Effect of initial contact surface condition on the friction and wear properties of bearing steel in cyclic reciprocating sliding contact

Y. Tanaka¹, M. Endo²,³, and S. Moriyama²,³

¹Graduate School of Engineering, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka 814-0180, Japan
²Department of Mechanical Engineering, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka 814-0180, Japan
³Institute of Materials Science and Technology, Fukuoka University, 8-19-1 Nanakuma, Jonan-ku, Fukuoka 814-0180, Japan

E-mail: endo@fukuoka-u.ac.jp

Abstract. Delamination failure is one of the most important engineering problems. This failure can frequently be detrimental to rolling contact machine elements such as bearings, gear wheels, etc. This phenomenon, called rolling contact fatigue, has a close relationship not only with opening-mode but also with shear-mode fatigue crack growth. The crack face interference is known to significantly affect the shear-mode fatigue crack propagation and its threshold behavior. Quantitative investigation on friction and wear at fatigue crack faces in the material is essentially impossible. Previously, thus, a novel ring-on-ring test by making use of fatigue testing machine was proposed to simulate a cyclic reciprocating sliding contact of crack surfaces. However, this test procedure had some problems. For instance, in order to achieve the uniform contact at the start of test, the rubbing of specimens must be conducted in advance. By this treatment, the specimen surfaces were already damaged before the test. In this study, an improvement of experimental method was made to perform the test using the damage-free specimens. The friction and wear properties for heat-treated high carbon-chromium bearing steel were investigated with this new method and the results were compared to the results obtained by using the initially damaged specimens.

1. Introduction

Delamination failure such as flaking, pitting, and shelling is caused by rolling contact fatigue. This failure often causes fatal problem for the reliability of various rolling contact machine elements like bearings, gear wheels, railway rails, etc. It is known that rolling contact fatigue is intimately related to shear-mode (mode II and mode III) as well as opening-mode (mode I) fatigue crack growth [1-4]. Generally, shear-mode fatigue crack growth and its threshold condition are significantly influenced by the interaction of opposing crack faces (i.e., crack face interference). In order to establish the reasonable design method based on fracture mechanics for rolling contact machine elements, a systematic research for the friction and wear at the shear-mode fatigue crack faces is strongly required. However, it is difficult to conduct this research because the real crack faces inside the material cannot be observed by using the conventional tribological testing methods. The amount of relative displacement between the surfaces of a shear-mode fatigue crack can be in the sub-millimeter order at
the central part and in the sub-micron order near the crack tip. The frictional properties of minimal slip distance in the micro- and nano-Newton range have extensively been investigated using an atomic force microscopy [5-7]. However, for the shear-mode fatigue cracks in the actual engineering elements such as bearings, gears, rails, etc., the knowledge about cyclic reciprocating sliding contact of surfaces with a contact area of square millimetres level under an apparent contact stress of MPa to GPa level is essential. In recent years, the material surface damage due to fretting is studied based on the finite element analysis [8-11], and this approach would surely provide useful information, but the experimental study on cyclic reciprocating sliding contact for a variety of materials under a wide range of experimental conditions is also essential to understand the mechanism of this phenomenon. In our previous study [12, 13], a new ring-on-ring testing procedure by making use of fatigue testing machine was developed. In this procedure, two end-surfaces of hollow cylinders are mutually contacted and relatively cyclically twisted. Under this condition, the cyclic reciprocating sliding contact of crack faces can be simulated. Then, using this testing method, the friction and wear properties of a high carbon-chromium bearing steel (JIS SUJ2) were investigated [13]. However, this method had the same problems. The uniform contact of specimens is indispensable at the start of this test. If the initial contact does not satisfy this condition, non-uniform contact is caused due to misalignment of specimens. In order to attain the uniform contact at the start of test, in the previous test procedure [12, 13], rubbing of the specimens was conducted before the actual test. This means that the contact surfaces had substantially been worn and damaged before the start of test. The alignment of specimens needs to accurately be adjusted without rubbing process so as to obtain the uniform contact condition and the damage-free specimens. In this study, a renovation of the testing method was conducted by developing an alignment fixture. This fixture can execute the centering and the angular adjusting of a specimen. Moreover, the friction and wear of bearing steel in cyclic reciprocating sliding contact was investigated again by using this improved method. In this paper, the effect of initial contact surface condition was newly discussed by comparing the present results without rubbing and the previous results with rubbing [13].

2. Experimental method

The material used in the test was a high carbon-chromium bearing steel (JIS SUJ2), which was held 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, HV, 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 an emery paper and buffing with an alumina paste. An MTS servo-hydraulic combined axial and torsional fatigue testing machine was used to conduct the ring-on-ring test, as shown by Figure 2. This machine is designed to carry out the high cycle fatigue test in which axial force or displacement and twisting moment or angle are 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 study, the end-faces of hollow cylinders shown in Figure 1 were attached mutually and the static compressive force was applied. The specimen was compressed, then the sinusoidal displacement of constant angular amplitude, \( \theta \), was applied by rotating the specimen at the driving side under the control of angular displacement, as illustrated in Figure 2. The cyclic reciprocating relative sliding was thus generated on the contact surfaces. The tests were performed at room temperature under dry condition.

A uniform contact condition at the contact surface is important during the test as mentioned previously. In order to obtain the uniform contact condition, the alignment fixture specialized for this novel ring-on-ring test procedure was developed, by which a flexible control of both centering and angular adjusting of a specimen became possible (cf. Figure 2). The capacities of this fixture are -60 kN for static compressive force and 300 Nm for twisting moment. Figure 3(a) shows the initial contact condition for which the pressure distribution on the contact surface was measured by a pressure-sensitive paper. As shown by this figure, the initial pressure distribution was not uniform. Then, better contact condition was sought by rotating the relative position of specimens by trial and error. The contact situation became better than Figure 3(a) but usually sufficient uniform contact was not attained,
as shown in Figure 3(b). Then, by adjusting the alignment of specimens using the alignment fixture shown in Figure 2, a satisfactory uniform contact was finally achieved, as shown in Figure 3(c). Accordingly, the sliding contact tests could be started with the damage-free specimens.

Table 1. Chemical composition of SUJ2 in mass%.

|   | C   | Si  | Mn  | P   | S   | Cu  | Ni  | Cr  | Mo  | O2   | Ti  |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|-----|
|   | 1.01| 0.25| 0.34| 0.017| 0.007| 0.10| 0.05| 1.41| 0.03| 5 ppm| 20 ppm |

**Figure 1.** Shape and dimension of the specimen.

**Figure 2.** Configuration of specimens and alignment fixture.
In this study, the nominal contact pressure, \( p \), was defined as:

\[
p = \frac{W}{A}
\]  

(1)

where \( W \) is the static compressive force, 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:

\[
F = \frac{T}{r}
\]  

(2)

where \( T \) is the twisting moment measured by the strain gauges attached on a rod of the alignment fixture (cf. Figure 2), and \( r \) is the mean radius of hollow cylinder. A nominal value of 7.0 mm was used for \( r \) (cf. Figure 1). The relative displacement at the contact surfaces, \( S \), was defined as:

\[
S = S_D - S_F
\]  

(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, and the target was attached to the jig made by a 3D-printer, as shown by Figure 4. The material of jig was light ABS resin, so that its inertia was negligibly small. The jig was mounted on each specimen at a distance of 1 mm from the edge of hollow cylinder. A 4-point support was used to fix the jig to the specimen (cf. Figures 4 and 5).

**Figure 3.** Contact conditions of the same surfaces; (a) the first contact condition, (b) the improved contact condition after rotation of the driving side specimen, and (c) the uniform contact condition after adjustment with the alignment fixture.

**Figure 4.** Shape of a jig with a target of laser light.
3. Results and discussion

3.1. Measurement of coefficient of kinetic friction

Figure 6(a) shows the time variation of the tangential force, $F$, and the relative displacement, $S$, which were measured under $p = 100$ MPa, $f = 1$ Hz and $\theta = 1$ deg, and at $N \approx 1000$ cycles after the start of the test. The variation of $F$ and $S$ was approximately of a rectangular waveform.

Figure 6(b) shows the relationship between $F$ and $S$ in the dashed frame of Figure 6(a). This relationship between $F$ and $S$ exhibited almost a rectangular hysteresis loop. The horizontal lines surrounded by the dotted frames in Figure 6(b) indicate the regions where an entire slip happened all over the contact surfaces. An expected slope of the relationship between $F$ and $S$ for a hollow cylindrical specimen calculated on the assumption of full adhesion, i.e., a simple thin-wall pipe, is also shown in Figure 6(b). The slope of vertical change of the hysteresis loop was almost identical to that of calculated line. In this study, the coefficient of kinetic friction for the entire slip was defined as

$$\mu_k = \frac{F_{km}}{W}$$  \hspace{1cm} (4)

where $F_{km}$ is the mean value of tangential force during the entire slip. With this equation, $\mu_k \approx 0.8$ was obtained.

Figure 7 shows the relationships between $\mu_k$ and $N$ that were observed under $p = 100$ MPa, $f = 1$ Hz and $\theta = 1$ deg. The values of $\mu_k$ were measured at $N = 10$, 100, 1000 and 10000 cycles, respectively. As shown by Figure 7, the value of $\mu_k$ under this condition converges to about 0.8 with increase of $N$.  

![Figure 5. Configuration of specimens and measurement jigs.](image)
3.2. Effect of initial contact surface condition

In the previous study, the effect of static compressive force on the coefficient of kinetic friction was investigated for the same material of SUJ2. Figure 8(a) shows the previous results [13]. As shown by this figure, $\mu_k$ under $p = 100$ MPa was almost constant and its value was about 0.8. On the other hand, $\mu_k$ under $p = 10$ MPa showed a larger scatter ranging from 0.4 to 1.0. The cause of this large scatter has been an open question.

Figure 9 shows the present results obtained using the damage-free specimens under the test conditions identical to the above previous test. All results show the convergence of $\mu_k$ to about 0.8 with increase of $N$, independently of the contact pressure, $p$. Compared to Figure 8, the test performed using the damage-free specimens provided a reasonable result with a small scatter. By comparing these results, it is expected that the coefficient of kinetic friction is affected by the initial contact surface condition, such as the roughness and plastic flow of the surface, etc. of base metal.
In what follows, the effects of the plastic flow and surface roughness are discussed. Figure 10 shows the cross-sectional surface observed after the test using the specimens damaged by rubbing. The rubbing was performed by the 1000 cycle reciprocating sliding of a specimen under the conditions of $p = 25$ MPa, $f = 1$ Hz and $\theta = 10$ deg. Thereafter, the test was started and continued to 10000 cycles under the conditions of $p = 100$ MPa, $f = 1$ Hz and $\theta = 1$ deg. As shown in Figure 10, the plastic flow was not observed at the contact surface at all. It is supposed that the large plastic flow did not happen by the initial rubbing. Therefore, the scatter of data seen in Figure 8 may have no relation with the plastic flow of initial contact surface.

Figure 11 shows the relationship between $\mu_k$ and $N$ for $p = 10$ MPa, $f = 1$ Hz, and $\theta = 1$ deg, which was obtained in the tests using specimens with rough surfaces. The contact surfaces were polished in the sliding direction using an emery paper with a grit size of ANSI #180. The values of $\mu_k$ converged to about 0.8. The scatter of data in the range of $N = 10^3 \sim 10^4$ cycles is a little larger than the data in Figure 9 but much smaller than the data in Figure 8. Accordingly, it is concluded that initial surface roughness has no significant effect on the value of coefficient of kinetic friction. Very recently, Pereira et al. [14] studied the effect of roughness on fretting wear by the finite element analysis. They showed that the surface asperities interaction had influence on the wear scars only for the initial thousands cycles, e.g. 1800 cycles. This result is consistent with the present result shown by Figures 9 and 11.

![Figure 8. Results obtained in the previous study [13].](image)

![Figure 9. Results obtained in this study.](image)

![Figure 10. Cross-section of contact surface after the test with damaged specimens.](image)
4. Conclusions

The previously proposed method of ring-on-ring test by making use of fatigue testing machine was renovated in this study. This renovated method made it possible to perform a cyclic reciprocating sliding contact test with the damage-free specimens. The coefficient of kinetic friction of JIS SUJ2 (high carbon-chromium bearing steel) was investigated by this improved method. Moreover, by comparing the results to the previous results using initially-damaged specimens, the effects of initial contact surface condition were newly discussed. The obtained results are summarized as follows:

- The renovated ring-on-ring test does not need the rubbing of specimens before the test. Therefore, the tests can be started using the damage-free specimens.
- The relationship between the tangential force (i.e., frictional force), $F$, and the relative displacement, $S$, exhibits approximately a rectangular hysteresis loop.
- The value of coefficient of kinetic friction converges to about 0.8 with increase of the number of cycles.
- Static compressive force has no influence on the coefficient of kinetic friction.
- Plastic flow does not happen by rubbing under $p = 25$ MPa, and therefore it is not responsible for the scatter of data.
- Surface roughness at the start of test has no significant influence on the coefficient of kinetic friction.

**Figure 11.** Relationship between $\mu_k$ and $N$ for $p = 10$ MPa, $f = 1$ Hz and $\theta = 1$ deg, which was obtained in the tests using the specimens polished with an emery paper (ANSI #180).
Acknowledgement
This work was in part supported by the JSPS KAKENHI (Grant Number: JP16K06057) and the NSK Foundation for the Advancement of Mechatronics. Their supports are gratefully appreciated.

References
[1] S. Beretta, M. Boniardi, M. Carboni and H. Desimone 2005 Mode II Fatigue Failures at Rail Butt-welds Engineering Failure Analysis 12 p 157-165.
[2] M. W. J. Lewis and B. Tomkins 2012 A Fracture Mechanics Interpretation of Rolling Bearing Fatigue J. Engineering Tribology 226 p 389-405.
[3] A. Otsuka, Y. Fujii and K. Maeda 2004 A New Testing Method to Obtain Mode II Fatigue Crack Growth Characteristics of Hard Materials Fatigue & Fracture of Engineering Materials & Structures 27 p 203-212.
[4] H. Matsunaga, N. Shomura, S. Muramoto and M. Endo 2010 Shear Mode Threshold for a Small Fatigue Crack in a Bearing Steel Fatigue & Fracture of Engineering Materials & Structures 34 p 72-82.
[5] E.-S. Yoon, S. H. Yang, H.-G. Han and H. Kong 2003 An Experimental Study on the Adhesion at a Nano-contact Wear 254 p 974-980.
[6] S. Achanta, D. Drees and J.-P Celis 2005 Friction and Nanowear of Hard Coatings in Reciprocating Sliding at Milli-Newton Loads Wear 259 p 719-729.
[7] V. L. Popov 2010 Contact Mechanics and Friction: Physical Principles and Applications Springer Heidelberg
[8] D. Kumar, R. Biswas, L. H. Poh and M. A. Wahab 2017 Fretting fatigue stress analysis in heterogeneous material using direct numerical simulations in solid mechanics Tribology International 109 p 124-132.
[9] T. Yue and M. A. Wahab 2017 Finite element analysis of fretting wear under variable coefficient of friction and different contact regimes Tribology International 107 p 274-282.
[10] N. A. Bhatti and M. A. Wahab 2017 Finite element analysis of fretting fatigue under out of phase loading conditions Tribology International 109 p 552-562.
[11] T. Yue and M. A. Wahab 2014 Finite element analysis of stress singularity in partial slip and gross sliding regimes in fretting wear Wear 321 p 53-63.
[12] M. Endo, T. Saito, S. Moriyama, S. Okazaki and H. Matsunaga 2015 Friction and Wear Properties of Heat-treated Cr-Mo Steel during Reciprocating Sliding Contact with Small Relative Motion International Journal of Fracture Fatigue and Wear 3 p 215-220.
[13] Y. Tanaka, M. Endo and S. Moriyama 2016 Frictional Behavior and Surface Damage in Cyclic Reciprocating Contact of Bearing Steel M&M2016 MATERIALS AND MECHANICS CONFERENCE PROCEEDINGS p 857-859.
[14] K. Pereira, T. Yue and M. A. Wahab 2017 Multiscale analysis of the effect of roughness on fretting wear Tribology International in press (http://dx.doi.org/10.1016/j.triboint.2017.02.024)