation in the cylinder pressure.

Comparison of the FEM model analysis results and the measurement results showed that the location with the greatest stress for both results was ch.5, which is subject to a large tensile load during both engine assembly and operation. The strain gauge for ch.6 was attached to the head side of the stud bolt meshing position, so the stress value results indicated a high compression stress. The results for the other ch.1 to ch.4 were all within the range of the tensile internal force of the cylinder pressure and the crankshaft main bearing load, indicating that tensile strain was generated in sync with the combustion timing.

Comparison of measurements and the simulation results confirmed a high qualitative and quantitative correlation, and verified the validity of the engine assembly FEM model.

2.3. Calculation of Fatigue Safety Factor and Evaluation of Fatigue Strength

To evaluate the fatigue strength of the crankcase, fatigue should be evaluated not using the stress values for a single load state, but rather in consideration of stress fluctuations during engine operation and the fatigue strength characteristics of the materials.

The method used by this study to evaluate fatigue strength first calculates the mean stress and stress amplitude based on the results of static stress analysis at multiple

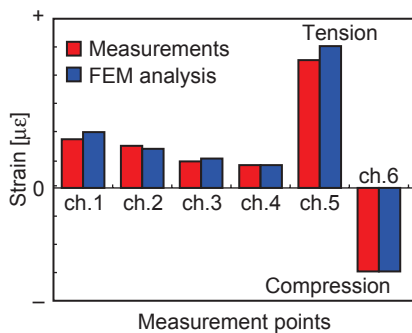


Fig. 12 Strain at points of attachment of gauges on crankcase: Measurements and FEM analysis results

crank angles, and then calculates the fatigue safety factor using a modified Goodman fatigue limit diagram as the strength judgment index. Figure 13 shows the flow through calculation of the fatigue safety factor.

Using the hypothetical case of durability tests performed at a constant speed as an example, stress analysis is performed for three conditions that are characteristic stress states that affect the crankcase fatigue strength. These are (1) the load state at the peak cylinder pressure, (2) the load state with the piston at the top dead center (TDC) before intake and the TDC side inertia force of the reciprocating system at a maximum, and (3) the state with the piston near the midpoint between the TDC and bottom dead center (BDC) and the crankshaft main bearing load at a minimum. The fatigue safety factor can be calculated at all nodes of the crankcase FEM model by performing the series of fatigue calculation processes on these analysis results.

This processing renders visible the fatigue safety factor and stress distribution at each crankcase location as shown in Fig. 13. This makes it easier to judge the strength, and can also be used as a reference for investigating forms, such as when the strength is insufficient or when reducing the weight.

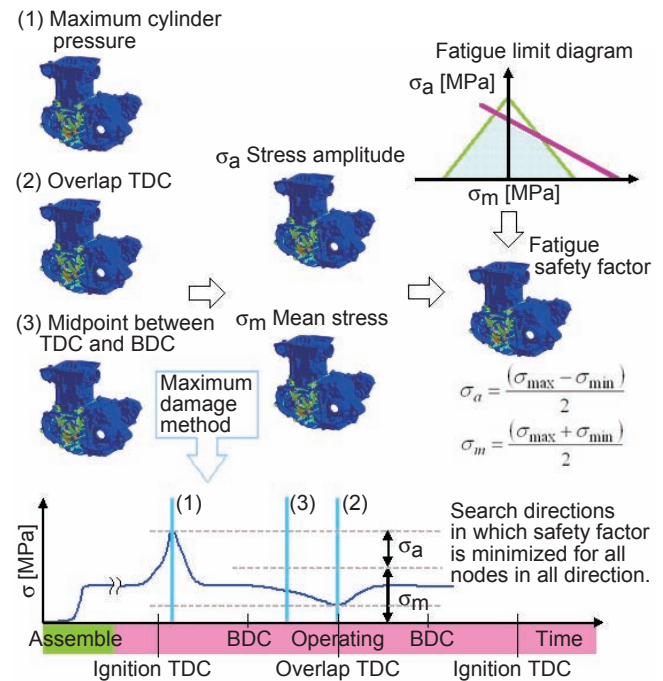


Fig. 13 Method of calculation of safety factor

3. Examples of Applying this Technology to Product Development

Two examples of using this analysis method to investigate the strength of the roots of internal threads are introduced below.

3.1. Study on Preventing Fractures at the Roots of Internal Threads by Using Stud Bolts with a Hollow Tip

One means of increasing the fatigue strength of the roots of internal threads is to use a hollow bolt tip as shown in Fig. 14, and this has been confirmed by durability tests to actually increase the crankcase fatigue strength. Analysis was performed to investigate the effects of a hollow form, with all conditions the same except for the presence or lack of a hollow form at the tip of the bolt. Figure 15 focuses on a cylinder head fastening bolt in a single-cylinder engine, and shows the mean stress and stress amplitude at the roots of the internal thread over a single circuit of the roots of the internal thread, plotted on a fatigue limit diagram. This shows that using a hollow-tip bolt reduced both the mean stress and stress amplitude at the roots of the internal thread. Previously only the experimental effects of hollow-tip bolts had been confirmed, but the developed technology enabled quantitative evaluation of the effects.

3.2. Study on Preventing Fractures at the Roots of the Internal Thread by Changing the Crankcase Form

This example increased the fatigue strength at the roots of the internal thread by modifying the crankcase form around the stud bolts. Stress analysis was performed and the fatigue strength at the roots of the internal thread was compared for crankcases A and B, which have different forms around the stud bolts. The durability test results clearly showed that crankcase B has a higher fatigue strength than crankcase A.

Stress calculation and fatigue evaluation processing

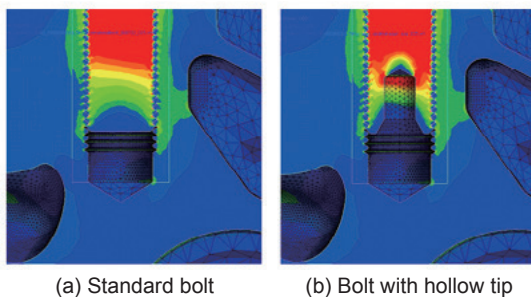


Fig. 14 Form of hollow cylinder at tip of bolt

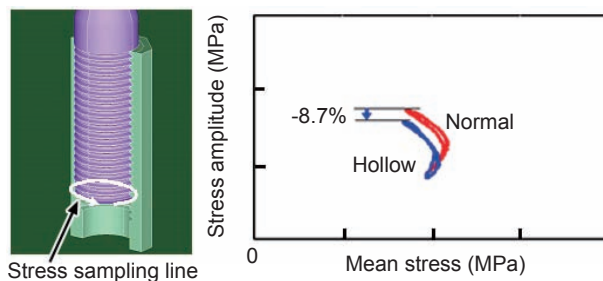


Fig. 15 Reduction of stress at root of internal thread using bolt with hollow cylinder at tip

was performed on engine assembly models incorporating crankcases A and B, using the same axial force and bearing load conditions. Figure 16 shows a graph that plots the mean stress and stress amplitude over a single circuit of the roots of the internal thread. Crankcase B exhibits a lower mean stress and stress amplitude at the roots of the internal thread than crankcase A, and these effects are greater than when using hollow-tip bolts. Modifying the form around the stud bolt fastening area in the design stage involves a high degree of design freedom and does not increase the cost or weight, so it can be said to be an efficient method.

The above examples show that the establishment of this technology enables efficient design of crankcases that are both lightweight and have the necessary fatigue strength.

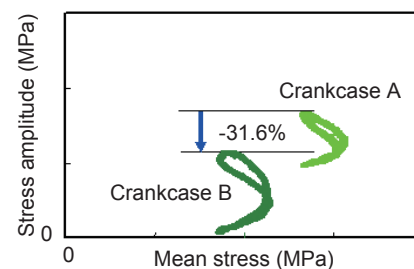


Fig. 16 Reduction of stress at root of internal thread by changing form around bolt fastening area

4. Conclusions

- (1) Technology for evaluating the fatigue strength of the entire crankcase was developed. This technology can evaluate the fatigue strength of the roots of the internal threads of the cylinder head fastening bolts and the crankshaft bearing fastening bolts.
- (2) The strength of the crankcase, including the roots of the internal threads, can be evaluated quantitatively in the design stage. This enabled efficient crankcase design that minimizes increases in weight and cost, by modifying the structure and form.

References

- (1) Fukuoka, T., Yamasaki, N., Kitagawa, H., Hamada, M.: Stress Concentration at the Root of a Screw Thread (Efficient of Root Radius and Friction Coefficient), Transactions of the Japan Society of Mechanical Engineers, A, 52 (481), p. 2201-2208 (1986)
- (2) Fukuoka, T., Nomura, M., Morimoto, Y.: Proposition of Helical Thread Modeling with Accurate Geometry and Finite Element Analysis, Transactions of the Japan Society of Mechanical Engineers, A, 72 (723), p. 1639-1645 (2006)
- (3) Momii, H., Ikeda, S., Tanoue, M., Ushijima, K., Takahashi, N.: Stress Analysis Method for Bolt Thread

under Operating Condition of Automotive Engine, 2009
JSAE Annual Congress Proceedings, No. 99-09, p.
13-16 (2009)

- (4) Niino, T., Iwamoto, T., Ueda, S.: Development
of simulation technology for dynamic behavior of
crankshaft systems in motorcycle engines, JSAE
Review, Vol. 23, p. 127-131 (2002)

■ Author ■



Hiroshi KURIBARA



Junya SAITO



Hideki SAITO



Daisuke SEKIYA