Numerical Investigation of Effect of Textured Surfaces in Starvation Conditions under Reciprocating Motion

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1. Introduction

Recent experimental results [1] show that the tribological performance in starved lubrication is improved because textured patterns can act as a micro-reservoir to transfer lubricant onto the lubrication track. However, few numerical simulations have captured that result, and the lubricant transport mechanism is still at the hypothetical stage. In this study, the refined Elrod-Adams model [2] with the realistic lubricant flow is used to study the effect of textured surfaces in reciprocation piston ring/liner interfaces. The CIP-CSL2 method [3] is chosen to solve the model for high-precision simulations. Mechanisms for improving the lubricant supply by the textured pattern is discussed.

2. Mathematical model

Figure 1 shows the schematic of the mathematical model in the initial state. The upper surface is the stationary surface. The width b and height δ of the ring were set to 1 mm and 32 μm, respectively. The lower surface is reciprocated with a constant sliding speed u. Dimples with a pitch d are created on the lower surface. The distance of a single stroke was set to be 1 mm for reducing calculation costs. After the film rupture, lubricant adheres mainly to the lower surface and the mass transport velocity α of the lubricant can be considered as the same as velocity of the liner (α = 1). A transition region Ω_t between the fully-flooded region Ω_f and the partially-filled region Ω_p is introduced to recover the uniqueness of θ at the boundary. The refined Elrod-Adams model with the CIP-CSL2 method based on the previous work [4] is employed to predict film thickness distribution. The 1D non-dimensional governing equation can be expressed as follows:

$$\frac{1}{\Lambda}\frac{\partial}{\partial X}\left(H^3\frac{\partial P}{\partial X}\right)=\frac{\partial(\alpha\theta H)}{\partial X}+\frac{\partial(\theta H)}{\partial T} \qquad (1)$$

where

$$\Lambda=\frac{12\mu U r_d}{p_a h_0^2}, X=\frac{x}{r_d}, H=\frac{h}{h_0}, P=\frac{p}{p_a}, T=\frac{t}{t_0}, t_0=\frac{r_d}{u}, \theta_{in}=\frac{h_s}{h}$$

Table 1 shows simulation parameters used in this study. To solve the above governing equations, the free boundary and following complementary condition is used:

In $\Omega_p(A)$ and $\Omega_t(A)$: $\theta<1, P=P_1$

In Ω_f: $\theta=1, P_{cav}=0$ (if enclosed cavitation occurs)

In $\Omega_p(B)$ and $\Omega_t(B)$: $\theta<1, P=P_2$ (2)

It should be noted that for the piston case, the outlet pressure P_2 in the combustion-chamber is larger than the inlet pressure P_1. The enclosed cavitation pressure in the fully-flooded region should be equal to the saturated vapor pressure of the lubricant, and the open cavitation pressure in the partially-filled region should be equal to the ambient pressure.

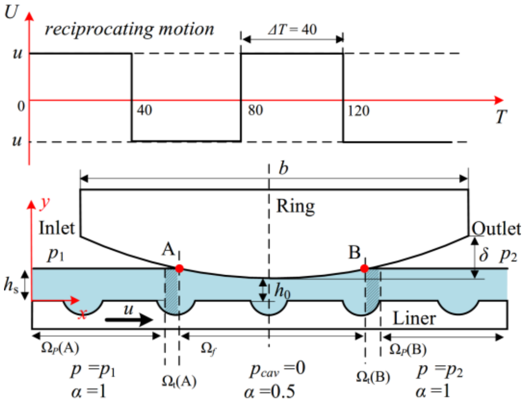

Fig. 1 Schematic of numerical model at T = 0

Table 1 Simulation parameters

Parameters	Value
Calculation zone, l	1 mm
Dimple radius, r_d	25 μm
Dimple depth, h_d	2 μm
Dimple pitch, d	0.2 mm
Initial lubricant supply, h_s	1.2 μm
Inlet pressure, p_1	0 atm
Outlet pressure, p_2	20 atm
Sliding speed, u	10 m/s
Minimum film thickness, h_0	1 μm
Viscosity, μ	0.01 Pas

3. Results and discussion

Figure 2 compares the pressure and film distribution during three strokes in the flat case and textured case. The results show that the hydrodynamic pressure is temporarily weakened due to the wedge action of the texture when the contact region is well lubricated. Notice that after the texture passes through the contact region, part of the lubricant inside the texture is transferred to the liner. When T increases to 75, the sliding direction is reversed. In the flat case, the lubrication condition changes to starved lubrication with less pressure generated. On the other hand, more lubricant is left near the inlet generating a greater pressure distribution in the textured case. At T = 115, the direction of rotation is restored. However, the lubricant is not accumulated at the inlet region, and cavitation is observed near the outlet in the flat case. Both the inlet and outlet regions are extremely poorly lubricated. In the case of the textured liner, the lubricant is accumulated at the inlet, and the lubricating condition improves

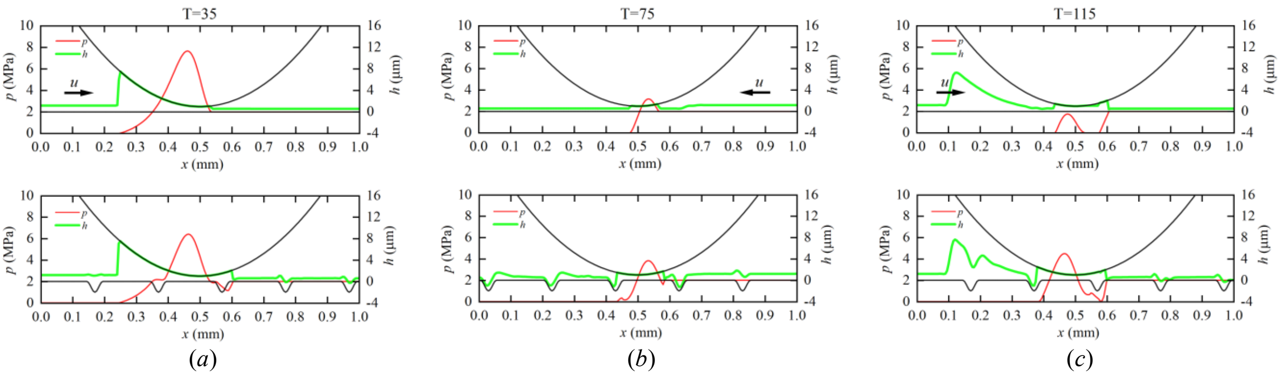

Fig. 2　Simulation results of textured liner and non-textured liner

significantly. It is demonstrated that the texture provides lubricant to the inlet region during the whole reciprocal motion.

Figure 3 shows variations in load-carrying capacity during three strokes. Figure 4 shows the ratio of the film thickness at lubricant boundary h_b to the minimum film thickness h_0 to evaluate the degree of starvation based on Wedeven's suggestion [5]. The characters of (a), (b) and (c) indicated in Figs. 3 and 4 correspond with those in Fig. 2. In the flat case, once the sliding direction is reversed, the load-carrying capacity drops nearly to one-fourth. The starvation degree also decreases sharply to about 1.4 at that time. It demonstrates that the film thickness at the inlet region suddenly decreases to near the minimum film thickness when the sliding motion is reversed. The degree of starvation does not change with time or sliding direction from the second stroke because no additional lubricant can be replenished into the inlet region.

On the other hand, although the load-carrying capacity is weakened due to the micro wedge action in the first stroke in the textured case, it does not decrease drastically like the flat case and still remains nearly half in the second stroke. The value of starvation degree increases periodically when each dimple enters the contact region. A more obvious advantage can be found in the third stroke, where the loss of load-carrying capacity due to the reversal is alleviated by the improved lubricated condition.

4.　Conclusions

This study investigated numerically the tribological behaviors of a textured surface in reciprocating motion under starved hydrodynamic lubrication. It was found that the textured surface could effectively improve the tribological performance of the system. When the textured pattern goes out the contact area, the texture can transfer the lubricant to the exit zone. When the motion is reversed, the textured pattern could carry with the transferred lubricant to improve the lubrication condition.

5.　References

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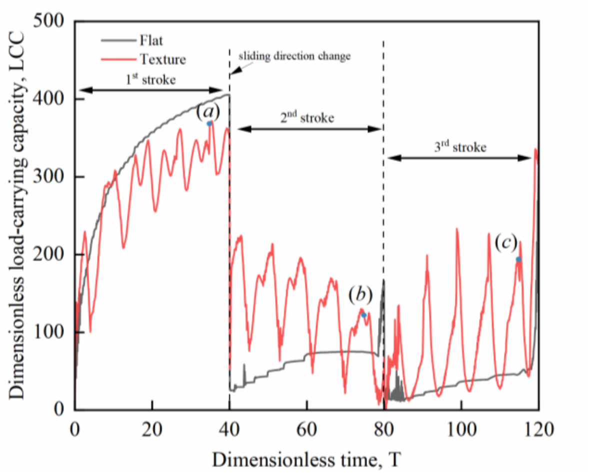

Fig. 3　Variations in load-carrying capacity with time T

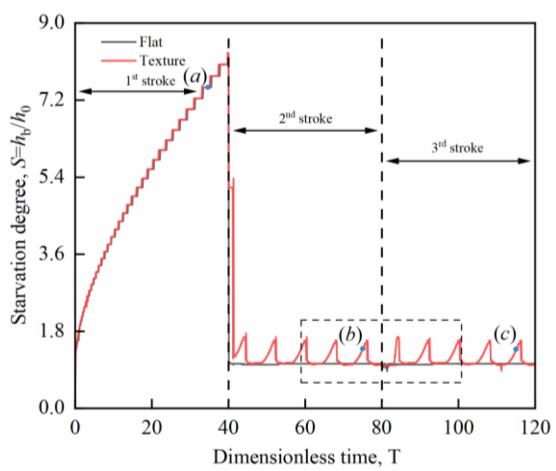

Fig. 4　Variations in starvation degree with time T