EFFECT OF FRICTION MODIFY AND EP ADDITIVE ON FRICTION CAUSED BY SOLID PARTICLES IN OIL

M. TOMIMOTO
Nihon PALL ltd., 46 Kasuminosato, Inashiki, Ibaraki, JAPAN; e-mail: makoto_tomimoto@pall.com

K. MIZUHARA
Tokyo Denki University, 2-2 Nishiki, Kanda, Chiyoda, Tokyo, JAPAN; e-mail: mizuhara@cck.dendai.ac.jp

T. YAMAMOTO
Tokyo University of Agriculture and Technology, 2-24-16 Naka, Koganei, Tokyo, JAPAN; e-mail: tyama@cc.tuat.ac.jp

SUMMARY

In lubricated sliding surfaces, effects of friction modify and EP additive on friction caused by particles were investigated with a simple sliding tester. To analyze the effects of these additives, oleic acids were used as a standard friction modify and TCP (tricresyl phosphate) as a standard EP (extreme pressure) additive. In addition, as solid particles, alumina particles and two types of steel beads were used. In the results, it was found that the effects of these additives on friction depended on the differences of the particle material, hardness and sliding velocity.

Keywords: additive, friction, oleic acid, particle, TCP

1 INTRODUCTION

In various lubricated environments, many kinds of contaminants are present. In sliding parts and rolling parts, solid contaminants of foreign abrasives and wear particles in oil can be observed. Even in new oil, such contaminants are already included. It was confirmed that these particles caused increasing wear and friction [1 - 18].

Regarding such solid contaminants, many papers on wear caused by particles in oil have been reported [6 - 9, 14 - 17]. However, papers on friction caused by particles in oil are very few [1 - 5, 11 - 14]. The first report on friction caused by particles in oil was for journal bearings in an automobile engine [1]. According to the report, it has been already confirmed that particles in oil cause friction in a journal bearing. However, the mechanisms of the friction have never been investigated enough prior to our report [11 - 13].

The first reason is that wear effect caused by particles on friction could not be neglected. The second reason is that it could not find effects of particle size on friction. Because most papers regarding friction had used not simple formed particles, such as spherical particles, but indefinite formed [1, 3, 4]. Therefore, effects of particle size on friction could not be discussed simply. Moreover, since it did not utilize a particle counter, it is impossible to discuss the effects of a number of particles on friction. For example, MoS2 particles that were broken easily while particles were interfering on the sliding surfaces; number and the size could not be discussed [4, 5]. The other reason why the mechanisms of friction caused by particles could not be investigated enough is that chemical effects on friction by oil had not been considered excepting our previous reports [11 - 14].

By conducting sliding tests while considering the points mentioned above, authors could explain the mechanisms of friction caused by particles (Fp) by means of the conventional four functions i.e. coefficient of friction, a number of an actual interference particles (Na), load supported by particles (Wp) and particle interference time (t) between sliding surfaces. In there, to be proportional relationship between friction caused by particles and interference particles (Na), dead time (t0) phenomenon was applied. This phenomenon is shown in one case by lifting up sliding surfaces by interference particles and in another case passing some particles without interfering [11 - 13]. This phenomenon has already been confirmed visually by means of a simple sliding tester [13]. The theory that we reported could be concluded under chemically stable test conditions i.e. using chemically stable oil polyether type [11 - 13]. However, in general, oil used in sliding parts equipped in actual machines include some additives such as friction modifies and EP additives. Therefore, in considering sliding friction caused by particles in actual machines, it is significant to investigate effects of additives on friction.

In this paper, effects of oleic acid as a friction modify and TCP as an EP additive on the friction are investigated.

2 EXPERIMENTAL

A friction tester shown in Figure 1 was used in these experiments. As shown in Figure 1, a disk is rotated and load is applied to the disk bottom via a lower specimen. Figure 2 outlines sliding parts. An inversed cylinder on disk shown in Figure 2 was used. Sample oil was fed onto the surface of the disk from the bottom. This structure was adopted because it was possible to observe the sliding surface through a transparent glass disk from the top. This structure was also effective in preventing
dust in the air from being deposited on sliding surface as although the tester was exposed to the air.

Table 1 shows characteristics of test specimens, oil and additives used in the experiments. Figures 3(a)-(c) show SEM images of alumina particles and steel beads. The purpose that two types of particle material (i.e. alumina, steel beads,) and two types of particle hardness with a same material (i.e. steel) were used is to investigate difference of additive effects in the material difference or the hardness difference on friction. Particle hardness was measured by means of a micro displacement meter calibrated with 2200 HV alumina particles shown in Figure 3(a). As shown in Figures 3(a) - (c), all particles used in this experiments are spherical in shape. Figure 4 shows relationships between a number of particles and particle-diameter of Figures 3(a) - (c) with an automatic particle counter. The counter was used to control cleanliness on all parts that are affected by friction. Table 2 shows test conditions. One volume percentage of each additive as shown in Table 2 was added into oil. The value of concentration used was in the same region of the actual concentration level used in general machines. In addition, it does not affect to the viscosity of base oil. This experiment was repeated 5 times under the test conditions shown in Table 2. The last test run using oil suspended particles (96 mg/l) was followed by the test run using oil with no particles (0 mg/l). The outcome of the next test run using particle-free oil was found almost to be the same as that of the first test run in which particle-free oil was used: > 0.1 m/s (hm; 0.6 microns) *1.

### Upper specimen (Disk)

<table>
<thead>
<tr>
<th>Material</th>
<th>2.5&quot; clear glass disk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>740HV</td>
</tr>
<tr>
<td>Young’s modulus, GPa</td>
<td>85.1</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.2</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>0.01</td>
</tr>
</tbody>
</table>

### Lower specimen (Cylinder)

<table>
<thead>
<tr>
<th>Material</th>
<th>SUJ2, diameter (D): 12 mm Width (b): 6 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>550 HV</td>
</tr>
<tr>
<td>Young’s modulus, GPa</td>
<td>207.8</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>0.05</td>
</tr>
</tbody>
</table>

### Base oil *2

<table>
<thead>
<tr>
<th>Content</th>
<th>Polyalkyleneglycol (no additive)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity, mm²/s</td>
<td>32.8 @313K (40 °C), 6.7 @373K (100 °C)</td>
</tr>
</tbody>
</table>

### Test conditions

<table>
<thead>
<tr>
<th>Test duration, sec</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load, N</td>
<td>0.8</td>
</tr>
<tr>
<td>Sliding velocity (v), m/s</td>
<td>0 to 1.2</td>
</tr>
<tr>
<td>Minimum film thickness [19], micron (see equation (2))</td>
<td>0 to 8</td>
</tr>
<tr>
<td>Oil temperature, K (degree C)</td>
<td>300 (27)</td>
</tr>
<tr>
<td>Method of oil supply</td>
<td>Fed into a sliding area</td>
</tr>
<tr>
<td>Oil flow rate, ml/min</td>
<td>20</td>
</tr>
<tr>
<td>Suspended particles in oil, mg/l</td>
<td>0, 96</td>
</tr>
<tr>
<td>Additives (1vol. % in oil)</td>
<td>Oleic acid, TCP</td>
</tr>
</tbody>
</table>

This finding proves that effects of wear on friction are negligible in any of the test runs. After the fifth test run using particle concentration of 96 mg/l, average surface roughness of the lower specimen was found about 0.05 - 0.1 microns. This means test condition to yield friction of 0.1 m/s (hm; 0.6 microns) or more corresponds to oil film parameter (Λ value) over 6.

*1 After the test run using lubricant oil with particle concentration of 96 mg/l, the specimen was cleaned with solvent in an ultrasonic cleaner for five minutes, and then it was used for the last test run with particle concentration of 0 mg/l.

*2 oil and additives used in this experiments were filtered with a 0.1 micron filter.
In general, region with \( \Lambda \) value of three or more is referred to as fluid lubrication regime [20]. It is speculated that the test specimens were evaluated in the fluid lubrication regime in this study. Figure 5 shows the examples of the test results of the first run (0 mg/l), the fifth run using 96 mg/l, the following test run using particle-free oil (0 mg/l). As shown in Figure 5, it can be confirmed that the value of friction in the last run (0 mg/l) can return to the value of the first test run 0 mg/l after the 96 mg/l test run under the sliding velocity over 0.1 m/s (hm; 0.6 microns) regardless of wear caused by particles. Therefore in the region over 0.1 m/s in Figure 5, the difference between the value of friction in 0 mg/l (F0) and 96 mg/l (F) under the same speed means friction caused by particles (Fp; see equation (1).)

(a) Alumina particles: 2200 HV

(b) Steel beads: 160 HV

(c) Steel beads: 870 HV

Figure 3: Solids particles

3 RESULTS AND DISCUSSION

Figures 6 – 11 show experimental results regarding relationships between friction force (F) and sliding velocity (v) in average. As shown in Figures 6 – 11, since friction in oil suspended particles (96 mg/l) is higher than friction in particle-free oil (0 mg/l), it is concluded that particles increase friction as well as the results in the previous reports [1 - 5, 10 - 14]. In addition, the difference of friction (Fp) between particle-free oil and oil suspended particles decrease with increase of the sliding velocity. According to our previous studies [11 - 14], it can be explained that this phenomenon is caused by decreasing functions which are an actual number of interference particles (Na), load supported by a particle (Wp) and particle-interference time between sliding surfaces (t) (see equation (1).)

Figure 4: Relationship between a number of solids particles and the diameter.

Figure 5: Wear effects on friction (F) and friction caused by particles (Fp) with 870 HV steel beads.

Figure 6: Effects of oleic acid: relationship between friction (F) and sliding velocity (v) with alumina particles.
Figure 7: Effects of TCP: relationship between friction (F) and sliding velocity (v) with alumina particles.

Figure 8: Effects of oleic acid: relationship between friction (F) and sliding velocity (v) with 160 HV.

Figure 9: Effects of TCP: relationship between friction (F) and sliding velocity (v) with 160 HV.

Figure 10: Effects of oleic acid: relationship between friction (F) and sliding velocity (v) with 870 HV.

Figure 11: Effects of TCP: relationship between friction (F) and sliding velocity (v) with 870 HV.

Oleic acid and TCP can slightly decrease friction caused by alumina particles under the sliding velocity over 0.3 m/s as shown in Figure 6 and Figure 7. The surfaces of the lower specimens after the tests with alumina particles, show roughened surfaces as shown in Figure 12 for example. Possibly, the cause of the favorable effects of these additives is oleic acid or TCP adsorb the worn surface i.e. nascent surface, and it might decrease friction. However, phosphorus on the surface after the test with TCP could not be confirmed with XES. It seemed that the phosphate surface could be too thin a layer to analyze with XES because under such mild test conditions as shown in Table 2. In steel beads, oleic acid does not affect friction caused by the particles regardless the hardness as shown in Figure 8 and Figure 10. However, TCP decreases only the friction caused by the softer steel beads i.e. 160 HV as shown in Figure 9, but the harder steel beads i.e. 870 HV (Figure 11). The favorable effect of TCP in 160 HV is shown under the lower sliding velocity. This tendency is different from the results of alumina particles. Moreover, the worn surface of the lower specimen after the test with 160 HV steel beads, cannot be confirmed regardless of the existence of TCP shown in Figure 13. Therefore, it is difficult to explain the cause of the favorable effect without worn surface such as mentioned above. Because it is difficult to think that TCP can react the sliding surface without wear i.e. nascent surface under such mild test conditions. However, for particles, there is a big difference between 160 HV and 870 HV steel beads. That is softer particles (160 HV) are flattened by interfering surfaces as show in Figure 14. 870 HV particles could not be confirmed as the phenomenon. Therefore, nascent surface could be on the surface of the particles.

Next, need to discuss the sliding dependence of the favorable effect on TCP in Figure 9. In our previous reports [11 - 14], load supported by a particle generated between an interference particle and the sliding surfaces, is decreased with increase of the sliding velocity. Because the sliding velocity increases the oil film thickness, and load support by an interference particle (Wp) between the sliding surfaces is decreased with increase of the oil film thickness. The contact pressure between an interfering particle and the sliding
surface could arrive at several-handled GPa in a calculation under the test conditions (Table 2). The load and the pressure is decreased with increase of the sliding velocity in calculation.

Figure 12: SEM image of the sliding surface (lower specimen) after alumina particle test with no additive.

Figure 13: SEM image of the sliding surface (lower specimen) after 870 HV steel bead test with no additive.

Figure 14: SEM image of the sliding surface (lower specimen) after 160 HV steel bead test with no additive.

This means that the particles can be flatted more under the lower velocity. Therefore, it can be explained that the favorable effect on TCP can be caused more under the lower sliding velocity in terms of the contact pressure than the higher velocity. However, the doubt why oleic acid could not affect the friction as shown in Figure 8 remained. In the case of alumina particles, oleic acid shows the favorable effect on friction as shown in Figure 6 as well as TCP. It seems that the effect of oleic acid on friction can be explained with the contact pressure and the reaction velocity. However, there is little information regarding this. Investigation of these causes will be further subjects.

4 CONCLUSIONS

In the results obtained in these experiments, it can be concluded as follows:

(1) Oleic acid and TCP decrease friction caused by alumina particles under the higher sliding velocity where thicker oil film thickness is. Under the lower sliding velocity, these additives do not affect the friction.

(2) TCP decreases friction caused by the softer particles (160 HV steel beads), which can be squashed by interfering the sliding surfaces under the lower sliding velocity. The favorable effect of TCP on the friction is not shown under the higher sliding velocity.

(3) The favorable effect of TCP on the friction is not shown with the harder particles (870 HV steel beads) regardless the sliding velocity.

(4) Oleic acid does not affect friction caused by steel beads at all regardless the hardness.

(5) Since (1), (2) and (4), the effect of oleic acid on the friction, which depends on particle materials and the sliding velocity.

(6) Since (1), (2) and (3), the effect of TCP on the friction, which depends on particle materials and hardness, the sliding velocity.

5 NOMENCLATURE

\( b \): cylinder width, m
\( D \): cylinder diameter, m
\( d \): spherical particle diameter, m
\( \Delta d \): average of interference height defined as \((d - h_m)\), m
\( F \): friction force \((=F_0+F_p)\), N
\( F_0 \): friction force generated by oil viscosity, N
\( F_p \): friction force generated by particles \((=F-F_0)\), N
\( h_m \): minimum oil film thickness, m
\( l \): interference length, m
\( Q \): quantity of fluid passing through the clearance per second, \(m^3/s\)
\( R \): cylinder radius, m
\( r \): particle radius, m
\( N \): number of particles larger than particle diameter per ml \(/ml\)
$N_i$: number of interfering particles, /s
$N_a$: actual number of interfering particle, /s
$t$: interfering time of particle between sliding surfaces, s
$t_a$: dead time (= actual interfering time of particle between sliding surfaces), s
$v$: sliding velocity of disk, m/s
$W$: load, N
$W_o$: load supported by fluid (oil) of $(h_m+\Delta d)$ film thickness, N
$W_p$: load supported by a particle, N
$\mu$: friction coefficient in interference particle theory, dimensionless
$\eta$: dynamic viscosity, Pa·s

6 EQUATIONS

\[ F_p = F - F_0 \] (1)

\[ h_m = 2.44748 \frac{\eta b R v}{W} \] (2)

\[ Q = \frac{1}{2} b \cdot h_m \cdot v \] (3)

\[ N_i = Q \cdot (N \times 10^6) \] (4)

\[ l = 2(R + r) \sin \left( \cos^{-1} \left( \frac{h_m + R - r}{R + r} \right) \right) \] (5)

\[ t = \frac{l}{v/2} = \frac{2l}{v} \] (6)

\[ N_a = N_i / (1 + t_a N_i) \] (7)

\[ \Delta d = \frac{1}{f(d)} \int_{h_m}^{d} (d - f'(d)) dd - h_m \] (8)

\[ W_o = 2.44748 \frac{\eta b R v}{h_m + \Delta d} \] (9)

\[ W_p = W - W_o \] (10)

\[ F_p = \mu \cdot N_a \cdot W_p \cdot t_a \] (11)

7 REFERENCES