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LIFE PREDICTION OF BEARING USING ACCELERATED LIFE TEST COUPLED WITH ANALYSIS

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Abstract. The amount of wear is a significant factor for evaluating bearing failure. However, it is difficult to predict the precise occurrence of failure, because the wear gradually happens for a prolonged period. Therefore, it is impossible to assure the bearing life experimentally. In this study, the accelerated life testing coupled with numerical analysis was performed to predict the accurate bearing life. The process can be described as follows: first of all, material characteristics and wear coefficients were obtained through tensile test and constant wear test; second, acceleration factor of wear depth was calculated by looking different test conditions, such as load and rpm; third, test response prediction function was derived and product life prediction function was determined by the acceleration factor; Finally, wear depth was calculated by solving two functions above. Meanwhile, to verify the result of the accelerated life test, the rating life of ISO standard was compared. Life prediction of the bearing for spalling calculated by accelerated life test was compared with the standard bearing life. The results showed that the accelerated life test result and the standard bearing life were similar. In conclusion, the accelerated life test coupled with numerical analysis could be employed to predict the bearing life the more rapidly and more accurately in comparison to other traditional test methods.

1 INTRODUCTION

It is important to predict the bearing life because defects and wearing occur during its use. Currently, the bearings life sold in the market is calculated according to the ISO 281. ISO states the theory of the bearing life called rating life, which calculates the bearing life by geometric factors, e.g. contact angle and ratio between roller and washer. Normally, the failure is judged by first appearance of spalling in roller and washer. However, spalling may not always be the critical problem of bearing life. For example, the wear depth of the bearing can be a criterion when the fit tolerance is important. In this study, failure was determined on the basis of wear depth.

The accelerated life test proposed in this study is performed at severe conditions to shorten the test period, because the life prediction test may require unreasonably long test time under actual use conditions. When the accelerated life test is conducted, there are various types of stress factors, e.g. lubrication, high load and high velocity. It is important to choose the correct types of stress factors by considering mechanism of the parts and the surrounding environment. Recently, there have been a number of researches on analysing the material characteristics and results of the accelerated life test. Mettas and Vassiliou (2004) studied how to analyze the test by dividing the stress factors.[1] Srivastava et al. (2011) applied various types of stress conditions, and then validated the suitability of ramp stress type in the accelerated life test.[2] The ramp test was performed by continually increasing the stress over time. Rajkumar et al. (2011) verified the model of the accelerated life test dependent on the material properties.[3] Chao Zhang et al. (2014) introduced the accelerated life test coupled with numerical analysis that could predict the life quantitatively without tests to predict life of the part according to the wear.[4] M. M. Mary et al. (2007) inferred wear damage in surface and contamination level by measuring the frequency.[5] Thncay Karacay et al. (2009) derived the vibration spectrum by performing the statistical measures, to control nucleation and location of the bearing damage.[6] As such, recent studies show increasing interest in the accelerated life test and numerical analysis. From the previous studies, ramp tests were utilized ramp tests in the accelerated life test. Also, the time to predict the life was reduced by applying the accelerated life test coupled with numerical analysis.

In this study, the accelerated life test was conducted to predict the bearing life. The test data and wear depth were obtained per 1,000 revolutions, and the response function for the bearing life was established. Then, material and wear characteristics were derived by performing the accelerated ramp test and the numerical analysis. Wear tendency for stress factor was obtained by the accelerated step test. Finally, ISO standard was compared with the accelerated life test to validate the result.

2 THEORY OF THE BEARING LIFE

2.1 Factors affecting bearing life

The Damage done to bearing is caused by many reasons, such as absence of lubrication, contamination or deviation of shaft, housing, and others. The wear of the bearing is a phenomenon which gradually reduces material surface mainly due to the friction force. Then, material surface becomes coarse and the rotation becomes instable, bearing may be spalled by the propagation of the fatigue crack in contact surfaces. This is inevitable even in the normal operation conditions, because of material fatigue. Therefore, the size of the spalling is used to predict the bearing life. Sometimes, damage of the bearing surface is locally burned, which is known as smearing. Smearing occurs when the bearing lubrication is inadequate during rotation. Excessive load is applied when rotating speed of bearing is slow or stopped, and as a result, the contact between washer and roller may lead to a plastic deformation called brinelling, which adversely affects friction, sound, and vibration.

In addition, there are many other factors that affect the bearing life which can be combined in a complex fashion, which further complicates identification of causes of damage. However, approximate bearing life can be predicted by identifying its operation environment and damage condition.

2.2 GTN damage model

Gurson (1977) analyzed plastic flow of elasto-plastic porous material, and defined yield model.[7] Tvergaard (1981) proposed a modified yield model in Eq. (1) by adding three parameters q_1, q_2 and q_3 to accurately predict strain rate at failure period.[8]

f^* is void volume fraction. σ_Y, q and p are yield stress, effective stress and hydrostatic stress, respectively. This yield model denotes the effect of the void to the flow behavior of material. This model takes the hydrostatic stress into the consideration even when its effect is small. Therefore, the softening of the material due to the void growth can be described. In other words, material strength is lowered when void is formed.

$$\Phi = \left(\frac{q}{\sigma_Y}\right)^2 + 2 f^* q_1 \cosh\left(\frac{3}{2} q_2 \frac{p}{\sigma_Y}\right) - \left(1 + q_3 f^{*2}\right) = 0 \quad (1)$$

Tvergaard corrected the parameter values as $q_1 = 1.5$, $q_2 = 1.0$ and $q_3 = 2.25$, which are able to predict failure through the experimental data.

2.3 Archard wear model

Wear of the material is influenced by various factors. Archard established the equation in Eq. (2) to define linear relation between the loads and wear ratio.[9] Through modified Archard equation which contains increased degrees of freedom for variables in order to make it possible to apply the equation depending on material characteristics, wear of the material can be predicted.

$$W = \int K \frac{p^a v^b}{H^c} dt \quad (2)$$

W and v are the wear depth and the sliding velocity. p, H and K are the normal pressure, the hardness and the wear factor, respectively. a, b and c are the degrees of freedom for the factor affecting the wear. This study uses the most common values, $a = 1$, $b = 1$ and $c = 2$.[10]

3 BEARING CHARACTERISTICS WITH ANALYSIS

3.1 Material characteristics

The bearing is generally made by bearing steel (SUJ2). In order to evaluate material characteristics of bearing steel, tensile tests was conducted. Tensile tests specimens were processed according to ASTM E 8M standard. Tensile tests at room temperature were conducted in INSTRON 3367 universal testing machine.

$$\sigma = A\left(B + \varepsilon\right)^n \quad (3)$$

Consequently, it is identified that flow stress of bearing steel is barely influenced by the strain rate. Load-displacement curve at the plastic region obtained from the tensile tests is shown in Fig. 1. Swift model is used in Eq. (3), which is a general flow stress equation. Coefficients of the flow stress model (A, B and n) were obtained by numerical analysis and compared with tensile tests results. Here, DEFORM 3D, commercial finite element analysis software, was used to conduct the numerical analysis.

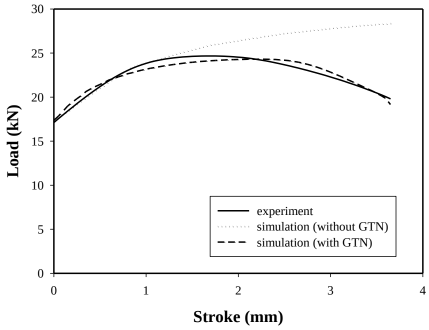


Figure 1: Results of the confirmation simulation for the GTN damage model

Relative error was defined as a difference of area in load-displacement curves between the numerical analysis and experimental data. Coefficients of flow stress model were derived by minimizing the relative error, and the values were shown in Table 1.

Table 1: Determined parameters of the flow stress model for SUJ2

Parameter	Value
A (MPa)	45.5
B	0.92
n	1.59

Results of the tensile tests are influenced by the damage characteristics which will be explained in section 3.2. Material parameters used before necking were obtained by minimizing the relative error. Progressive Quadratic Response Surface Modeling (PQRSM) method was used to minimize the relative error in this study. [11]

3.2 Damage characteristics

The Damage characteristics of bearing steel were evaluated by using GTN ductile failure model. In order to use the GTN model, nine coefficients should be determined by employing the previously described methods. GTN model coefficients were derived in Table.2, which minimized the relative error. Commonly used values were applied, $q_1 = 1.5$, $q_2 = 1.0$ and $q_3 = 2.25$.

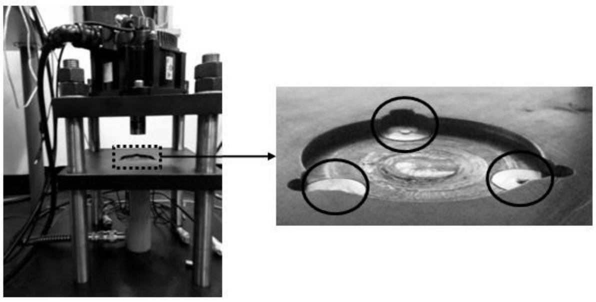
Table 2: Determined parameters of the GTN damage model for SUJ2

Parameter	Value
ε_N	0.033
s_N	0.121
f_n	0.328
f_0	0.002
f_c	0.28
f_f	0.295

Load-displacement curve which applies the GTN models is shown in Fig. 3. GTN model accurately described the material behavior, and it was greatly affected on failure. Therefore, GTN model should be applied within flow stress model in order to simulate the actual behavior of bearing steel.

3.3 Wear characteristics

In order to perform wear analysis of the bearing, modified Archard model was applied as bearing rotation mechanism. Wear of thrust roller bearing used in this study occurred at the contact surface between washer and roller, causing the total height of bearing to be reduced. Thus, the height reduction of bearing was selected as a test response, which could be measured quantitatively by performing wear tests.



(a) (b)

Figure 2: (a) Bearing wear test equipment (b) Locations of three load cells

Tests for height reduction, which is the test response, were performed by measuring the same point at each rotation to increase accuracy. In order to identify trends of the wear, constant stress test was conducted with 1000kgf load. The height was measured at a total of seven times per 10,000 cycles. Wear depth was increased consistently as shown in Fig.3. Then, Eq. (4) was obtained by linear interpolation.

$$\Delta H(N) = 0.0548N \quad (4)$$

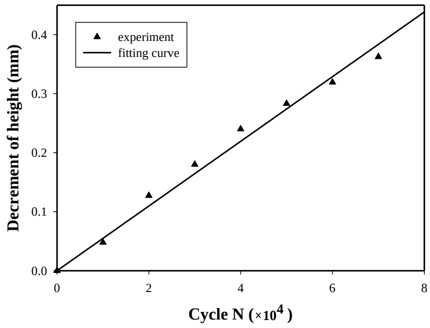


Figure 3: Experiment result of wear test for bearing

Wear coefficient of the modified archard model was determined by using finite element analysis, and the actual wear aspects of the bearing applied to the wear coefficient could be simulated. Through the wear analysis, a linear function indicated in Fig. 4 was confirmed. Accordingly, prediction function of the wear coefficient K was obtained in the form in Eq. (5).

$$\Delta H(K) = (1.1545 \cdot 10^7)K + 0.0079 \quad (5)$$

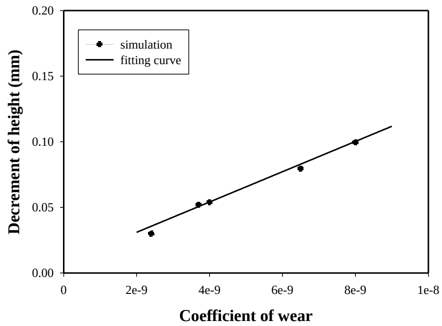


Figure 4: Decrement of height by wear coefficient of bearing at 10,000 revolutions

Wear coefficients which satisfied Eq. (4) was selected as Table.3 to verify whether experimental value and analysis values showed similar trends. The amount of difference between analysis result and the actual test result was less than 2%, so wear coefficient was verified.

Table 3: Difference between experiment and simulation result for wear depth

Parameter	Decrement of height
	Per 10,000 revolution
Test result	0.0548 [mm]
Computation result	0.0533 [mm]
Wear coefficient	3.989e-09

3.4 Spalling characteristics

In this study, increment of spalling in the bearing was selected to be a test response along with wear depth. The test for spalling was conducted to quantitatively measure the amount of spall according to the number of revolutions, as shown in Fig. 5. The test was performed with 4330kgf rating load and 800rpm. The amount of spall was measured by microscope observing roller and washer per 1,000 cycles. The amount of spall exponentially increased, while wear depth of the bearing showed linear increase.

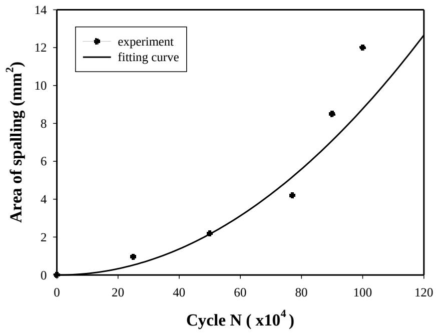


Figure 5: Experiment result of spalling test for bearing

4 ACCELERATED LIFE TEST COUPLED WITH ANALYSIS

4.1 Procedure of the test

Accelerated life test coupled with numerical analysis can predict the life of the part more efficiently by conducting accelerated test along with simulation. The simulation can obtain data which is difficult to be derived in the actual test. The amount of the severe conditions in accelerated life test is defined as AF (Acceleration Factor). It is possible to quantitatively predict the product life by selecting the stress conditions and derive the test response prediction functions.

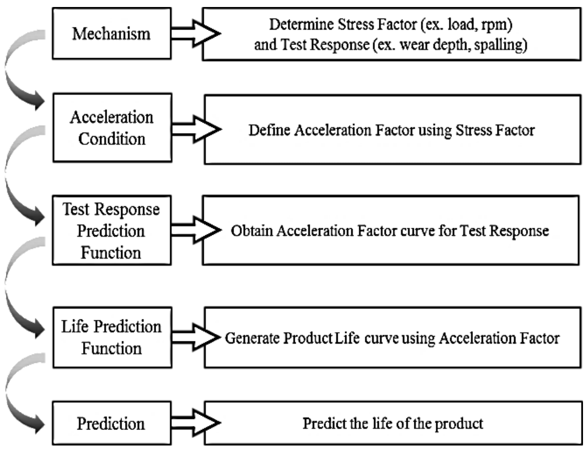


Figure 5: Procedure of accelerated life test coupled with numerical analysis

The overall procedure of accelerated life test coupled with numerical analysis is shown in Fig. 5. First, the stress factors resulting in the product failure and test response are selected. Then, the accelerated life test conditions are designed, and the step stress test is applied by using the selected stress factors. Also, the acceleration factor is defined in this step. Next, the test response prediction function is derived according to the differences of the life in each product. Finally, domain and range of the product life curve are defined, and the product life function is generated by considering the test response prediction function.

4.2 Results of the test

Material characteristics and constants of the damage and wear model were derived to predict the bearing life the by applying the accelerated life test coupled with numerical analysis. Then, the test response prediction function was induced by using the step stress condition, which was applied by increasing 500kgf per 2,000 cycles in the wear test. For the verification of the accelerated life test coupled with numerical analysis, results of the step stress test were compared with the analysis results.

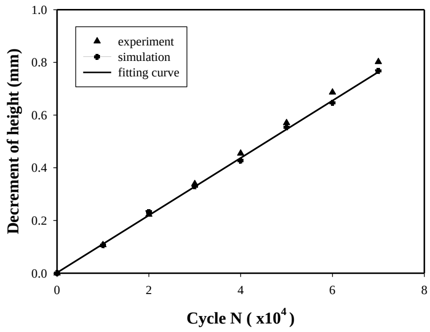


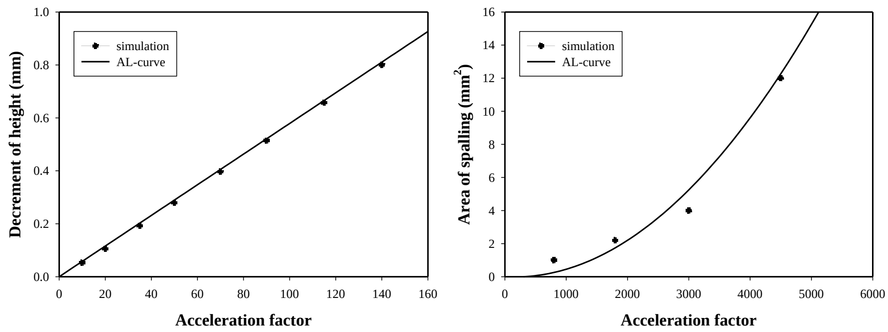
Figure 6: Comparison between test result and computation result for bearing wear test

The comparison is shown in Fig. 6, and it is verified that the accelerated life test coupled with numerical analysis can present the actual wear phenomenon within 5% error. The amount of wear depth distribution according to increasing number of rotations is presented, and the increase of the wear can be confirmed as rotation numbers are increased. The decentralized distribution of the amount of wear results from eccentric load in operated bearing. Eccentric load is represented by a position of the axis within the bearing. When external or internal load is applied to machine, the location of the eccentric load can changed.

Based on the results from Fig. 6, the test response prediction function can be derived as shown in Eq. (6), and the accelerated life (AL) curve of the function is shown in Fig. 7 (a). In addition, the test response prediction function for spalling and its AL curve are represented in Eq. (7) and Fig. 7 (b), respectively.

$$AL_{height}\left(AF\right) = 5.79 \cdot 10^{-3} AF \tag{6}$$

$$AL_{spalling}\left(AF\right) = 6.52 \cdot 10^{-7} AF^2 - 2.2 \cdot 10^{-4} AF \tag{7}$$

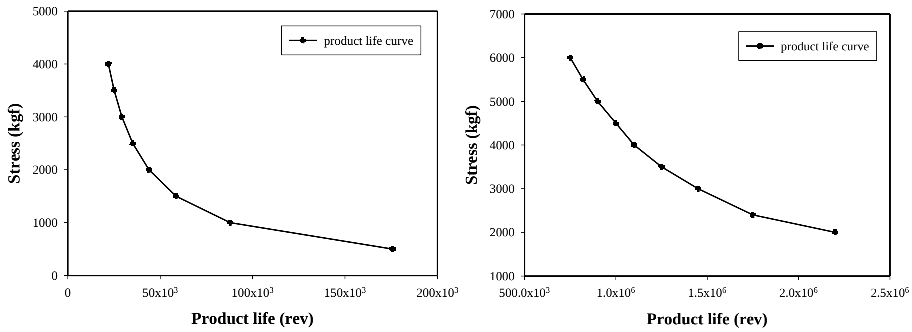


(a) (b)

Figure 7: Computation by AF and AL-curve of bearing for (a) wear depth and (b) spalling

Test response prediction function is the acceleration factor function. Larger acceleration factor leads to the larger stress factor. Therefore, the amount of wear is larger. The height decreases linearly as acceleration factor increases, but spalling increases exponentially. Tendency of increasing amount of spalling depending on the number of revolution is shown in Fig. 5.

The product life function of bearing was generated by using the derived test response prediction function, which is presented in Fig. 8 (a). 0.5mm is selected as the product failure standard, which is the difference of height between the spacer and roller. When wear of the roller is progressed, spacer and washer will be contacted, because roller size will be smaller. Fig. 8 (b) is the product life function for failure resulted from spalling. The product failure standard for spalling was determined as 6mm2, which is the standard used in most bearing companies.



(a) (b)

Figure 8: Product life curve of bearing for (a) wear depth of 0.5mm and (b) spalling of 6mm^2

Through the product life prediction function, the life prediction of bearing was able to be predicted, when stress factor was applied consistently. Also, the product life prediction function can be generated, when other parameters were chosen as the test responses besides wear depth or spalling.

4 DISCUSSIONS

When the actual use conditions are 500kgf and 500rpm, acceleration factor indicates 87.85, and the product life is 175,700 rev, as shown in Fig. 8 (a). These results are identical with actual wear test results, which confirm the validity of procedure of the accelerated life test coupled with numerical analysis. The derived product life function has shorter value than the actual bearing life, which may be due to the lack of lubrication system in the test setting. However, since the life was found to be consistent in the bearing environment of wear tester, analysis model predicting general bearing life can be derived if lubrication is considered in the accelerated life test.

Also, the process of the accelerated life test coupled with numerical analysis was verified by conducting the life test for ISO standard spalling. The product life curve for spalling is shown in Fig. 8 (b), in which the 4183.6kgf is the maximum load that guarantees 1,000,000 rev. Although there is a little different when the value is compared with the rating load of, 4330kgf, this may be due to the effect of the rpm. Therefore, it can be concluded that the values are almost same. It is said that the quantitative life prediction of the bearing is possible in various life standards. Moreover, many types of tests can be implemented and more factors can be considered by using analysis.

5 CONCLUSIONS

This study generated the life function of the thrust roller bearing by using the accelerated life test coupled with numerical analysis. The product life function was used in accordance with the established procedure, and then the life prediction of the bearing was validated when using the product in actual conditions. This indicates that the reliable design is possible and guarantees the product life at the design stage without actually conducting acceleration life test. If criterion for the failure is selected and the operating mechanism is analyzed in FEA, the quantitative life can be predicted. Then, the reliable design of the bearing may be possible and maximize the efficiency of the bearing in use.

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