

Technology for Prediction of Housing Wear due to Outer Ring Creep under Bearing Load

Yayoi NAGASOE*

Shigeharu WAKUI*

Yuta MAEYOSHI*

ABSTRACT

A method for the prediction of the amount of wear occurring to the housings of automotive transmissions due to the rotation of the outer rings of the bearings has been newly developed. The method employs a 3D dynamic analysis in order to simulate the creep behavior of the outer rings of the bearings. The amount of wear to the housing is calculated based on the contact pressure and creep distance of the outer rings of the bearings determined by analysis and the specific wear rate measured in a unit wear test. Because the direction of wear differs for each shift stage, the amount of wear is totalized with consideration of the direction of load. Predictions of the amount of wear to housings display a high level of correlation with the results of durability tests. The high-accuracy prediction of the amount of housing wear makes it possible to study specifications for the control of housing wear from an early stage of the design.

1. Introduction

Growing demand for technologies that will increase fuel efficiency have seen the layouts of automotive transmissions tending to become more complex, with the use of multi-stage and multi-shaft configurations that seek to realize further electrification and wider operating ranges. In addition, demands for reduced weight and greater compactness are tending to reduce the space between neighboring shafts in order to make it possible to fit parts more closely in restricted spaces.

The rolling bearings used for each shaft are fitted in a cast aluminum case housing (Fig. 1). When the rolling bearings are reduced in size or the stiffness of the housing is reduced in order to reduce weight and increase compactness, the outer rings of the bearings rotate in relation to the housing, and the section of the housing in which the bearings are fitted can be subject to wear. This wear is termed housing wear. Because it causes deviation of the positioning of the shaft supports, this type of wear may produce misalignment of the gears, resulting in noise and durability issues.

Responses using indicators including the contact pressure of the outer rings have been investigated in attempts to control housing wear. However, even when factors such as the diameter of the bearings or the housing layout are modified, the process can become one of trial and

error, and this has represented an issue in relation to short development periods.

The need to respond to increasingly complex configurations and boost accuracy in relation to predictive indicators for housing wear was therefore increasing.

The phenomenon of rotation of the outer rings of the bearings, which produces housing wear, is termed outer ring creep. A great deal of research has been conducted on the mechanism of outer ring creep and analysis of its effects⁽¹⁾⁻⁽³⁾, but there do not appear to be any reports concerning the prediction of the amount of wear occurring to the housing.

This paper will discuss the development of a method of prediction of the amount of housing wear from the design review stage that is sufficiently accurate for practical use.

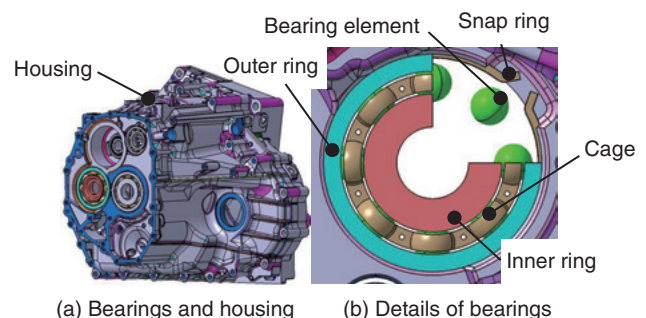


Fig. 1 Bearings

* Automobile R&D Center

2. Housing Wear Resulting from Bearing Outer Ring Creep

At room temperature, the outer rings of the bearings that support the shafts are pressed into the section of the housing in which they are fitted, and are therefore constrained. However, when the unit is in use its temperature increases, and gaps appear due to the difference in thermal expansion between aluminum and iron. As a result, the outer rings become unconstrained in the circumferential direction. Outer ring creep, which results in wear, is a phenomenon in which the outer rings rotate slowly in the same direction as the inner rings in contrast with the fixed housing.

According to Zhan et al.⁽¹⁾, this phenomenon originates in elastic deformation of the surfaces of the outer rings as a result of the fact that the bearing elements forcefully press the outer rings as they rotate. Teramoto et al.⁽³⁾ reproduced creep in a CAE model and an actual transmission unit, and reported on the degree of contribution to creep of factors related to the bearings.

Housing wear occurs when the bearing outer rings are pressed against the inner wall of the housing in the load direction and slide against the housing due to creep. As Fig. 2 shows, housing wear progresses in the direction of the load on the bearings, and the amount of wear is manifested as the degree of change in the diameter of the housing. Because the outer rings of the bearings are manufactured from steel and ground to a high level of accuracy, they display good surface roughness, and there is no change in their dimensions or the state of their surfaces even after the completion of durability tests. The housing is cast from aluminum, and wear therefore occurs on the housing side only. Housing wear proceeds at the slow pace of around several hundred μm per 1,000 hr. Because of this, the wear face remains smooth, and does not adhere. The abrasion powder produced floats

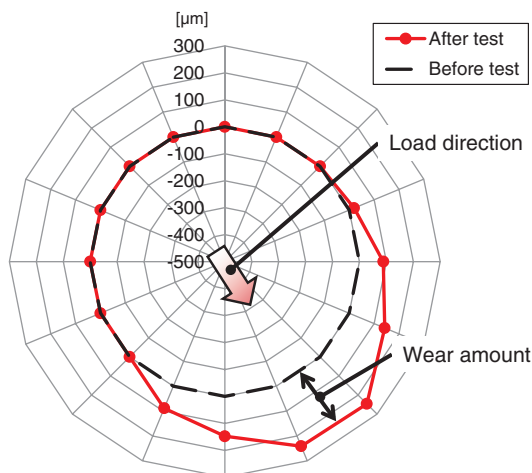


Fig. 2 Housing wear profiles

in the oil without settling, and is so fine that it cannot be identified with the naked eye.

During durability tests, the amount of wear increases in proportion to the duration of the test, as shown in Fig. 3. Given this, it was hypothesized that the amount of housing wear would display a high correlation with the degree of accumulation of wear-related factors during the durability test. Based on this consideration, the method discussed in this paper attempted to approximately calculate the amount of wear by appropriately cumulating wear-related factors.

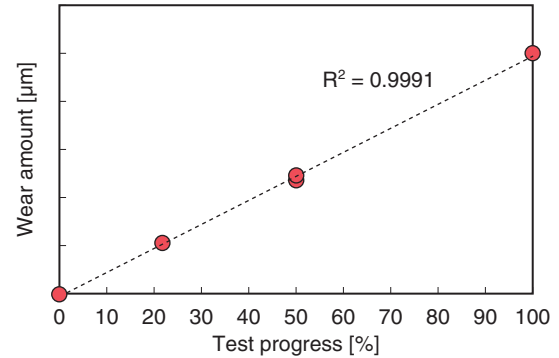


Fig. 3 Progression of housing wear in durability test

3. Development Goals

The amount of wear is generally expressed using the following Eq. (1), with the contact pressure and slip distance of the wear faces as the wear-related factors⁽⁴⁾.

$$W = k \cdot P \cdot V \cdot t \quad (1)$$

W : Estimated amount of wear

k : Specific wear rate⁽⁵⁾

P : Bearing load contact pressure

V : Creep speed

t : Creep time

The following substitutions are made in this paper:

$$\begin{aligned} W &= k \cdot P \cdot L \\ &= k \cdot P \cdot l \cdot n \end{aligned} \quad (2)$$

L : Total creep distance

l : Creep distance for each passage of bearing elements

n : Total number of passages of bearing elements

Because the direction of wear differs for each shift stage, it is necessary to calculate wear separately and total it. First, the contact pressure and creep distance for each shift stage are calculated from the test time chart items and multiplied by the specific wear rate in order to convert them to the amount of wear. Because the form of housing wear is affected by the amount of

wear for all shift stages, the figures are totaled with consideration of the direction of load in each shift stage. The method of totaling the amount of wear for shift stages A and B (Fig. 4) will be considered as an example. The calculated amount of wear indicates the distance that the center of the bearings travels in the direction of bearing load. In this case, the form of wear is crescent-shaped, representing the distance between the initial housing holes and the bearing diameter following the movement of the center of the bearings. The amount of crescent-shaped wear is calculated for each angle on the circumference of the circle. The amount of crescent-shaped wear for each angle on the circumference of the circle is totaled for each shift stage, making it possible to calculate the form of wear produced by the two shift stages, A and B. As indicated above, relational equation (2) was hypothesized based on the fact that housing wear increases in a proportional relationship with the progress of the durability test. This made it possible to establish calculation methods for the following two items:

- (1) A simulation technology for the behavior of outer ring creep
- (2) A prediction technology for the amount of housing wear

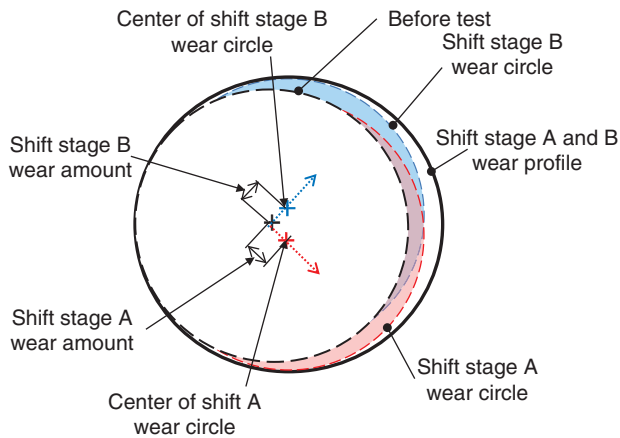


Fig. 4 Totaling housing wear profiles

4. Simulation Technology for Behavior of Outer Ring Creep

An analysis was conducted using general-purpose nonlinear dynamic analysis software in order to reproduce the macro behavior of the bearings and the micro-deformation of the outer rings. Part of the housing, the outer rings, the inner rings, the bearing elements, the cage and the snap rings were modeled in order to reproduce brake behavior as affected by the housing stiffness and the snap rings. Figure 5 shows the 3D analysis model.

Each part was defined as an elastic body other than

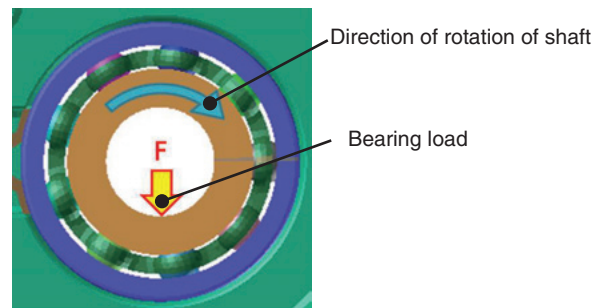
the bearing elements, which were defined as rigid bodies in order to reproduce the smooth forms of the elements.

In order to reproduce states in an actual transmission unit, as boundary conditions for the analysis, the outer circumference of the housing was completely constrained, while the bearing load for each shift stage was applied to the inner rings and the inner rings were subjected to forced rotation at a constant speed. A coefficient of friction of 0.15 was used between the outer rings and the housing and for the snap rings, and a coefficient of 0.05 was used for the interiors of the bearings.

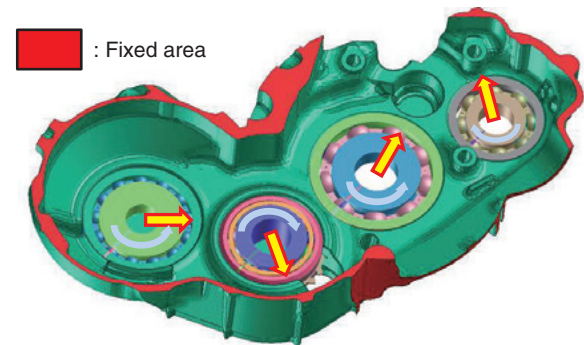
4.1. Study of Distribution of Contact Pressure

Measurements were conducted of contact pressure between the outer rings and the housing in an actual transmission unit in order to verify the accuracy of outer ring contact pressure in the simulation. The measurements were conducted by positioning a thin-film pressure sensor (thickness: 0.1 mm; 56 × 56 mm) between the housing and the outer rings of the bearings. The hole diameter of the housing was increased with consideration of the thickness of the sensor. The sensor was positioned in the direction of load; dummy sheets of equivalent thickness to the sensor were used in the remaining sections (Fig. 6).

Figure 7 shows the results of measurements conducted using the thin-film pressure sensor and the



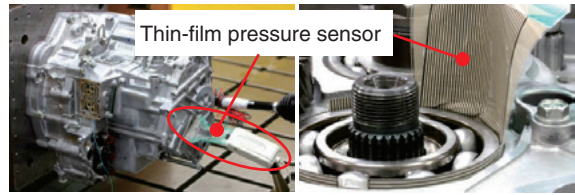
(a) Concentrated nodal load and speed of rotation



(b) Displacement boundary conditions

Fig. 5 3D-analysis model

results of calculations of contact pressure in the dynamic analysis. Normally when the housing stiffness is uniform, the direction of maximum contact pressure on the bearing elements and the direction of bearing load correspond, but in this case the housing stiffness was low in the



(a) Test equipment

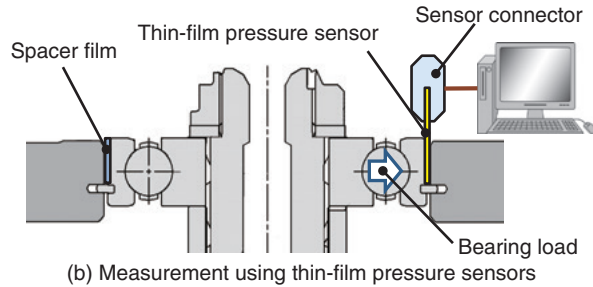
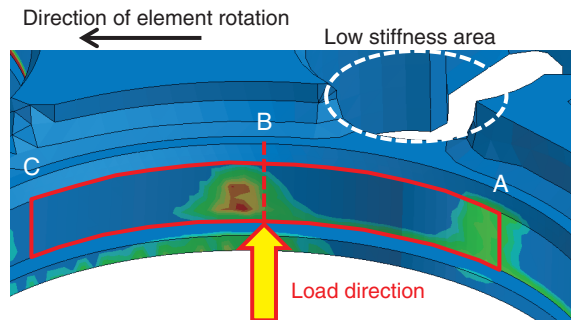


Fig. 6 Schematic of test equipment



(a) Area for measurements

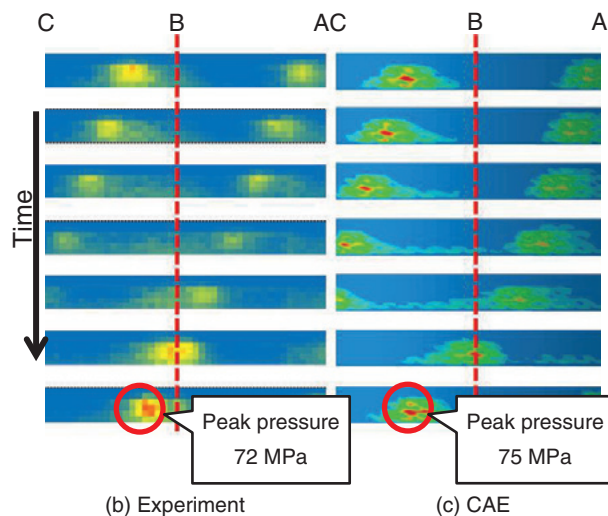


Fig. 7 Comparison of contact pressure

direction of load, and the directions did not match in the measurements. It was possible to reproduce the deviation in direction and absolute value of maximum contact pressure by means of faithfully 3D modeling the shape of the surrounding housing and dynamically rotating the bearing elements.

4.2. Calculation of Outer Ring Creep Distance

Figure 8 indicates the results of calculation of displacement of the outer circumferences of the outer rings in the direction of load using the 3D dynamic analysis discussed above. The outer rings move in the direction of progress of the bearing elements, but temporarily move in the opposite direction. Figure 9 explains this behavior.

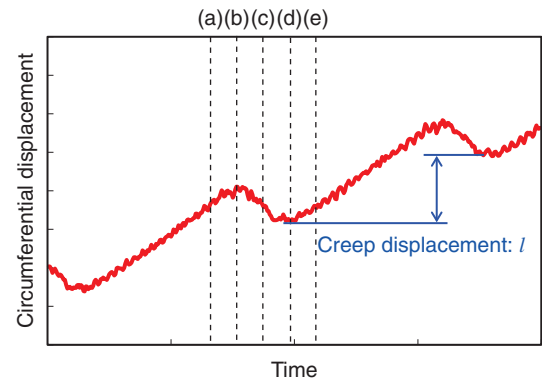


Fig. 8 Circumferential displacement at evaluation point

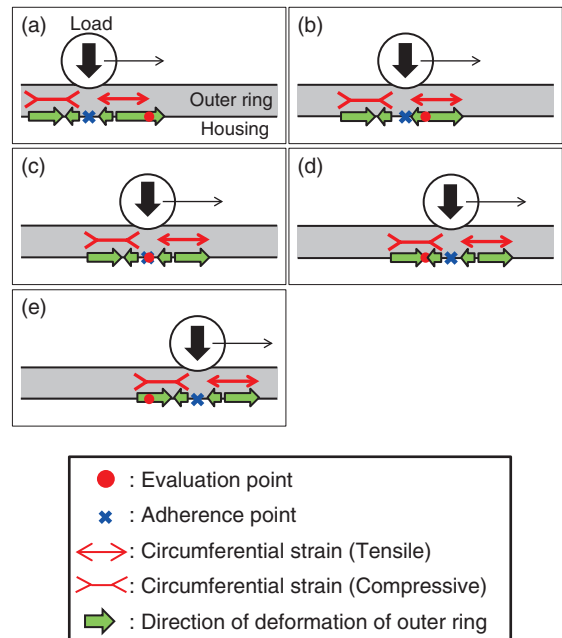


Fig. 9 Behavior of outer ring and ball

- (a) Before the passage of the bearing elements, circumferential strain on the surfaces of the outer rings increases in the vanguard of the direction of progress of the bearing elements. Because of this, the evaluation point for maximum contact pressure moves in the direction of progress of the bearing elements.
- (b) As the bearing elements approach the evaluation point, the evaluation point moves in the opposite direction due to the effect of the adherence point.
- (c) When the bearing elements are directly above the evaluation point, the evaluation point adheres to the housing, and moves in the opposite direction to the bearing elements⁽²⁾.
- (d) When the bearing elements separate, the evaluation point moves in the same direction as the bearing elements due to the effect of the adherence point.
- (e) After the passage of the bearing elements, because strain in the circumferential direction on the surfaces of the outer rings declines in the rear of the direction of progress of the bearing elements, the evaluation point moves in the same direction as the bearing elements. Following this, the process returns to (a).

In the calculations conducted in this research, the creep distance produced by one passage of the bearing elements was termed l . It was therefore possible to calculate the total outer ring creep distance, L , by multiplying this figure by the total number of passages of the bearing elements, n .

The total number of passages of the bearing elements was calculated based on parameters including shaft speed, engine torque, and shift stage from test time history data.

4.3. Study of Speed of Outer Ring Creep

Because the direct measurement of micro-displacement is challenging, the accuracy of the simulation was verified by means of measurements of outer ring creep speed.

Figure 10 shows the set-up for measurement of outer ring creep speed in an actual transmission unit. A hole was drilled into the housing in order to render a section of the bearings visible, and a mark was machined on an outer ring to help enable measurement of the speed of outer ring creep.

Figure 11 shows results for actual measurements and simulation calculations of the speed of outer ring creep when the shift stage was fixed and the inner rings were rotated at 5,500 rpm.

Simulation predictions of outer ring creep speed basically matched the measurements taken in an actual transmission unit.

This demonstrated that the developed simulation technology for the behavior of outer ring creep provides a method of predicting contact pressure and creep distance in actual operation.

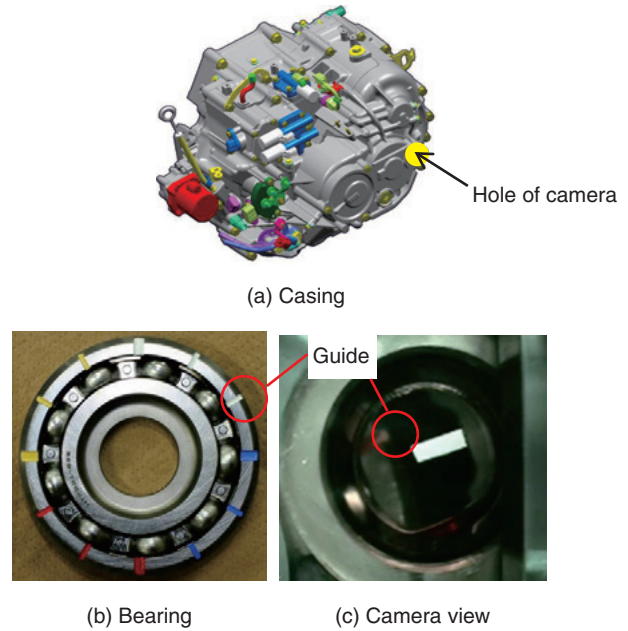


Fig. 10 Measurement of creep speed in bearing outer ring

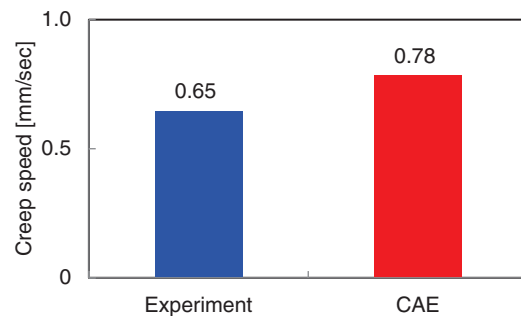


Fig. 11 Comparison of creep speed

5. Technology for Prediction of Housing Wear

5.1. Measurement of Specific Wear Rate

Pin-on-disc unit wear tests simulating the environment in an actual transmission unit were conducted in order to determine the specific wear rate for housing wear. Using a friction and wear tester (FPR-2300; RHESCA CO., LTD), a pin test piece was pressed against the upper edge of a disc-shaped test piece of 80 mm in diameter revolving horizontally, and sliding tests were conducted. The tip of the pin test piece had a cylindrical shape of 1.1 mm in diameter. In order to reproduce conditions corresponding to those in an actual transmission unit, the test was conducted using a pure Honda Automatic Transmission Fluid (ATF) lubricant at 80°C, under contact conditions of friction speeds of

0.4, 1.0, and 1.5 mm/sec and a contact pressure of 51.6 MPa (with a load of 5,000 g). The pin test piece was manufactured from the aluminum material employed in transmission housings. The disc was manufactured from the high carbon chrome steel (SUS2) used for bearings. To help ensure that the disc displayed identical surface properties to bearings, a surface roughness (R_z) of 0.5 μm was used.

During the tests, the amount of wear of the pin was measured over time, and the relationship between the amount of wear and the friction distance was plotted on a graph. In the range within which the amount of wear increased linearly with increase in friction distance, the amount of wear per unit friction distance and contact pressure was calculated as the specific wear rate (mm^2/N). Tests were conducted three times for each friction speed and the average value of the calculated specific wear rate in each case was taken as the representative figure for that friction speed.

Figure 12 shows the relationship between specific wear rate and friction speed. The specific wear rate increases as the friction speed declines. This is considered to be due to an increase in the contact areas between the disc-shaped test piece and pin test piece as the friction speed declines. Wear is a phenomenon that occurs in the contact areas, and the amount of wear therefore increases with a greater amount of areas in contact. In addition, when the test pieces are sliding together under lubrication, lubricant films are decreasingly formed the lower the sliding speed, increasing the amount of the contact area⁽⁵⁾.

Actual outer ring creep proceeds at a pace of 1.0 mm/sec or less, and the range in which the friction speed is 1.0 mm/sec in Fig. 12 corresponds to the speed range under an actual use state. The value on the horizontal axis that the line connecting the maximum values of the specific wear rate for each speed intersected with was taken as the maximum value of the specific wear rate in the speed range corresponding to that of an actual transmission unit (the value indicated by the arrow in Fig. 12; $1.3 \times 10^{-8} \text{ mm}^2/\text{N}$), and was used to predict the amount of wear.

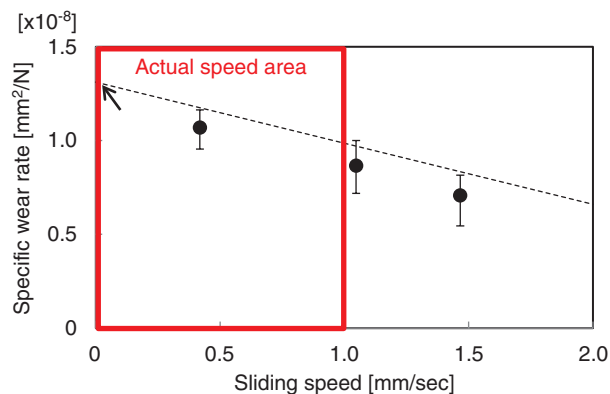


Fig. 12 Specific wear rate in relation to sliding speed

Table 1 Specifications of transmissions

Type	Bearing type
A	Ball
B	Ball
C	Double row angular contact ball
D	Ball
E	Ball
F	Ball
G	Four-point contact ball

5.2. Accuracy of Prediction of Housing Wear

CAE predictions of the amount of housing wear occurring during durability tests were compared with actual measurements in order to verify the general applicability of the developed prediction technology. Results were compared for transmissions using different forms of shift. Table 1 shows the bearings used in each of the transmissions for which comparisons were conducted.

Figure 13 shows results for the bearings in the

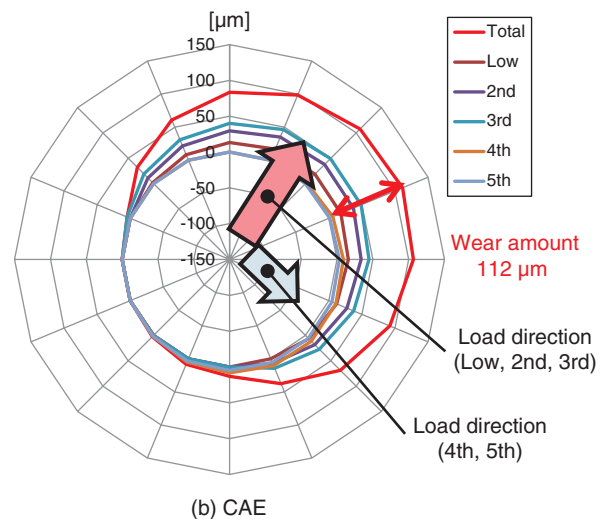
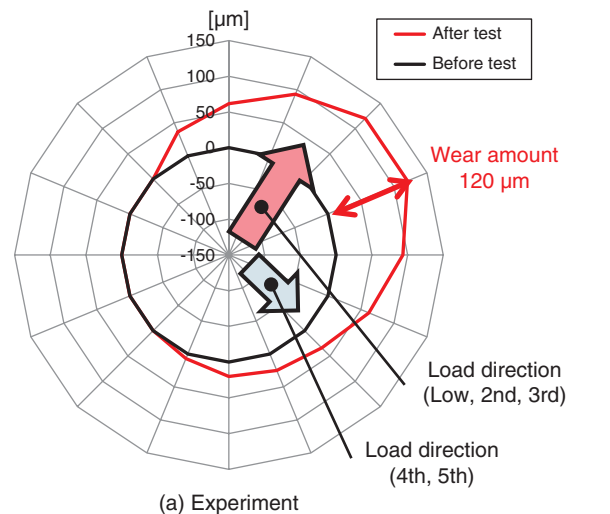


Fig. 13 Housing wear profiles

Type-B transmission. Even when the direction of the load on the bearings differed for each shift stage, this method produced results for maximum amount of wear, direction of wear and form of wear corresponding to measurements.

Figure 14 shows a plot of measured values and CAE predictions for Type-A to -G transmissions. Irrespective of the type of transmission or bearings, there is a high level of correlation between measurement results and CAE predictions.

This demonstrates that it is possible to predict the amount of wear that will occur in a transmission housing using the contact pressure on the outer rings and the creep distance that accumulates in the outer rings.

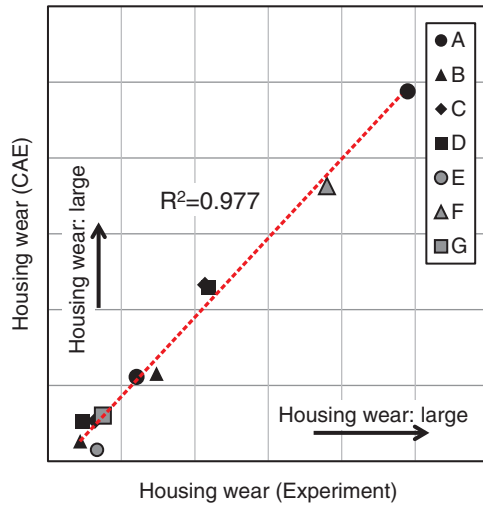
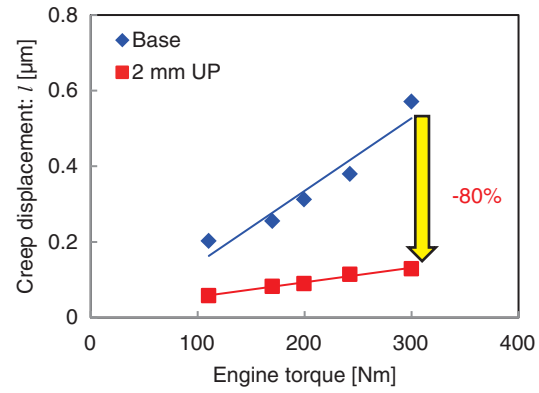


Fig. 14 Comparison of correlation between CAE predictions and measurements of housing wear

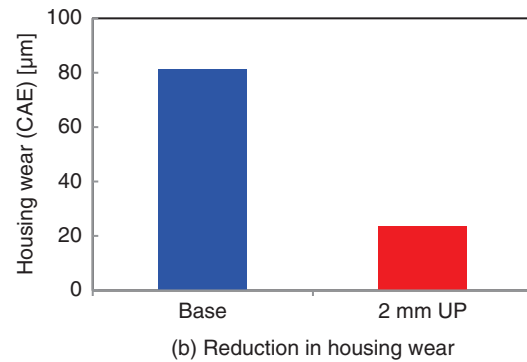
6. Application in Model Development

This chapter will discuss an example in which the developed method was employed to predict the amount of wear occurring in a transmission housing during a development, resulting in changes to the bearing specifications.

In the prediction result using the developed method, shown as Fig. 15, housing wear became a concern. It was predicted that increasing the thickness of the outer rings of the bearings by 2 mm would reduce outer ring creep distance by 80%, and it was possible to review the specifications by means of a theoretical 3D dynamic analysis.



(a) Reduction in creep displacement



(b) Reduction in housing wear

Fig. 15 Results of study of proposed measure

7. Conclusion

A method of prediction of the amount of wear occurring in the housing of an automotive transmission due to the rotation of the outer rings of the bearings has been developed.

- (1) A 3D dynamic analysis was conducted in order to reproduce the macro behavior of the bearings and the micro-deformation of the outer rings. This made it possible to reproduce outer ring creep behavior.
- (2) A technology for the prediction of the amount of wear to the housing based on the contact pressure and creep distance of the outer rings of the bearings and the specific wear rate was developed.

Application of the method to a variety of bearings of transmissions demonstrated that it was able to predict the maximum amount of wear, the direction of wear, and the form of wear with a high level of correlation with results obtained from actual transmission units.

This method will make it possible to review designs for the control of housing wear, helping to verify specifications at an early stage of development.

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■ Author ■



Yayoi NAGASOE



Shigeharu WAKUI



Yuta MAEYOSHI