Frictional property of a 3D-capillary-structured surface fabricated by selective laser melting

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KEYWORD
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Anti-seizure property

ABSTRACT
In this study, a self-oil-circulating structure, termed a 3D-capillary structure, has been proposed to improve the frictional properties of sliding elements. The 3D capillary structure can collect excessive lubricant from a sliding surface and resupply to the interface by capillary action. Selective laser melting was utilized to fabricate the 3D capillary structure because of its complex 3D microstructure. The oil supplying function of the 3D capillary structure was confirmed by performing a reciprocating sliding test with digital camera observation. The frictional property was evaluated using four specimens with different surfaces: (1) non-textured surface, (2) conventional dimpled surface, (3) 3D-capillary-structured surface and (4) surface with 3D capillary structure and conventional dimpled structure. Experiment results showed that the 3D capillary structure exhibited excellent anti-seizure properties. It was also concluded that the specimen with a mixed 3D capillary structure and conventional dimple had the best anti-seizure and low friction properties.

1.0 INTRODUCTION
In sliding elements, seizure typically results in an increase in friction and temperature at the sliding interface due to oil starvation (Sulaiman et al., 2018; Wang et al., 1997). Therefore, preserving of oil in the sliding contact region is important to prevent the occurrence of seizure under severe operation conditions. Surface texturing, which is the process of realizing specific roughness and geometries on a surface to change tribological properties, is a well-known technique to preserve oil in the contact region (Yuan et al., 2011; Li et al., 2010; Nakano et al., 2009). The roles of surface texturing under boundary or mixed lubrication regimes have been
previously reported, and it mainly has two functions: maintaining the oil lubricant on the sliding surface (Etsion et al., 2004; Wos et al., 2017; Wakuda et al., 2003; Pettersson et al., 2007) and trapping of wear debris (Pettersson et al., 2003). However, preventing seizure effectively is difficult in case of conventional surface texturing since the quantity of oil that can be preserved in the surface geometries is limited (Kuroiwa et al., 2013; Wang et al., 2003; Kangmei et al., 2014). Therefore, more effective tribo-systems for preserving oil in the sliding surface are required.

In the last decades, surfaces with various tribological functions have been developed by controlling roughness and the process of realizing different surface geometries and by employing several coating methods. Recently, applying the complex 3D micro-structure by utilizing a selective laser melting (SLM) process has attracted much attention as a novel surface modification technology. SLM, also known as metal 3D printing, can directly fabricate 3D objects from 3D-CAD data (Brandl et al., 2012; Louvis et al., 2011; Childs et al., 2004; Abe et al., 2001). A SLM object is fabricated by layering metal powder and selective laser irradiation. Laser irradiation heats the powder material, which melts and forms a liquid pool when sufficient laser power is applied. Then, the molten pool cools down quickly and solidifies, and the coagulated material forms the object. After the cross-section of a layer is scanned, a new layer of powder is deposited. These processes are repeated until the SLM objects are completed. SLM can be employed to fabricate components with a complicated mechanical structure that are difficult to fabricate by conventional methods such as cutting and casting. By applying SLM to the tribological field, we have already proposed the inner-structure with lubricant supply paths connected to sliding surfaces and a syringe pump (Yonehara et al., 2018). This tribo-system could actively control the tribological properties by supplying lubricant additives to the sliding surface directly through lubricant supply paths. Therefore, using SLM, promising novel tribological surfaces with complex 3D micro-structures and various functions and can be realized.

In this study, we propose a novel tribo-system termed the “3D capillary structure”, inspired by the structure of wharf roach legs, as a novel means to supply oil to the sliding surface. The wharf roach, an organism found at the seashore, can transport water using micro structure in its legs with a capillary action (Ishii et al., 2013). Our proposed 3D-capillary-structured surface can collect excessive lubricant from a sliding surface and can resupply it to a sliding interface through small paths by capillary action similar to that in the wharf roach-water transport system. Further, the effectiveness of the 3D-capillary-structured surface fabricated by SLM was investigated.

2.0 CONCEPT AND EXPERIMENT DETAILS

2.1 Capillary action

Figure 1 shows a schematic of the capillary action, wherein the height of the liquid surface in a tube becomes higher owing to surface tension. The height of the liquid column \( h \) is given by equation (1).

\[
h = \frac{2\gamma \cos \theta}{\rho g r}
\]

Here, \( \gamma \) is the liquid surface tension, \( \theta \) is the contact angle, \( \rho \) is the density of the liquid, \( g \) is the gravitational acceleration, and \( r \) is the radius of the tube. To calculate the height of the liquid column \( h \), the surface tension \( \gamma \) of Poly-Alpha-Olefin 4 (PAO 4) and contact angle \( \theta \) of PAO 4 on the
test specimen made of AISI S17400 were measured by a contact angle analyzer (P300T, Surface Electro Optics, Korea).

Figure 1: Schematic of the capillary action.

In this study, to confirm the capillary action-driven height of PAO 4 in paths, a liquid column specimen that has paths with various depths and diameters was fabricated, as shown in Figure 2. It has supply paths with various depths – 5 mm, 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, and 50 mm – and diameters – 0.4 mm, 0.8 mm, 1.6 mm, and 2.0 mm – to the surface connected to an oil reservoir fully-filled with PAO 4, and it was used to evaluate the capillary action-driven height of PAO 4.

Figure 2: Schematic of the test specimen to evaluate the height of the liquid column.
2.2 Test specimen

The test specimen with the 3D capillary structure was fabricated by a SLM apparatus (ProX DMP 300, 3D Systems, USA). The material used for fabricating was an AISI S17400 powder with an average particle diameter of 20 μm. Table 1 shows the SLM processing parameters for fabricating the test specimen. Figure 3 shows the schematic diagram of the test specimen with the 3D capillary structure. The test specimen had small paths to supply the oil lubricant to the sliding surface and an oil reservoir to maintain the oil lubricant removed off the sliding surface; further the paths and the oil reservoir were connected under the sliding surface. The diameter of the paths was 0.4 mm and the depth of the paths was 6.9 mm, which were optimized based on the liquid column test. The pitch of the paths was 1.5 mm, and five paths were arranged on the surface.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power</td>
<td>150 W</td>
</tr>
<tr>
<td>Scan speed</td>
<td>1200 mm/s</td>
</tr>
<tr>
<td>Scan pitch</td>
<td>60 μm</td>
</tr>
<tr>
<td>Layer thickness</td>
<td>40 μm</td>
</tr>
<tr>
<td>Powder</td>
<td>AISI S17400</td>
</tr>
</tbody>
</table>

Figure 3: Schematic of the specimen with the 3D capillary structure.

As shown in Figure 4, four specimens with different surfaces were used: non-textured surface, conventional dimpled surface, 3D-capillary-structured surface, and mixed surface with 3D capillary structure and conventional dimples. The paths and the oil reservoir for the conventional dimpled specimen were not connected. Two types of conventional dimpled specimens with different path depths were fabricated. The paths depth of the conventional dimpled specimens 1 and 2 were 6.9 mm and 0.1 mm, respectively. The specimen with the mixed surface had three paths for the 3D capillary structure and two paths with the depth of 0.1 mm, which is same as the case of the conventional dimpled specimen 2.
Figure 4: Schematic of test specimens: (a) non-textured specimen, (b) conventional dimpled specimen 1, (c) conventional dimpled specimen 2, and (d) mixed-structure specimen.

2.3 Oil supplying function test

A sliding test was conducted to confirm whether the 3D capillary structure could effectively supply the oil lubricant. A Bowden-Leben-type cylinder-on-plate friction tester was used. The cylinder (φ 5 mm × 5 mm length) was made of AISI 52100. Table 2 shows the sliding test conditions. As 300 µL of PAO 4 was injected into the oil reservoir, the sliding test was initiated with a non-oil lubricant on the surface. The oil behavior on the sliding surface was monitored by using digital camera (D5300, Nikon, Japan).

Table 2: Sliding test conditions to confirm the oil supplying function of the 3D capillary structure.

<table>
<thead>
<tr>
<th>Load</th>
<th>20 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sliding speed</td>
<td>20 mm/s</td>
</tr>
<tr>
<td>Temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Stroke</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

2.4 Friction tests

Friction tests were conducted with the five different types of the specimens to evaluate their frictional and anti-seizure properties. A cylinder-on-plate sliding tester (SRV 4, Optimol, GE) was used. The cylinder (φ 6 mm × 8 mm length) was made of AISI 52100. The friction test conditions are given in Table 3. Figure 5 shows the schematic diagram of the friction test. The 300 µL of PAO 4 was injected into the oil reservoir and the 50 µL of PAO 4 was dropped on the surface. The load was increased from 5 N to 100 N by 5 N every 5 min. In these friction tests, a running-in period was defined as the period until the friction coefficient reached a stable value below 0.3. As the friction coefficient increased drastically above 0.4 after the running-in period, the friction test was stopped. The load when the friction test was stopped was defined as the seizure load.
Table 3: Friction test conditions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>5~100 N</td>
</tr>
<tr>
<td>Frequency</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Temperature</td>
<td>80 °C</td>
</tr>
<tr>
<td>Stroke</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

Figure 5: Schematic of sliding test.

3.0 RESULTS AND DISCUSSION

3.1 Evaluation of capillary action using the liquid column test specimen

First, we will discuss the details of capillary action for the combination of our proposed 3D capillary structure and PAO 4. The surface tension $\gamma$ of PAO 4 was measured as 26 mN/m. It was impossible to measure the contact angle $\theta$ of PAO 4 on the test specimen because of the high wettability. It was thus approximated as 0 degree. The density $\rho$ was 0.82 g/cm$^3$. From these parameters, the height of the liquid column $h$ with a 0.4 mm diameter path was calculated according to the following equation (2):

$$h = \frac{2\gamma \cos \theta}{\rho gr} = \frac{2 \times 26 \times 10^{-3} \times \cos 0}{0.82 \times 10^{-3} \times 9.8 \times 0.2 \times 10^{-3}} = 32 \times 10^{-3} \text{ m}$$

Table 4 shows the experimental results for the height of the liquid column. The circle in Table 4 denotes the supply of an oil lubricant to the surface whereas the "X" denotes the supply of a non-oil lubricant to the surface. The obtained results showed that the height of the liquid column for the 0.4 mm diameter path was higher than 30 mm and less than 35 mm. The height of the liquid column for the 0.8 mm diameter path was higher than 15 mm and less than 20 mm. PAO 4 was not supplied to the surface for the 1.2 mm and 1.6 mm diameter paths. According to experimental results, it was suggested that the height of the liquid column calculated by equation (1) was a reasonable estimation.
Table 4: Experimental results for the height of the liquid column.

<table>
<thead>
<tr>
<th>Diameter [mm]</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>○</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>1.2</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>1.6</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td></td>
</tr>
</tbody>
</table>

3.2 The oil supplying function

Figure 6 shows images of oil lubricant behavior on the sliding surface. Before the sliding test, a meniscus was not formed for PAO 4 on the surface. However, a meniscus was observed for PAO 4 between the cylinder and the surface as the sliding test started and the cylinder touched the path. The meniscus was maintained between the cylinder and the surface during the sliding experiment. Therefore, PAO 4 was supplied to the entire surface by a 3D capillary structure. The experimental results suggest that the 3D capillary structure could effectively supply the oil lubricant.

Figure 6: Oil lubricant behavior on the sliding surface.

3.3 Friction tests

Figure 7 shows the applied-load and the frictional behavior as a function of sliding time. The friction coefficient for the conventional dimpled specimen 2 was lower than that of the conventional dimpled specimen 1. It was considered that the friction coefficient decreased owing to the large load capacity because of the short dimple depth (Ma et al., 2011; Caramia et al., 2015). The friction coefficient of the non-textured specimen increased abruptly at 50 N and that of the conventional dimpled specimen 1 increased abruptly at 45 N. It increased abruptly at 75 N for conventional dimpled specimen 2. An increase in the friction coefficient to above 0.4 was not observed for the 3D-capillary-structured specimen and the mixed-structure specimen.
Figure 7: Variation in friction coefficient with increasing load for the non-textured specimen, 3D-capillary structured specimen, conventional dimpled specimen 1, conventional specimen 2, and mixed-structure specimen.

Figure 8 shows the average seizure load of the three tests. As seen in Figure 8, the 3D capillary structure was effective in improving the anti-seizure properties. According to the results displayed in Figure 7 and Figure 8, the mixed-structure specimen showed the lowest frictional properties and best anti-seizure properties of all the specimens. It was considered that these results were obtained because of a synergistic action between the oil supplying effect owing to the 3D capillary structure and the large load capacity of conventional dimple specimen 2. Our results suggest that the 3D capillary structure is a novel tribo-system that is more effective for friction reduction and improving anti-seizure properties than a conventional system. Further, it presents an effective way to actively control the tribological performance under boundary lubrication.
Figure 8: Average seizure load of the three friction tests for the non-textured specimen, 3D-capillary-structured specimen, conventional dimpled specimen 1, conventional dimpled specimen 2, mixed-structure specimen.

4.0 CONCLUSION

In this study, we proposed the 3D-capillary-structured surface to develop the more effective tribo-system than the surface texture. SLM was utilized to fabricate the 3D-capillary-structured surface. The 3D capillary structure exhibited effective oil lubricant supplying function by capillary action. The oil supplying effect of the 3D capillary structure improved the anti-seizure property. The mixed-structure specimen showed the lowest frictional and best anti-seizure properties of all the specimens because of a synergistic effect of the oil lubricant supplying effect and large load capacity. Our proposed 3D capillary structure is a novel tribo-system that is more effective for friction reduction and improving anti-seizure properties than a conventional system.

REFERENCES


