The Secondary Lubrication Effect under Fluid Lubrication

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Abstract. Surface texturing under fluid lubrication has been effectively used to improve the tribological performance. However research on the ‘secondary lubrication effect’ in the later stage of fluid lubrication is scarce. This study aimed to examine the friction reduction mechanism of the ‘secondary lubrication effect’ under fluid lubrication and to investigate factors that affect the effect. Lubrication models were developed under fluid lubrication. Friction force and hydrodynamic pressure of the lubricant were analyzed. Furthermore, the texture’s oil-storage and -release capacities which may affect the ‘secondary lubrication effect’ were studied respectively. The results showed that the ‘secondary lubrication effect’ reduced friction by generating hydrodynamic pressure. The friction force in the later stage was higher than that in the early stage of fluid lubrication. The decrease in friction caused by the ‘secondary lubrication effect’ decreases in proportion with the loss of the lubricant. The lubricant infiltration capacity will affect the ‘secondary lubrication effect’ by influencing the texture’s oil-storage capacity. Additionally, the release mechanism of the lubricant inside the texture was also obtained. Texture depth had a significant effect on the ‘secondary lubrication effect’ by affecting the texture’s oil-release capacity.

1 Introduction

Surface texturing has been effectively used to improve the tribological performance. The texture can effectively capture abrasive debris under dry friction [1]. The texture can store lubricant and add it to the surface of friction pair under mixed lubrication, which is called the ‘secondary lubrication effect’[2]. The hydrodynamic pressure lubrication effect which refers to a phenomenon wherein the relative movement of a friction pair causes the lubricant film on the contact surface to generate pressure and bear the external load, thereby reducing the friction under fluid lubrication [3].

Fluid lubrication means that lubricant is filled between the friction pair without contact and mixed lubrication means that there is a lubricant film between the friction pair but there is also a small amount of surface contact whose main friction reduction mechanism is the ‘secondary lubrication effect’ which means that the lubricant stored in textures can be added to the contact surface to avoid direct contact of the friction pair when there is insufficient lubricant on the contact surface in the Stribeck curve. In normal case, the typical film thickness under mixed lubrication is less than 1μm and that under fluid
lubrication is 1-100μm. It is worth noting that there is a state which refers to that lubricant on the contact surface is sufficient to ensure that there is no direct contact between the friction pair and some lubricant is stored in the texture that are discontinuous which is similar to mixed lubrication when the surface lubrication transitions from fluid lubrication to mixed lubrication. The state belongs to fluid lubrication but has some characteristics of mixed lubrication which means that lubricant in the texture can be added to the contact surface like the ‘secondary lubrication effect’. Therefore, fluid lubrication can be divided into early stage when lubricant is sufficient and continuous and later stage when lubricant is enough to ensure that there is no direct contact between the friction pair but it is not continuous. The texture has been proven to have a hydrodynamic lubrication effect in the early stage[4]-[6]. However there is little research on the later stage even though it is an important part of fluid lubrication. It must be noted that the objective to examine the 'secondary lubrication effect' in the later stage of fluid lubrication is to ensure that lubricant is added more effectively to the contact surface, to prolong the fluid lubrication process and reduce the average friction. However, an effective period of fluid lubrication cannot be ensured by investigating the fluid lubrication state only in the early stage; in this scenario, only the tribological performance in the early stage of the fluid lubrication state can be enhanced. Therefore, it is necessary to study the mechanism in the later stage which we call the ‘secondary lubrication effect’ under fluid lubrication.

The textures can store lubricant and release it to the contact surface, thereby improving the tribological performance [7]. Thus, it is of great significance to study the texture's oil-storage and -release capacities which refers to the ability of the texture to store and release lubricant. This study aimed to investigate the mechanism of the ‘secondary lubrication effect’ and to identify the factors influencing it, by studying the texture's oil-storage and release capacities respectively.

2 Methods

2.1 Geometric modelling

The coupled Euler-Lagrange (CEL) fluid-structure coupling algorithm was used which was implemented in ABAQUS developed by Dassault SIMULIA in study which actually means that disassembling a fluid-mechanics problem becomes a fluid and solid mechanics problems, set to the same coordinates, suitable fluid-solid coupling surface and the same solution step can complete the parameter transfer on the coupling surface[8]. The model shown in figure 1(a) consists of a cylinder, a textured stainless steel specimen, and the lubricant. The model was used to study the mechanism of the ‘secondary lubrication effect’. In order to demonstrate that the lubricant cannot seep into the texture under certain conditions, which will affect the texture's oil-storage capacity and thus affect the ‘secondary lubrication effect’ and to reduce the computing, the model shown in figure 1(b) was chosen which will not affect the results.

The model consists of a specimen and the lubricant. The dimensions, material properties are shown in table 1. The array and direction of the textures and the thickness direction of the lubricant were parallel to the x-, y-, and z-axis.

2.2 Boundary conditions

In figure 1(a), The lower surface of the specimen was fixed. The speed of cylinder was set to Vy=0, Vx=300 mm/s under an applied normal load of 0.5N. In figure 1(b), the lower
surface of the specimen was fixed. The temperatures of the simulation environments were constant at 20°C.

Figure 1. (a) CFD model for sliding tests involving a lubricant and (b) CFD model used to study the factors that influenced the ‘secondary lubrication effect’.

Table 1. Mesh sizes and material properties of the models shown in figure 1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Sample</th>
<th>Dimensions</th>
<th>Material properties</th>
<th>Reasons for material selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>figure1(a)</td>
<td>Cylinder (GCr15)</td>
<td>Radius: 4mm</td>
<td>Elasticity: 208GPa, Density: 7810 kg/m^3, Poisson ratio: 0.3</td>
<td>High strength</td>
</tr>
<tr>
<td>figure1(a)</td>
<td>Specimen (SUS420J2 stainless steel)</td>
<td>Length: 24mm Width: 24mm Thickness: 20mm</td>
<td>Elasticity: 214.6GPa, Density: 7672 kg/m^3, Poisson ratio: 0.289</td>
<td>Good wear resistance</td>
</tr>
<tr>
<td>figure1(a)</td>
<td>Lubricant (PAO40)</td>
<td>Length: 15mm Width: 10mm Thickness: 0.1mm</td>
<td>Viscosity: 42.5 cSt, Density: 0.8678 kg/l</td>
<td>Wide usage</td>
</tr>
<tr>
<td>figure1(b)</td>
<td>Specimen (SUS420J2 stainless steel)</td>
<td>Length: 4.4mm Width: 0.6mm Thickness: 0.5mm</td>
<td>Elasticity: 214.6GPa, Density: 7672 kg/m^3, Poisson ratio: 0.289</td>
<td>Good wear resistance</td>
</tr>
<tr>
<td>figure1(b)</td>
<td>Lubricant (PAO40)</td>
<td>Length: 4.4mm Width: 0.6mm Thickness: 0.05mm</td>
<td>Viscosity: 42.5 cSt, Density: 0.8678 kg/l</td>
<td>Wide usage</td>
</tr>
</tbody>
</table>

3 Results and discussion

3.1 Surface textures

In order to investigate the mechanism of the ‘secondary lubrication effect’, figure 2 shows plots of the temporal variation of the friction force under the early and later stages of fluid lubrication. The lubrication state can be characterized by the amount of lubricant in the initial state. The blue region represents the Euler area, which refers to the area where the lubricant can flow, and the red region represents the lubricant-filled area[9]. From the figure 2, it is worth noting that the friction force in the later stage was higher than that in
the early stage of fluid lubrication and the fluctuation of the friction force curve in the later stage is weaker than that in the early stage of fluid lubrication when the friction curves reach a steady state. The reasons are as follows: (1) The hydrodynamic pressure lubrication effect is weakened when the lubricant is insufficient, which increases the friction force. (2) The lubricant on the contact surface can easily flow into the texture under the action of the cylinder movement when the lubricant is insufficient, thereby reducing the mutual extrusion between the lubricant, which reduces the fluctuation of the friction force.

Figure 2. Schematic of the initial states considered: (a) The later stage of fluid lubrication, (b) The early stage of fluid lubrication and friction–time curves for different lubricated conditions, (c) The later stage of fluid lubrication and (d) The early stage of fluid lubrication.

The mechanism of the ‘secondary lubrication effect’ was further investigated by comparing the hydrodynamic pressure distribution diagrams of the lubricant for the early and later stages of fluid lubrication, as shown in figure 3. The texture can store lubricant and add it to the surface of the friction pair[10]. As it can be seen from figure 3(a), the hydrodynamic pressure is generated to improve the surface load capacity and reduce the surface friction. Therefore, the ‘secondary lubrication effect’ of fluid lubrication reduces friction also by generating hydrodynamic pressure, in addition to supplementing the lubricant to the contact surface. However, the hydrodynamic pressure in the later stage is smaller than that in the early stage of fluid lubrication whose reason is that there is no sufficient lubricant on the contact surface to generate a larger hydrodynamic pressure. Therefore we can infer that the decrease in friction caused by the ‘secondary lubrication effect’ decreases in proportion with the loss of the lubricant.

Figure 3. Hydrodynamic pressure distributions under different lubricated conditions: (a) The later stage of fluid lubrication and (b) The early stage of fluid lubrication.

3.2 The influencing factor of the texture’s oil-storage capacity

Pendurthi et al. used a CO2 laser engraving machine to obtain a superoleophobic textured surface [11]. Han et al. employed an ultrafast laser to fabricate a superoleophobic textured surface [12]. Therefore, the texture may repel oil and lubricant cannot seep into the texture.
Figure 4(a) shows the distribution of the lubricant at the beginning and end of the relaxation process which refers to the free flow of the lubricant on the specimen before the start of the friction experiment. The lubricant infiltration capacity in the texture during the relaxation process can be characterised by observing the change in the distribution of the lubricant. Figure 4(b) shows the effect of the texture width and the distance between textures on the lubricant infiltration capacity. Therefore lubricant cannot seep into some textures and the reason may be its surface tension and internal friction. The surface tension, namely, the tendency of the lubricant surface to shrink. Therefore, the ‘secondary lubrication effect’ is limited. If the lubricant cannot seep into the textures, it will not be achieved.

Figure 4. (a) Lubricant infiltration capacity for texture widths of 350 μm and the distance between the textures of 350 μm, (b) Lubricant infiltration capacity for texture widths of 350 μm and distance between the textures of 50 μm and (c) Lubricant infiltration capacity for texture widths of 50 μm and distance between the textures of 50 μm.

3.3 The release mechanism of the lubricant inside the texture

Figure 5 shows the lubricant distribution and the corresponding specimen stress diagram at different moments. The grid color characterizes the concentration of the lubricant, stress in the specimen, and hydrodynamic pressure. We set the initial moment as Moment A and t = 7.33e-05 as Moment B. At moment A, the cylinder is stationary, the stress in the specimen is zero, and the hydrodynamic pressure is zero. At moment B, the cylinder starts to move, and a stress is generated on the contact surface. The lubricants on the contact surface and inside the texture correspond to Regions A and B.

Figure 5. The lubricant distribution map for: (a) Moment A and (b) Moment B. The stress distribution diagram in specimens for: (c) Moment A and (d) Moment B. The hydrodynamic pressure distributions for: (e) Moment A and (f) Moment B.
3.4 The influencing factor of the texture's oil-release capacity

The width, depth and density of the texture may all have an influence on the ‘secondary lubrication effect’. However, we believe that the texture depth considerably influences the phenomenon. Due to space limitations, we focus on the influence of the texture depth. Figures 6(a) and (b) show the lubricant distribution of the specimens with different texture depths. Regions A and B correspond to the lubricants on the contact surface and inside the texture, respectively. It can be noted that Region B rebounds in figure 6(a) but not in figure 6(b). Figures 6(c) and (d) indicate that at a larger texture depth, the stress is more likely to be concentrated in a region, and the stress on the texture at the front end of the cylinder is smaller. A larger stress corresponds to a larger texture deformation, which facilitates the rebounding of the lubricant inside the texture. Therefore, a larger depth corresponds to a lower probability of rebounding of the lubricant inside the texture. As shown in figure 6(b), Region C represents the lubricant compressed into the texture by the cylinder. Since the amount of compressed lubricant is low, and it cannot fill the entire area, the color of this grid is blue. Figures 6(e) and (f) show the hydrodynamic pressure distribution diagrams of the lubricant with different texture depths. As shown in figure 6(e), a hydrodynamic pressure area is generated from the contact surface and across the texture, which indicates that Region A generates hydrodynamic pressure under the action of the cylinder movement and propels Region B to the contact surface. No hydrodynamic pressure is generated in the condition shown in figure 6(f), which indicates that no hydrodynamic pressure exists in Region A, as it is compressed by the cylinder under a lack of contact with Region B. In summary, a smaller texture depth facilitates the rebounding of the lubricant inside the texture and its movement to the contact surface; this aspect enhances the oil release capacity of the texture, which strengthens the effect.

![Figure 6](image-url)  
*Figure 6.* The lubricant distribution map for texture depths: (a) 100 and (b) 150 μm. The stress distribution diagram in specimens for texture depths: (c) 100 and (d) 150 μm, the hydrodynamic pressure distributions for texture depths: (e) 100 and (f) 150 μm.

The later stage of fluid lubrication exists widely in the industrial production which is rarely studied. The study obtained the friction reduction mechanism and characteristics of the ‘secondary lubrication effect’. Additionally, we studied the influencing factors by researching the texture's oil-storage and -release capacities. The lubricant infiltration capacity affect the oil-storage capacity. The oil-release mechanism obtained refers to that the lubricant inside the texture is brought to the contact surface due to the deformation of
the texture and the effect of the lubricant being squeezed into the texture. Texture depth will affect the oil-storage capacity. The oil-storage and -release capacities affect the ‘secondary lubrication effect’. Due to the low accuracy of the model, it needs more deep research. We will study the effect of other texture dimensions on the later stage of fluid lubrication.

4 Conclusion

The ‘secondary lubrication effect’ in the later stage of fluid lubrication reduces friction by generating hydrodynamic pressure except by supplementing the lubricant to the contact surface whose effect decreases with the loss of lubricant. The lubricant infiltration capacity affects the oil-storage capacity and texture depth will affect the oil-release capacity. The texture's oil-storage and -release capacities will affect the ‘secondary lubrication effect’.

The conclusions of this study can serve as a reference for research on fluid lubrication and help improve simulation accuracy.

References