Correlation between Tribofilm Formation and Friction Coefficient in Continuously Variable Transmission at the Initial Stage of Rubbing

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Abstract

To improve the transmission efficiency of a continuously variable transmission (CVT) system, it is effective to form a tribofilm with higher friction coefficient. Therefore, understanding of the correlation between the tribofilm formation and friction coefficient in a CVT fluid has been a great deal. In this study, the tribofilm formation on a bearing steel ball surface under the simulated additive oil was investigated. We used ball–on–disk tribological test and optical microscopy imaging to observe the temporal changes in the tribofilm growth. Atomic force microscopy and energy-dispersive X-ray spectrometry analyses revealed that the tribofilm consisted of pad-like structures derived by tricresyl phosphate and calcium sulfonate additives. A binary imaging analysis showed that the total area of the pad-like structure was a key parameter determining the friction coefficient. The pads were repeatedly desorbed and reformed during the sliding test. These results improve the design of future CVT systems and lubricants.

Keywords

tribofilm, lubricant additives, continuously variable transmission, boundary lubrication

1 Introduction

Continuously variable transmission (CVT) is a type of automatic transmission (AT) that continuously changes the gear ratio using mechanism other than the gear. Compared with step AT using a stepwise transmission system for switching gears, the most common belt CVT enables a seamless variability between the highest and lowest speed ratios. Therefore, the belt CVT provides a more usable power transfer, better fuel efficiency, and smoother driving than those of the traditional automatic transmission. The belt CVT consists of input/output pulleys and laminated steel ring with steel elements. The laminated steel ring does not directly contact the pulley, but pushes the element against the pulley. The element transmits power by the metal–metal frictional force [1]. Therefore, in order to achieve a high transmission efficiency, high friction coefficient and wear resistance between the sliding surfaces of the pulley and element are required.

The commercial CVT fluid contains chemical additives such as friction modifiers, antiwear agents, detergents, dispersants, viscosity modifiers and more. These additives directly absorb on the steel surfaces or cause tribochemical reactions under boundary lubrication conditions, forming a boundary film referred to as tribofilm on the sliding surface of the metal [2–4]. In order to provide a higher CVT transmission efficiency, it is effective to form a tribofilm with higher friction coefficient [5–7]. Tricresyl phosphate (TCP) is an effective antiwear additive generally contained in commercial CVT fluids. It induces multilayer films on a steel surface by tribochemical reactions and reduce wear [8–13]. It is also worth noting that calcium sulfonate detergents generate a rigid tribofilm on a steel surface [13–15]. These tribofilms effectively reduce the abrasive and adhesive wears, but increase the friction coefficients at sliding surfaces. Therefore to clarify the mechanism of tribofilm formation by these additives on steel surface and reveal the interaction with friction coefficients leads to a higher improvement of the belt CVT.

The mechanisms governing the tribofilm growth have well studied by Zinc dialkyldithiophosphate (ZDDP). It is a commonly used extreme-pressure additive in engine oils known to generate a tribofilm with a pad-like structure and exhibits superior antiwear properties [8, 9, 16–19]. Spikes et al. have reported the kinetics of ZDDP tribofilm growth by using a minitraction machine-spacer-layer imaging setup (MTM2-SLIM, PCS Instruments) [16, 19]. They proposed the thick ZDDP tribofilm enhance the mixed lubrication friction and cause the
Table 1: Properties of the test oils used for friction tests

<table>
<thead>
<tr>
<th></th>
<th>Base oil</th>
<th>Additive oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity (mm²/s) 100°C</td>
<td>4.217</td>
<td>4.700</td>
</tr>
<tr>
<td>Viscosity (mm²/s) 40°C</td>
<td>19.35</td>
<td>22.36</td>
</tr>
<tr>
<td>Density (g/cm³) 15°C</td>
<td>0.836</td>
<td>0.842</td>
</tr>
<tr>
<td>Viscosity index</td>
<td>124</td>
<td>132</td>
</tr>
</tbody>
</table>

Table 2: Properties of additive agents contained in the test oil used for friction tests

<table>
<thead>
<tr>
<th>Additive</th>
<th>Conc. (mass%)</th>
<th>Chemical agent</th>
<th>Condensed formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction modifier</td>
<td>0.3</td>
<td>Oleylamine</td>
<td>CH₃(CH₂)₇CH=CH(CH₂)₇CH₂NH₂</td>
</tr>
<tr>
<td>Antiwear agent</td>
<td>0.06</td>
<td>Tricresyl phosphate</td>
<td>(CH₃C₆H₄O)₃PO</td>
</tr>
<tr>
<td>Detergent</td>
<td>0.06</td>
<td>Calcium sulfonate</td>
<td>[CH₃(CH₂)₃C₆H₄SO₃]₂Ca</td>
</tr>
<tr>
<td>Dispersant</td>
<td>5</td>
<td>Succinimide</td>
<td>C₆H₅NO₂</td>
</tr>
</tbody>
</table>

2.1 Lubricant oils

In order to exclude the effect of indeterminate additives contained in the commercial CVT fluid, two test oils were prepared. One of them is a base oil of isoparaffin without additives. The other is an additive oil with the following additives formulated in the base oil: 0.3 mass% of oleylamine (as a friction modifier), 0.06 mass% of TCP (as an antiwear agent), 0.06 mass% of calcium sulfonate (as a detergent), and 5 mass% of succinimide (as a dispersant). These are general additives contained in the CVT fluid. The properties of the test oils, and details of additives are shown in Tables 1 and 2, respectively.

2.2 Tribological test

Friction tests were carried out with a tribometer (Rhesca, FPR-2100) using a ball–on–disk configuration. Bearing steel balls (JIS SUJ2, AISI 52100) and carbon tool steel disks (JIS SK85, AISI W1-8) were prepared as test specimens. The diameters of the test balls were 3/8 inch. The diameters and thicknesses of the test disks were 14 and 3 mm, respectively. The surface roughness of balls and disks were less than Rₐ = 25 nm. Test specimens were washed with hexane and acetone, and kept in the base oil prior to the experiment. Friction test condition was referred to average values in the standard test method for metal on metal friction characteristics of belt CVT fluids (JASO M358) [21]. The test conditions are shown in Table 3. The normal load and the maximum Hertz contact pressure were 1 N and 481 MPa, respectively. Several tests were conducted on the same disk specimen, therefore the rotational speed was controlled to equalize the linear sliding velocity as 30 mm/s in each test. All of the tests were carried out in the lubricant oils of 60°C. The chemical compositions of steels used for specimens are shown in Table 4.

In this study, two different friction tests were carried out. “Test-1” was a normal sliding test, in which the friction coefficients were continuously recorded until a certain number of rotation or distance. In the “Test-2”, at each rotation of the friction test, we observed the temporal change in the test ball sliding surface by an optical microscope (VK-9500, Keyence).

Table 3: Conditions of ball-on-disk friction tests

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Ball</th>
<th>Bearing steel ball (JIS SUJ2, AISI 52100)</th>
<th>Disk</th>
<th>Carbon tool steel disk (JIS SK85, AISI W1-8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal load</td>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact pressure</td>
<td></td>
<td>Max. 481</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sliding velocity</td>
<td></td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil temperature</td>
<td></td>
<td>60</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Chemical compositions of steels used for friction test specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Chemical composition (mass%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball (JIS SUJ2)</td>
<td>C 95.5 - 1.10, Si 0.15 - 0.35, Mn ≤ 0.05, P ≤ 0.025, S ≤ 0.025, Cr 1.30 - 1.60, Ni ≤ 0.25, Mo ≤ 0.08, Cu ≤ 0.25</td>
</tr>
<tr>
<td>Disk (JIS SK85)</td>
<td>C 80.0 - 0.90, Si 0.10 - 0.35, Mn 0.10 - 0.50, P ≤ 0.030, S ≤ 0.30, Cr ≤ 0.30, Ni ≤ 0.25, Mo ≤ 0.25, Cu ≤ 0.25</td>
</tr>
</tbody>
</table>
For this test, a test ball holder that achieves the repeated interchange between the tribometer and optical microscope was fabricated. This will enable to observe the temporal change of the same sliding surface on the same sample, and the influence due to differences of the true contact area in each test specimen can be minimized. During the Test-2, the specimens were not allowed to wash out the test oil in order to keep the same condition.

2.3 Surface analysis
After the friction tests, the test specimens were washed by hexane in order to remove residual oil and wear debris. The morphology of the tribofilm was measured by AFM (XE-70, Park Systems). All of the AFM measurements were carried out by using the contact scanning mode. A Si-based cantilever (PPP-CONTSCR, Nano World) with a small force constant of 0.2 N/m was employed. The radius of curvature of each cantilever was approximately 10 nm.

The chemical species in the tribofilms were analyzed by energy-dispersive X-ray (EDX) spectrometry (JED-2300, JEOL). An electron beam voltage of 10 kV was used for the EDX mapping analysis. This low voltage was reasonably surface sensitive enabling imaging of the organic species.

3 Results and discussions
3.1 Tribological properties
The results of Test-1, the ball–on–disk friction tests carried out in the base oil and additive oil are shown in Fig. 1 as a function of the sliding distance. In both tests, the friction coefficients were continuously recorded. In the base oil test, the friction coefficient rapidly decreased in the beginning of the sliding and then gradually decreased with the increase of the sliding distance. The final coefficient was 0.112. In contrast, the friction coefficient in the additive oil test increased after the initial decrease reaching a final value of 0.133, which is 18% higher than that in the base oil test. Figure 2 shows optical microscopy images of the test specimens. Some sliding scratches and wear debris were observed on the test ball sliding surfaces in the base oil test. On the other hand, in the additive oil test, strongly adsorbed blackish spots were generated on the sliding area of the test ball. In compare with test balls, slight wear tracks were shown on the disk surface. The bearing steel ball was harder than the disk material, therefore initial wear process occurred in both test oils. Since fewer wears have occurred on the specimen by the additive oil test, we assumed that blackish spots on the ball surface belong to the tribofilm derived by the additives, which prevent abrasions and lead to higher friction coefficients. Therefore, we focused on the tribofilm formation on the sliding surfaces of the test balls.

3.2 Correlation between the tribofilm formation and friction coefficient
In order to investigate the correlation between the tribofilm formation and friction coefficient, temporal changes in the sliding surfaces were observed by Test-2. The friction test was paused to demount/remount the ball holder in each rotation. The trend of the friction coefficient was the same as that in Fig. 1. Three selected optical microscopy images are presented in Figs. 3 (a)–(c), showing the sliding surface of the test ball at the 4th, 8th, and 14th rotation, respectively. The sliding distances were (a) 0.08, (b) 0.18, and (c) 0.31 m. As shown in Fig. 3, numerous blackish spots were formed on the sliding surface for the quite short sliding distance of 0.08 m. This suggests that the tribofilm can be generated even under a short sliding distance, if the local shear stress and thermal energy are enough to cause chemical reactions. Furthermore, as shown in Fig. 3, the number of blackish spots increased with the sliding distance. Although the existence of another boundary films which difficulty observed by the optical microscopy is also considered, we focused on the obvious trend of blackish spots as the tribofilm.

In order to evaluate the variations in the tribofilm, the total area of blackish spots was determined as follows. First, threshold binary images were generated from original optical microscopy images. Second, marks of sliding scratches and wear debris were carefully deleted from the binary images, and the total area of the spots was summed, which was regarded
as the total area of the tribofilm. Figure 4 shows the friction coefficient plotted against the area of tribofilm estimated from three different tests carried out on the same disk specimen. The maximum sliding distance in these tests was 1.10 m. As shown in Fig. 4, the results demonstrate the proportionality between the friction coefficient and total area of the tribofilm in the additive oil test. Figure 5 shows the relationship between the area of the tribofilm and sliding distance, which estimated from the same tests shown in Fig. 4. The region with the tribofilm did not continue to expand. The expansion of the tribofilm formation is limited to 0.44 m; subsequently, a gradual decrease is observed reaching a constant value of approximately $5 \times 10^3 \mu m^2$. In order to explain this tendency, we compared differences between two tribofilms in adjacent sliding distances. Figures 6 (a) and (b) show the binary images of the tribofilms at sliding distances of 0.44 and 0.88 m, respectively. When subtract the image of 0.44 m from that of 0.88 m, remained regions are where the tribofilm newly generated. Figure 6 (c) shows increased tribofilm regions in red color. Contrarily, when subtract the image of 0.88 m from that of 0.44 m, remained regions are where the tribofilm removed. Figure 6 (d) shows decreased tribofilm regions in blue color. These results suggest that the tribofilm was repeatedly desorbed and reformed during the sliding in the additive oil, maintaining a constant tribofilm area after the limiting value.

### 3.3 Morphology of the tribofilm

The tribofilm morphologies were measured by AFM. Figure 7 shows topography images of the tribofilms formed on the test balls by the additive oil. The scan size of each AFM topography image is $20 \times 20 \mu m^2$. These samples were obtained in the Test-1, where the friction coefficients were continuously recorded until the preset distances. As shown in Fig. 7, the tribofilm derived by the additive oil has a pad-like structure. The sizes of the pads in the plane direction increased with the sliding distance. Moreover, the maximum height of the pads,
regarded as the thickness of the tribofilm, also shown slight
increase with the sliding distance. Figure 8 illustrates the
relationships between the friction coefficient, maximum height
of the pad-like structure ($H_{\text{max}}$), and sliding distance.
$H_{\text{max}}$ was calculated from multiple AFM topography measurements at
each sliding distance. As shown in Fig. 8, the friction coefficient
increased by 32% between the sliding distances of 0.08 and
0.44 m, while $H_{\text{max}}$ was almost constant (approximately 60 nm).
In contrast, as shown in Fig. 5, the total area of the pad-like
structure remarkably increased until the sliding distance of
approximately 0.4 m. Therefore, as compared with the height
of tribofilm, the total area of the tribofilm was considered the main
factor responsible for the increase in the friction coefficient in
the initial stage of sliding. It is worth noting that no pads higher
than approximately 90 nm were observed in other samples.

It should be noted that the pad-like structure might be
buried in the sliding surface because of wear or another
boundary films [18]. Whereas it is insufficient to evaluate the
tribofilm thickness only by AFM measurement, it is worth
noting that the maximum height of pad-like structure is similar
to past reports. Yamazaki et al. reported the tribofilm formation
by a friction test in a commercial CVT fluid [5]. They carried out
an 8000 m sliding test using the actual V-shaped steel elements
and pulley of the CVT. The thickness of the final tribofilm
formed on the sliding surface of the element was only 80 nm,
similar to our result of 1.09 m sliding test. Such a thickness
saturation of tribofilms has also been reported for other
additives. The film derived by ZDDP has a pad-like structure,
which tends to grow to a thickness of 50–150 nm and then
becomes stable [19, 22]. Zhang and Spikes proposed that the
ZDDP tribofilm formation is driven by shear stresses at asperity
conjunctions [19]. Therefore, the film does not further grow
when the shear stress becomes too low to drive the process. This
may occur if the pads start to yield in a plastic manner, thus
increasing their contact areas [23]. Although further studies are
needed to reveal the mechanism of tribofilm formation in the
CVT, we believe that the critical film thickness is related with
the desorption mechanism of the pads discussed in Section 3.2.

### 3.4 Chemical analysis of the tribofilm

Figure 9 shows EDX spectroscopy chemical analysis
results of the tribofilm. The vertical axis represents the atomic
concentrations of P, Ca, and S contained in the additives,
while the horizontal axis represents the sliding distance. The
scanning size was $10 \times 10 \mu m^2$, in which defined to contain pad-
like tribofilm area of 50%. The results at the sliding distance of
0 m, without tribofilm, were obtained from the ball specimen
immersed in 60°C additive oil for 1 hour. Since the penetration
depth of EDX analysis is approximately 1 μm, results contain
the composition of ball specimen. As shown in Fig. 9, both P
and Ca concentrations increase in the initial stage of sliding.
Only the concentration of P exhibits a remarkable increase
after the sliding distance of 0.4 m. On the other hand, the
concentration of S was low in the whole sliding distance range.
The trend of the sliding distances and the atomic concentrations
had reproducibility. In this study, P originates from TCP as
the antwear agent, while Ca and S originate from calcium
sulfonate as the detergent (Table 2). According to a previous
study, phosphate esters react significantly more rapidly with
iron oxides than with iron [24]. The TCP tribofilm formation
that the continuous growth or expansion of the tribofilm leads to the desorption of the pad-like structures. The results suggested that adsorptions of phosphate esters immediately occur on the oxide surface of the steel specimen. On the other hand, Ca cations produced from calcium sulfonate also have a high affinity to absorb on hydroxyl groups of the oxidized surface. This suggests competition between the phosphate esters and Ca cations in the initial stage of sliding. According to previous studies, the tribofilm of TCP has a flat multilayer structure acting as a lubricious film [25]. In contrast, calcium sulfonate generates a tribofilm with a pad-like structure leading to a high friction coefficient. The sizes of the pads depended on the concentration or total base number of the detergents [13, 15]. Therefore, the origin of the pad-like structure observed in this study could be attributed to the calcium sulfonate detergents on the steel surface.

4 Conclusion

Ball-on-disk tribological tests and optical microscopy imaging have been combined to reveal the tribofilm formation and factors determining the friction coefficient in a CVT fluid. Although our method is ex-situ observation, it has the advantage that can trace the temporal change of the same surface on the same sample, and the influence due to differences of each test specimen can be minimized. Thus, we successfully observed the temporal changes in the sliding surfaces of a bearing steel ball. We focused on the initial stage of sliding, where the friction coefficient significantly changed. In the additive oil test, the tribofilm had the pad-like structure derived by tricresyl phosphate (TCP) and calcium sulfonate additives, and indicated higher friction coefficient than that in the base oil test. A binary imaging analysis showed that the friction coefficient was proportional to the total area of the pad-like structure. However, both the thickness growth and the total area expansion indicated saturation values.

The formation mechanism was explained based on results from this and previous studies. In the initial stage of sliding, the film formation began atasperity conjunctions, where the contact pressure and shear stress had the highest values. Under these conditions, we assumed that the region with adsorbed Ca cations acted as a base layer of the tribofilm, and thus pad-like structures were formed. Subsequently, a new layer was formed upon the TCP growth on the pads. However, the tribofilm could not grow over 90 nm, which was attributed to the desorption of the pad-like structures. The results suggested that the continuous growth or expansion of the tribofilm leads to a higher friction coefficient in the CVT.

References