Abstract: Rolling contact machine elements like bearing, gear wheel and railway rail have a problem of delamination failure such as flaking, pitting and shelling. It is known that this failure is closely related to shear-mode (mode II and mode III) as well as opening-mode (mode I) fatigue crack growth. In general, the shear-mode fatigue crack growth and its threshold behavior can be significantly influenced by the interaction of opposing crack faces. Therefore, understanding of the mechanism of friction and surface damage of crack faces is essential and a novel testing method that can estimate these properties is required. In this study, the influences of the cyclic reciprocating sliding contact with microscale relative motion on the frictional behavior and the surface damage of a bearing steel were studied under dry condition. The material investigated was a heat-treated high carbon-chromium bearing steel (JIS SUJ2). As a new friction and wear testing method, a cyclic ring-on-ring test was performed by making use of a hydraulic-controlled combined axial and torsional fatigue testing machine. The coefficient of kinetic friction was ranged from 0.4 to 1.0 and its average value was about 0.75.

Keywords: Shear-mode fatigue crack growth, Bearing steel, Ring-on-ring test, Coefficient of kinetic friction, Damage of contact surface

1. Introduction
Delamination failure is one of the most important engineering issues for rolling contact machine elements such as bearing, gear wheel and railway rail. For instance, to maintain the quality of high-integrity bearings, the statistical method and empirical rule based on the experiments with a large number of real products are employed for each redesign as affairs stand. However, this design procedure is time-consuming and costly, and even worse it has no applicability to massive products such as a bearing used for a wind generator. Consequently, an innovative change of design procedure is demanded all over the world. This demand is not only for bearing but also for other machine elements production. In specific, a new design method using fracture mechanics is required to achieve a rational design based on mechanics. On the other hand, it is known that the delamination failure is highly related to shear-mode (mode II and mode III) as well as opening-mode (mode I) fatigue crack growth [1-4]. Generally, the mutual effect of opposing crack faces (i.e., crack face interference) can have a significant influence on the shear-mode fatigue crack propagation and the threshold behavior. In the literature, the shear-mode threshold stress intensity factor ranges, \( \Delta K_{th} \), were reported, but there is the discrepancy in these values due to the different treatment of crack face interference [3-7]. Therefore, it is essential to understand the mechanism of friction and wear on crack faces. However, it is difficult to conduct a quantitative research for friction and wear on real crack faces in material. For this reason, a fundamental study with a relatively simple experimental setup is needed. Moreover, it is reasonable to carry out the tests with two surfaces to mimic the crack faces that undergo the cyclic reciprocating sliding contact. In our previous study [8], the ring-on-ring test method, in which two end faces of cylinders were bilaterally contacted and relatively cyclically slid by using a servo-hydraulic combined axial and torsional high cycle fatigue testing machine, was developed. This procedure has some merits such as the non-existence of boundary edge of contact surfaces and the flexibility of settings for contact pressure, tangential force, relative displacement and cyclic frequency during the test. In addition, it is straightforward to define the coefficient of friction that represents frictional property between contact surfaces, and one can easily determine the coefficient as functions of contact pressure, number of cycles and relative displacement. In the previous study [8], the cyclic reciprocating relative slip contact tests for heat-treated Cr-Mo steel (JIS SCM435) were conducted with the micro-meter level of relative displacement. In this study, the coefficients of kinetic friction of bearing steel were measured under comparatively high pressure condition because a very large pressure above 1 GPa is frequently imposed on the actual crack surface in bearings. Furthermore, the contact surfaces after the test were observed by using an optical microscope to inspect the relation between the surface roughness and the value of coefficient.

2. Experimental Method
The material investigated was a JIS SUJ2 (high C-Cr bearing steel), which was heat treated at 840 °C for 30 minutes, oil-hardened and then tempered at 170 °C. Table 1 shows the chemical composition in mass%. The Vickers hardness, \( H_V \), measured with a load of 9.8 N was 753. Figure 1 shows the shape and dimensions of the specimen. The end surfaces of hollow cylinders were finished by polishing with emery papers and then buffing with an alumina paste.
Moreover, it is reasonable to carry out the tests with two study with a relatively simple experimental setup is needed. For this reason, a fundamental conduct a quantitative research for friction and wear on different treatment of crack face interference [3-7].

However, there is the discrepancy in these values due to the behavior can be significantly influenced by the interaction of opposing crack faces. Therefore, understanding of the failure is highly related to shear-mode (mode II and mode III) as well as opening-mode (mode I) fatigue crack growth.

1. Introduction

Keywords

Investigation of Friction and Surface Damage of Bearing Steel in Cyclic Reciprocating Sliding Contact.

Shear-mode fatigue crack growth, Bearing steel, Ring-on-ring test, Coefficient of kinetic friction, Damage of mechanical properties of materials.

2. Experimental Method

The material investigated was a heat-treated high carbon-chromium bearing steel (JIS SUJ2). As a new friction and wear bearing used for a wind generator. Consequently, an engineering issues for rolling contact machine elements such as bearing, gear wheel and railway rail. For instance, the situation got better by only changing the relative position between the specimens (cf. Figs. 4 (a) and (b)). Furthermore, the uniform contact was achieved appropriately (cf. Fig.4 (c)). Accordingly, the contact surfaces were already worn by rubbing before the actual test. Finally, the tests were conducted after removing the debris from the contact surface.

Table 1 Chemical composition of SUJ2 in mass%

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
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<td>1.01</td>
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<td>0.34</td>
<td>0.017</td>
<td>0.007</td>
<td>0.10</td>
</tr>
<tr>
<td>Ni Cr Mo O 2 Ti</td>
<td>0.05</td>
<td>1.41</td>
<td>0.03</td>
<td>5 ppm</td>
<td>20 ppm</td>
</tr>
</tbody>
</table>

Fig. 1 Shape and dimensions of specimen

Fig. 2 Configuration of specimens and devices for measurement

Fig. 3 Shape of jig for a target of laser light

An MTS servo-hydraulic combined axial and torsional fatigue testing machine was used to conduct the ring-on-ring test, as shown by Fig. 2. This machine was designed to carry out the high cycle fatigue test in which axial force or displacement and torsional torque or angle were flexibly superimposed. The capacities are 100 kN for axial load and 1000 Nm for twisting moment. The operating frequency, $f$, can be applied up to 60 Hz.

In this experiment, the end faces of hollow cylinders shown in Fig. 1 were attached to each other and the static compressive axial force was applied. While maintaining this state, the sinusoidal displacement with constant angular amplitude, $\theta$, was applied by rotating the specimen at the driving side under the control of angular displacement, as illustrated in Fig. 2. The reciprocating relative sliding motion was generated on the contact surfaces. The test was conducted at room temperature under dry condition.

In this tests, the nominal contact pressure, $p$, was defined as

$$ p = \frac{W}{A} \tag{1} $$

where $W$ is the static compressive force measured by a load cell equipped in the testing machine, and $A$ is the nominal contact area for which a value of 44.0 mm$^2$ was used for the calculation. The tangential force, $F$, was defined as

$$ F = \frac{T}{r} \tag{2} $$

where $T$ is the twisting moment measured by the load cell, and $r$ is the mean radius of hollow cylinder. Its nominal value of 7.0 mm was used. The relative displacement between the contact surfaces, $S$, was defined as

$$ S = S_d - S_f \tag{3} $$

In this equation, $S_d$ and $S_f$ are the displacements of the driving side specimen and the fixed-end side specimen, respectively. These displacements were measured by a laser displacement meter (KEYENCE: LK-H020). A mirrored thin plate made from cermet tip was used as a target of laser light (cf. Fig. 2), and the target was attached to the jig made by a 3D-printer, as shown by Fig. 3. The material of jig was light ABS resin, so its inertia was negligibly small. The jig was mounted on the specimen surface with a distance of about 2 mm from the edge of hollow cylinder. 4-point support was used to fix the jig to the specimen (cf. Figs. 2 and 3).

The uniform contact on the contact surface is necessary during the test, but it was not so at the initial contact. Therefore, to attain the condition of uniform contact before starting the test, the contact condition was checked and adjusted by using a pressure-sensitive paper. Then, the contact surfaces were rubbed to each other under $p = 25$ MPa, $\theta = 10$ deg, $f = 1$ Hz and the number of reciprocating cycles, $N$, $\approx 1000$ cycles. Thereafter, uniform contact was checked by a pressure-sensitive paper again.

Figure 4 shows the papers after checking the contact states. The
3. Results and Discussion

3.1 Measurement of coefficient of kinetic friction

Figure 5 (a) shows the change of the tangential force, \( F \), and the relative displacement, \( S \), as a function of time, \( t \), which were measured under \( p = 100 \text{ MPa}, f = 1 \text{ Hz}, \theta = 1 \text{ deg} \) and \( N \approx 100 \) cycles after the start of the test. The variation of \( S \) was approximately sinusoidal curve, but that of \( F \) was similar to rectangular waveform.

Figure 5 (b) shows the relationship between \( F \) and \( S \) in the horizontal lines surrounded by the dotted frames in Fig. 5 (a). This relationship between \( F \) and \( S \) exhibited approximately a parallelogram hysteresis loop. The horizontal lines indicate the regions of entire slip happen all over the contact surfaces. An expected relationship between \( F \) and \( S \) for hollow tubular specimen was assumed a full adhesion is shown as a straight line in Fig. 5 (b). The vertical linear portion of experimentally-obtained relationship coincides with the calculated line. In this region, therefore, no virtual slippage is considered to take place. However, the initial point of the entire slip was not well-defined, suggesting the gradual start of slip on the contact surface. In this study, the coefficient of kinetic friction for the entire slip was defined as

\[
\mu_k = \frac{F_{\text{tan}}}{W}
\]  

where \( F_{\text{tan}} \) is the mean value of tangential force during the entire slip.

Figure 6 shows the relationships between \( \mu_k \) and \( N \) that were observed under \( p = 100 \text{ MPa}, f = 1 \text{ Hz} \) and \( \theta = 1 \text{ deg} \). They were measured at \( N = 10, 100, 1000 \) and 10000 cycles, respectively. As shown by Fig. 6, the coefficient under this condition is almost constant and its value is about 0.8.
3.2 Effects of test conditions
In this study, the effects of the test conditions on the coefficient of friction were investigated. In particular, the tests were conducted under the respective test conditions in which only one of parameters of the test was changed from the basic setup. The basic setup was \( p = 100 \) MPa, \( f = 1 \) Hz and \( \theta = 1 \) deg. These parameters were changed as \( p = 10 \) or \( 100 \) MPa, \( f = 0.1 \) or \( 1 \) Hz and \( \theta = 1 \) or \( 5 \) deg. Figure 7 shows the test results as a function of \( N \). As shown by Fig. 7, the coefficients, \( \mu_k \), under \( p = 100 \) MPa are approximately same level and fall within a narrow band ranging from 0.6 to 0.9 (the average value of \( \mu_k \approx 0.75 \)), though the test frequency or sliding speed is appeared to have a little influence on the value of \( \mu_k \). Furthermore, the sliding distance may exert almost no influence on \( \mu_k \). On the other hand, it is appeared that \( \mu_k \) under \( p = 10 \) MPa have larger variation than under \( p = 100 \) MPa. In the following section, this variation is briefly discussed.

3.3 Observation of contact surfaces
It is likely that the surface damage caused by prior rubbing under \( p = 25 \) MPa affects the actual test results under \( p = 10 \) MPa. For systematic investigation of the effect of this damage, however, further development of measuring techniques is necessary. In this paper, in order to seek the reason for the large scatter of the test results under \( p = 10 \) MPa, the contact surfaces were observed by using an optical microscope. Figures 8, 9 and 10 show the worn surfaces tested under \( p = 10 \) MPa, \( f = 1 \) Hz and \( \theta = 1 \) deg. The mean values of the coefficient were about 0.95 for the surface shown by Fig. 8 and 0.5 for the surfaces shown by Figs. 9 and 10. Note that the surface roughness shown in Figs. 9 and 10 are apparently different from each other.

By comparing Fig. 8 with Fig. 9, the roughness of the surface exhibited by Fig. 8 is relatively higher. In general, the coefficient of friction becomes larger with increase of the surface roughness. At present, it is not clear that the difference of roughness caused the discrepancy of the coefficient in Fig. 7. Furthermore, the contact surface shown in Fig. 10 has the roughest surface but its coefficient value is the lowest. The surface roughness of the above worn surfaces was almost unchanged after removing debris on the surfaces by acetone with absorbent cotton probably because of strong adhesion. Therefore, it seems that under the condition of \( p = 10 \) MPa, the roughness does not have an influence on the kinetic coefficient.

In addition, as shown by Fig. 7, \( \mu_k \) under \( p = 10 \) MPa has a distinct and relatively large variation (i.e., \( 0.4 < \mu_k < 1.0 \)). It is suspected that this result was caused by the lack of test samples. Note that the number of samples for each experimental condition is insufficient to statistically estimate the value of the coefficient for bearing steel under cyclic reciprocating sliding with dry condition. It is expected that the intermediate value of \( \mu_k \) (i.e., \( \mu_k \approx 0.7 \)) could be measured in the future experiments.
4. Conclusions
The cyclic reciprocating sliding contact experiment for JIS SUJ2 (high carbon-chromium bearing steel) was conducted to investigate the characteristics of friction and wear and the effects of the number of reciprocating cycles, test frequency, relative displacement and static load. The obtained results are summarized as follows:

1. The relationship between friction force, $F$, and relative displacement, $S$, exhibited nearly parallelogram hysteresis loop.
2. The slip on the surface started gradually.
3. The coefficient of kinetic friction was approximately constant independently of the number of reciprocating cycles, $N$.
4. The test frequency, $f$, may have a little influence on the coefficient of kinetic friction.
5. The relative displacement, $S$, may have almost no influence on the coefficient of kinetic friction.
6. Under the condition with $p = 10 \text{ MPa}$, the coefficient of kinetic friction had a relatively large variation ranging from 0.4 to 1.0.
7. Under the condition with $p = 100 \text{ MPa}$, the coefficient of kinetic friction was about 0.75.

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References