

Prediction of Fracture of Cylinder Block Main Bearing by Fretting Fatigue and Development of Verification Method

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ABSTRACT

A method of prediction of the occurrence of fretting fatigue fracture of the main bearing in the cylinder block development process and a method of verification of the results of predictions have been developed.

Because fretting fatigue strength differs from material fatigue strength when fretting does not occur, a fatigue limit diagram when fretting occurs was obtained using material test pieces, and criteria for the evaluation of stress generated in an actual engine were determined. A method of measurement of stress amplitude and relative slip using a unit test apparatus was developed, making it possible to predict fretting fatigue fracture before the stage of tests using actual engines. The development of a method of conversion of strain values determined using the unit test apparatus into figures for relative slip made it possible to formulate a method of evaluation of relative slip in an actual engine.

1. Introduction

With growing environmental awareness worldwide, demand on the automotive industry to reduce the weight of engine parts in order to boost fuel efficiency is increasing. The use of a configuration that makes the bearing cap in the main bearing supporting the crankshaft independent is available as a means of reducing the weight of the cylinder block, one of the parts making up the engine⁽¹⁾. However, connection rigidity is lower in a configuration with an independent bearing cap than with a ladder configuration, and micro-slip occurs in the bearing cap mating faces, which can result in fractures due to fretting fatigue⁽²⁾.

Fretting fatigue fractures are known to occur as a result of the development and propagation of fatigue cracks due to the destruction of surface oxide films and the presence of abrasion powder adhering to surfaces⁽³⁾. Stress measurements of the mating faces of the main bearing conducted in actual engines during cylinder block strength evaluations show that the stress generated when fatigue fractures occur due to fretting is lower than the fatigue strength of materials when fretting does not occur. Because of this, it is challenging to predict fretting fractures, and it has been necessary to verify specifications in endurance tests using actual engines. This accounts for a significant amount of time during the

cylinder block development process.

Fault tree analysis (FTA) was employed to break down the phenomenon of fretting fatigue fracture based on its mechanism of occurrence, and showed that the two major causes of fatigue fracture are stress amplitude and relative slip⁽³⁾.

The research discussed in this paper studied the fatigue strength of materials in relation to these two major causes, obtaining fatigue limit diagrams when fretting occurs, and developed a method of investigation that can be applied to actual engines. In addition, a test method employing a unit test apparatus was devised, and a method of prediction of fretting fatigue at a stage prior to actual engine tests was developed.

2. Development Goals

The development set out to establish a method of prediction of fretting fatigue fractures using a cylinder block unit test apparatus. In addition, it aimed to develop a method of investigation of fretting fatigue fracture using actual engines.

By means of achieving these goals, the research sought to reduce the man-hours focused on fretting fatigue in the cylinder block development process.

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3. Materials Tests

3.1. Aim of Tests and Test Method

Fretting fatigue tests were conducted in accordance with the fretting fatigue test method specified by the Japan Society of Mechanical Engineers (JSME)⁽³⁾. The aim of the tests was to establish criteria for evaluation of stress amplitude and relative slip, the two major factors in fretting fatigue fractures, by determining the correlation between these factors and material fatigue strength in tests in which slip and a load were simultaneously applied to test pieces.

The test method is shown in Fig. 1. Using this method, fretting was reproduced by pressing a contact pad (FC250) onto a test piece (ADC12). Surface pressure was imparted to the contact area by tightening a bolt, and calculated from the value of strain in a ring-shaped fixing jig. The relative slip between the test piece and the contact pad was directly measured by affixing high-temperature clip gauges to each with stays. There is no reference to the use of clip gauges to measure relative slip in the JSME fretting fatigue test method; the method was devised specifically for the tests under discussion. The test piece was machined from vacuum diecast material, and the contact pad was machined from material cut from cylinder block bearings. Figure 2 shows the shapes of the test piece and the contact pad. In order to vary the magnitude of relative slip, contact pads of 10, 15, and 30 mm in width (shown as L in Fig. 2) were prepared. Table 1 shows the test conditions. Fatigue tests were conducted in a constant-temperature oven at 150°C. Push-pull fatigue was applied at a test speed of 15 Hz. The maximum number of repetitions was 10^7 . Fatigue lifetime in relation to relative slip was calculated from the relationship between stress amplitude and fatigue lifetime (S-N curves) obtained for each test condition. Tests were considered completed when the test piece fractured, and the number of repetitions at this time was evaluated.

3.2. Test Results

Figure 3 shows the results of measurements of fatigue strength in relation to relative slip at 10^7 repetitions. There is a correlation between relative slip and fatigue strength. At a relative slip of 15 μm , fatigue strength declines by approximately 25%.

These tests clarified values to serve as criteria for the evaluation of stress when fretting occurs, and made it possible to define a fretting fatigue limit diagram.

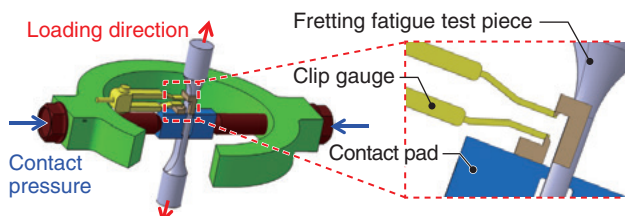
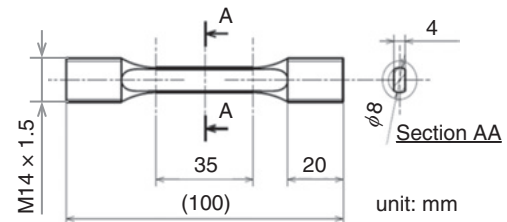


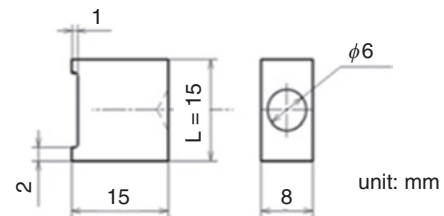
Fig. 1 Fretting fatigue test method

Table 1 Test conditions

Test machine	SERVO PULSER
Test temperature, atmosphere	150°C, air
Test speed	15 Hz
Contact pressure	50, 100, 150 MPa
Number of cycles	Max 10^7



(a) Fretting fatigue test piece



(b) Contact pad

Fig. 2 Fretting fatigue test pieces

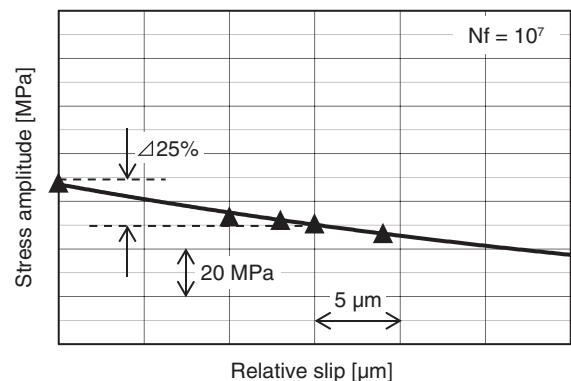


Fig. 3 Relationship between stress and relative slip measurement

4. Cylinder Block Unit Tests

4.1. Aim of Tests and Test Method

Sections of actual cylinder blocks were cut out, and a cylinder block unit test apparatus was produced (Fig. 4).

Using this test apparatus, the main bearing of the unit cylinder block was shaken to produce fretting, and stress

amplitude and relative slip were measured. The aim of the test was to make it possible to predict fretting fatigue fracture without using a complete engine by plotting the measurement results on the fretting fatigue limit diagram obtained from unit tests using test pieces.

The test apparatus shook the crankshaft on two orthogonal axes. Independent control of the amplitude and phase of the shakers on each axis made it possible to set load conditions as desired.

The cylinder block was cut to make it possible to impart loads to the central bearing section in isolation. The central bearing section has the highest force amplitude of the main bearing of an inline 4-cylinder (L4) engine, and is a site at which fretting fatigue occurs.

Strain gauges were affixed to the surfaces of the cylinder block and the main bearing at regular intervals in opposing pairs in order to measure stress amplitude and relative slip. Strain was measured in a direction parallel to the mating faces of the cylinder block and main bearing, and the strain gauges were affixed in positions as close as possible to the mating faces (Fig. 5).

Stress amplitude and relative slip were calculated from the strain measurement results. In order to calculate relative slip, the difference between cylinder block and main bearing strain was found, and the difference in strain

at each measurement point was integrated. The resulting value was considered to represent relative slip. Figure 6 shows the calculation method. Equation (1) was used in the calculations.

$$S_{\text{strain}} = \sum (\varepsilon Ai - \varepsilon Bi) \times L \quad (1)$$

In order to evaluate the measured stress amplitude and relative slip using the fatigue limit diagrams determined in fretting fatigue tests, it was necessary to establish a correlation between the relative slip measured by the strain gauges and the values measured by the clip gauges used in the fretting fatigue tests. In order to do so, clip gauges were attached to the cylinder block and the main bearings, and measurements were taken using these gauges at the same time as the strain gauges (Fig. 7). The determination of the correlation between relative slip measured by the strain gauges and relative slip measured by the clip gauges made it possible to use strain gauges to measure relative slip in unit tests and in actual engines, in which clip gauges cannot be used.

The coefficient of correlation between relative slip calculated from strain gauge results and that calculated from

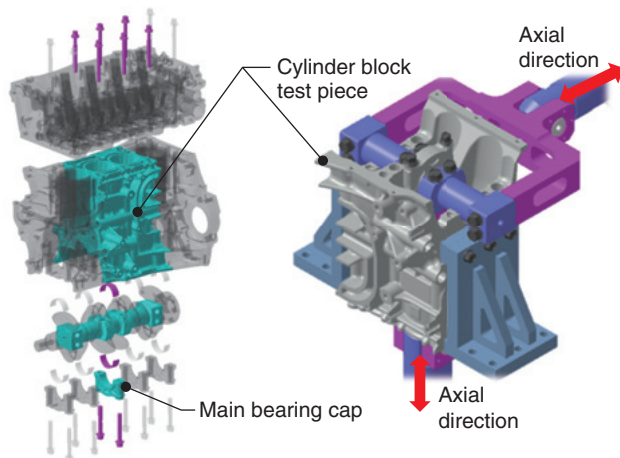


Fig. 4 Test equipment

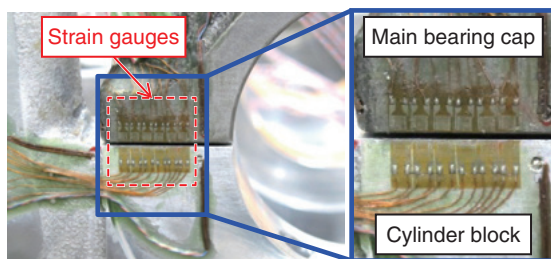


Fig. 5 Cylinder block and main bearing with strain gauges

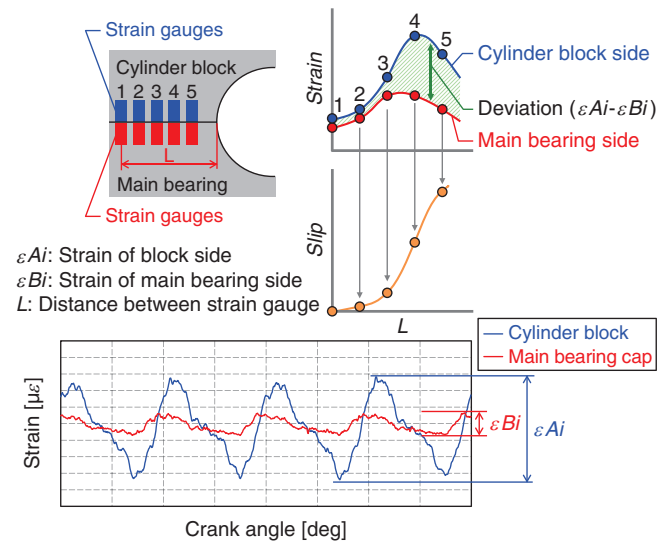


Fig. 6 Method of calculation of slip

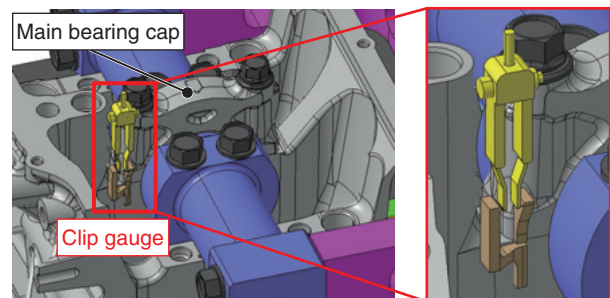


Fig. 7 Test equipment with clip gauge

Table 2 Test conditions

Force amplitude	15 kN
Frequency	100 Hz
Phase difference	90 deg
Bolt axial force	Base: 11% reduction
Stiffness	Base: Width 5% reduction

clip gauge results, termed K , was determined. Figure 8 shows results for the coefficient of correlation.

Finally, the following equation was employed for the calculation of relative slip using strain gauge results:

$$S_{clip} = \sum (\varepsilon Ai - \varepsilon Bi) \times L \times K \quad (2)$$

4.2. Test Conditions and Test Results

The test conditions are shown in Table 2. The force amplitude was imparted on two axes (horizontal and vertical directions) with a 90° phase difference. It was possible to reproduce a load configuration similar to that occurring in an L4 engine by generating a synthetic load from the loads on each axis (Fig. 9). The maximum load was 15 kN, corresponding to the maximum load in an actual engine.

For the tests, the crankshaft force amplitude and frequency were held constant, and the values of the main bearing bolt axial force and the main bearing stiffness (mating face width), parameters that fretting stress displays sensitivity to, were varied.

In addition, tests based on quality engineering have clarified the contribution of the surface forms of the cylinder block and main bearing mating faces to fretting fatigue fracture^{(4), (5)}. The surface properties of the test pieces were therefore measured prior to the tests. A stylus roughness tester was employed in the measurements. Surface data based on measurement point group information was obtained using a sensing-pin device that measures roughness

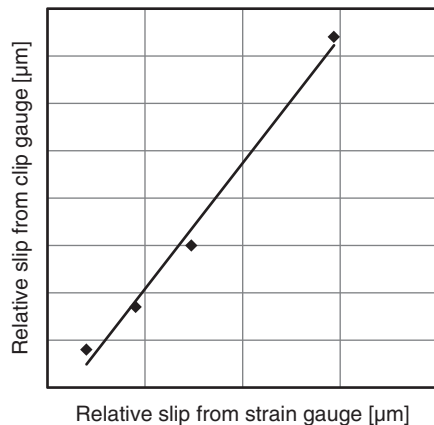


Fig. 8 Relationship between strain gauge and clip gauge

in the lateral direction combined with a longitudinal feeder. Measurement scans of cross-sectional shape were conducted 140 times, and the differences in height of the surfaces were numericized. Figure 10 shows results for measurements of the surface shape of the main bearing. Tests were conducted using cylinder blocks produced with the aim of achieving differences in surface height within 10 μm. The incorporation of numericized surface shape data in simulations of fretting fatigue fracture will help to increase the predictive accuracy of the simulations.

Figure 11 shows results for measurements of stress amplitude and relative slip. Results for stress amplitude and relative slip for the base specifications were lower than values on the fretting fatigue limit diagram obtained from unit tests

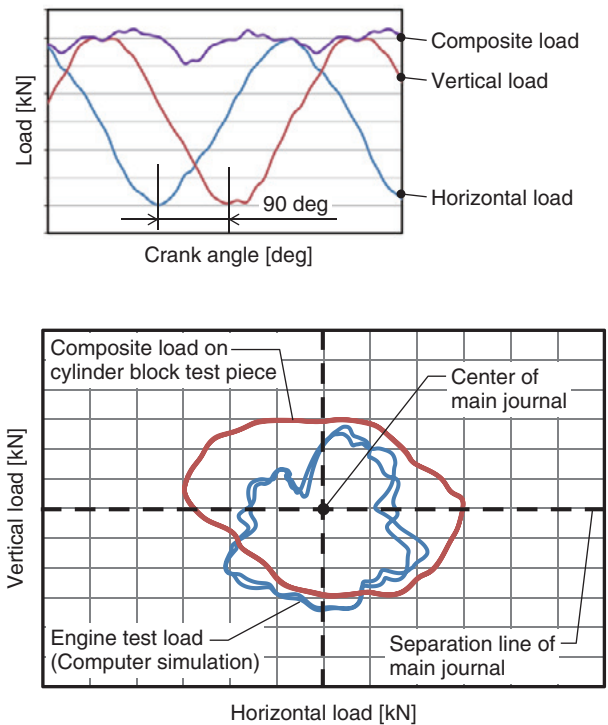


Fig. 9 Cylinder block test piece test loads

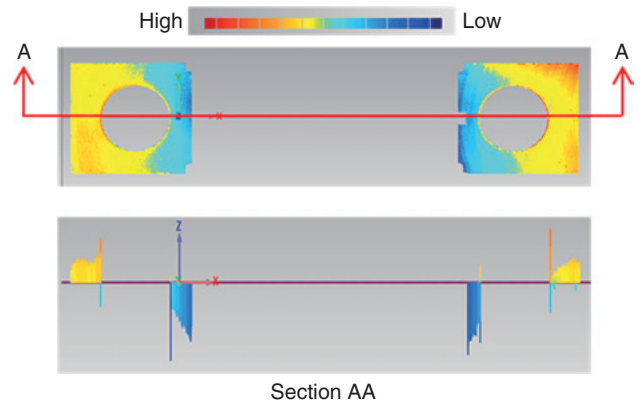


Fig. 10 Surface property from measurements

on material test pieces, and fractures did not occur even in endurance tests involving continuous vibration. Results for stress amplitude and relative slip for a specification in which the bolt axial force and the block stiffness were reduced were higher than values on the fretting fatigue limit diagram, and fractures occurred in endurance tests involving continuous vibration. The facts that the bearing mating face turned black and the fracture originated in the mating face were considered to indicate that fretting wear was a factor in the development of the fracture⁽³⁾. Figure 12 shows the results of inspection of the surface affected by the fretting fracture.

Based on these results, it was possible to verify a correlation between the relationship between stress amplitude and relative slip obtained using the developed test method and the fretting fatigue limit diagram and the occurrence or non-occurrence of fretting fatigue fracture. This is believed to indicate that it is possible to predict fretting fatigue fracture without using an actual engine, by means of the developed test apparatus that models an engine.

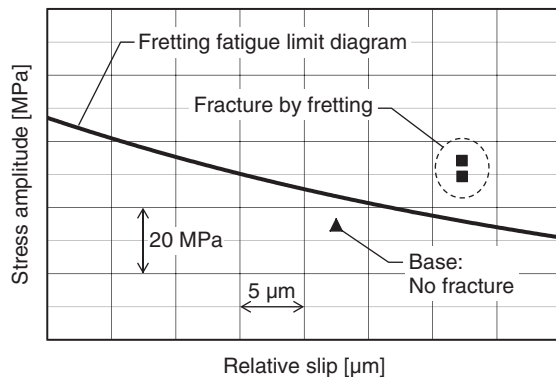


Fig. 11 Results of stress and relative slip measurements

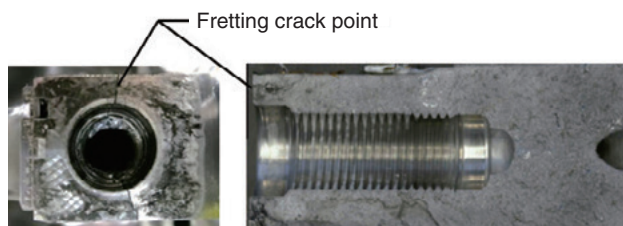


Fig. 12 Results of material inspection after cylinder block test

5. Establishment of Method for Verification in Actual Engine

5.1. Verification Test Conditions

In order to verify that tests using an actual engine would produce the same results as cylinder block unit tests, endurance tests were conducted on an actual engine, and

Table 3 Test conditions

	Test 1	Test 2
Engine type	1.5 L Engine	Same as left
Oil temp	80°C	Same as left
Water temp	80°C	Same as left
Engine speed	6800 r/min	Same as left
Endurance test time	100 hr	26 hr
Bolt axial force	Base	11% reduction
Force amplitude on crankshaft	Base	56% increase

stress amplitude and relative slip were measured using the method employed in unit tests. Because clip gauges could not be fitted in an actual engine, measurements were conducted using strain gauges.

Tests were conducted using two patterns in which the main bearing bolt axial force and the force amplitude on the crankshaft (factors that stress amplitude displays sensitivity to) were varied⁽⁵⁾.

Table 3 shows the engine test conditions.

5.2. Results of Verification Tests

Figure 13 shows the results of stress amplitude and relative slip measurements. The results for stress amplitude and relative slip in Test 1 were lower than the values shown in the fretting fatigue limit diagram, and fracture did not occur even after 100 hours of endurance testing at 6800 rpm. The results for stress amplitude and relative slip in Test 2 were higher than the values shown in the fretting fatigue limit diagram, and fracture occurred after 26 hours of fatigue testing at 6800 rpm. Fracture occurred between 1×10^6 and 1×10^7 repetitions in the results for measurement of stress amplitude and relative slip, according with the results of predictions. The state of the bearing mating face following the endurance tests and the

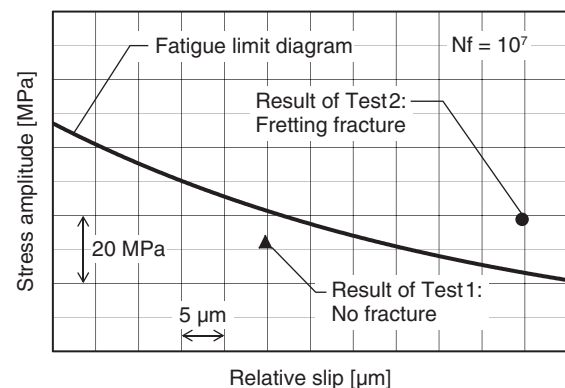


Fig. 13 Results of stress and relative slip measurements

origin point of the fracture were the same as the results of unit tests, and it was therefore considered that a fretting fatigue fracture had occurred. Figure 14 shows the results of inspection of the fracture face.

The results obtained using the developed test method displayed the same tendency as the results of cylinder block unit tests, demonstrating its validity as a method of evaluating fretting fatigue fracture in actual engines using strain gauges.

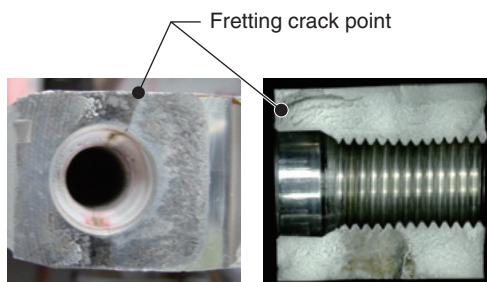


Fig. 14 Results of material inspection after actual engine test

6. Conclusion

The research discussed in this paper developed a method of prediction of fretting fatigue fracture in the cylinder block development process prior to the implementation of endurance tests and a method of verification of prediction results, producing the outcomes discussed below. The results of this research will make it possible to reduce the number of endurance tests performed on actual engines in order to study fretting fatigue fracture, and thus reduce the number of man-hours involved in the development process.

- (1) Unit tests of material test pieces showed that fatigue strength declined by approximately 25% at a relative slip of 15 μm when fretting occurred, and made it possible to define a fretting fatigue limit diagram.
- (2) The development of a method of evaluation of fretting fatigue fracture in unit tests using test pieces cut from actual cylinder blocks has enabled prediction of fretting fatigue fracture prior to endurance tests using actual engines.
- (3) The development of a method for the evaluation of fretting fatigue fracture in actual engines using strain gauges has made possible simple verification of results in a short time period.

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