ナノ厚さ液体膜を介した固体摺動面間の摩擦特性の数値解析

Numerical Study of Frictional Properties of Solid Sliding Surfaces Intermediated with Nanometer-thick Liquid Films

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The establishment of effective nano-lubrication is crucial for realizing reliable and durable advanced mechanical systems. To elucidate nano-lubrication phenomena, we have developed a high-precision pin-on-disk type micro-tribotester and measured frictional properties between solid sliding surfaces intermediated with nanometer-thick liquid films. In this study, to interpret the measurement results, we proposed a mathematical model that incorporates forces specific to the nanoscale gap into the conventional continuum theory of elastohydrodynamic lubrication (EHL) and conducted a numerical analysis using the finite difference method. The calculated friction forces correlate well with the measured values over a wide velocity range of 1–100 mm/s. The analysis results suggest that while the EHL theory applies to nanometer-thick films, proper incorporation of short-ranged surface forces is indispensable, especially at low sliding velocities.

Key Words : Nano-lubrication, Elastohydrodynamic lubrication theory, Finite difference scheme, Hydrodynamic force, Structural force, Adhesive force

1.　Introduction

Motivated by the need for higher functionality, performance, and energy efficiency, miniaturization of mechanical systems or some of their elements is constantly progressing, resulting in diminishing gaps between solid sliding surfaces. For instance, the gaps are as small as nanometer-scale in hard disk drives and nanoimprint lithography. In automobiles and industrial working machines, the gaps also tend to fall in the nanometer scale because the use of lubricating oils with low viscosity is desired to reduce the energy loss caused by viscous friction. Consequently, the establishment of effective nano-lubrication is crucial for realizing reliable and durable advanced mechanical systems. To elucidate nano-lubrication phenomena, we have developed a high-precision pin-on-disk type micro-tribotester and measured frictional properties between sliding solid surfaces intermediated with nanometer-thick liquid films(1). In this study, to interpret the measurement results, we proposed a mathematical model that incorporates forces specific to the nanoscale gap into the conventional continuum theory of elastohydrodynamic lubrication (EHL) and conducted a numerical analysis using the finite difference method.

2.　Methods

Same as in our measurements with the micro-tribotester(1), we analyzed frictional behavior between a spherical pin and a flat disk lubricated with nanometer-thick liquid lubricant films (Fig. 1). As the in-plane dimension of tribological conjunctions is generally 1000 times larger than the gap, up to the micrometer scale, it is computationally efficient to calculate the flow of lubricants with continuum theory. In addition to the flow-induced hydrodynamic pressure, the pressures specific to the nanoscale gap should be considered. Hence, we propose the total pressure p_T on micro-sized conjunctions intermediated with nanometer-thick liquid films to be given by[2]

$$p_\mathrm{T} = p_\mathrm{h} + p_\mathrm{s} + p_\mathrm{a} \tag{1}$$

where p_h is the hydrodynamic component, p_s is the structural force component, and p_a is the adhesive force component. All the three components are functions of film thickness h, which is given by

$$h(x, y) = h_0 + h_\mathrm{s}(x, y) + \delta(x, y) \tag{2}$$

where h_0 is the minimum film thickness, h_s is the contribution of the shape of sliding pin, and δ is the elastic deformation of solid surfaces. We dictate p_h by a modified Reynolds equation based on Elrod's cavitation algorithm[3], p_s by a function fitted to experimental data[4], and p_a by a Lennard-Jones type adhesive correlation[5]. Thus, the pressure components and the film thickness can be determined by iterative calculations, which converge when the integration of p_T over the pressurized region is balanced with the load applied on the sliding pin. Then, the shear stress is calculated using

$$\tau_\mathrm{T} = \eta_0 e^{\alpha p_\mathrm{T}} \left(\frac{u}{h}\right) + A \left(\frac{u}{h}\right)^{1-B} + C|p_\mathrm{a}| \tag{3}$$

where η_0 is the bulk lubricant viscosity, α is the viscosity-pressure coefficient, u is the sliding velocity, and coefficients A, B, and C are determined by fitting the experimental data to the simulated shear properties of nanometer-thick liquid lubricant films[6]. It should be noted that the three terms on the right side of Eq. (3) represent the contributions from hydrodynamic, structural, and adhesive forces, respectively. Finally, the friction force is calculated by integrating τ_T over the pressurized region.

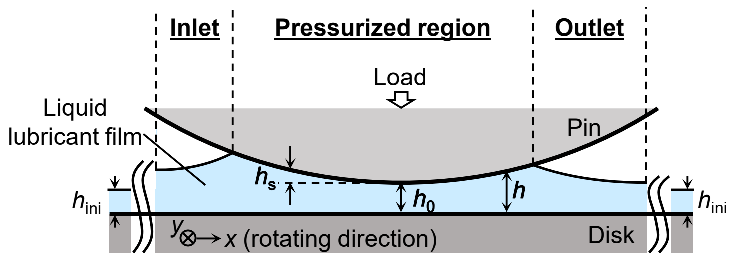

Fig. 1 Tribological conjunction between a spherical pin and a flat disk lubricated with nanometer-thick liquid lubricant films

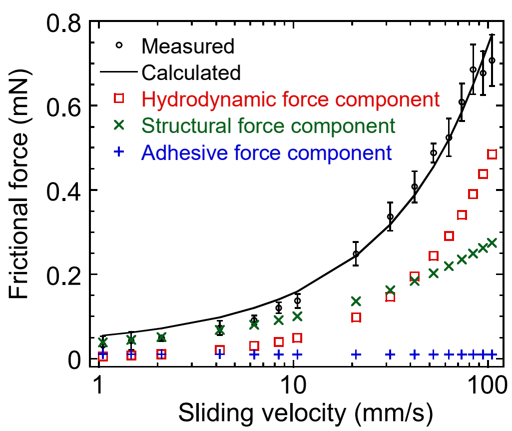

Fig. 2 Comparison of calculated and measured friction forces between a glass sliding pin and a magnetic disk lubricated with a 1.7 nm thick nonpolar perfluoropolyether film.

3. Results and Discussion

Figure 2 compares the calculated and measured friction forces between a glass sliding pin and a magnetic disk lubricated with a 1.7 nm thick nonpolar perfluoropolyether film. The radius of the sliding pin was 7.5 mm, the applied load was 2.0 mN, and the sliding velocity varied from 1 to 100 mm/s[1]. The calculated total friction forces increase with sliding velocity and correlate well with the measured values over the entire velocity range. With increasing sliding velocity, the friction forces due to hydrodynamic and structural forces increase, whereas the friction force due to adhesive force remains roughly constant and is negligibly small as compared to the other two components. At velocities below 10 mm/s, frictional characteristics are dominated by the structural force component. At 40 mm/s, the hydrodynamic force component exceeds the structural force component and begins to take over the total frictional characteristics.

4. Conclusion

To gain insight into frictional characteristics between solid sliding surfaces intermediated with nanometer-thick liquid films, we proposed a mathematical model that incorporates forces specific to nanoscale clearance into the conventional continuum theory of EHL and conducted a numerical analysis using the finite difference method. The calculated friction forces correlate well with the measured values over a wide velocity range of 1–100 mm/s. From the analysis results, we suggest that while the EHL theory applies to nanometer-thick films, proper incorporation of short-ranged surface forces is indispensable, especially at low sliding velocities.

Acknowledgments

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References

(1) Zhang, H., Takeuchi, Y., Chong, W.W.F., Mitsuya, Y., Fukuzawa, K., and Itoh, S., "Simultaneous in Situ Measurements of Contact Behavior and Friction to Understand the Mechanism of Lubrication with Nanometer-Thick Liquid Lubricant Films", *Tribology International*, Vol. 127 (2018), pp. 138–146.

(2) Chong, W.W.F., Teodorescu, M., and Rahnejat, H., "Effect of Lubricant Molecular Rheology on Formation and Shear of Ultra-Thin Surface Films", *Journal of Physics D: Applied Physics*, Vol. 44 (2011), p. 165302.

(3) Elrod, H.G., "A Cavitation Algorithm", *ASME Journal of Lubrication Technology,* Vol. 103, No. 3 (1981), pp. 350–354.

(4) McGuiggan, P.M., Gee, M.L., Yoshizawa, H., Hirz, S.J., and Israelachvili, J.N., "Friction Studies of Polymer Lubricated Surfaces", *Macromolecules*, Vol. 40, No. 6 (2007), pp. 2126–2133.

(5) Yu, N. and Polycarpou, A.A., "Adhesive Cntact based on the Lennard–Jones Potential: A Correction to the Value of the Equilibrium Distance as Used in the Potential", *Journal of Colloid and Interface Science,* Vol. 278, No. 2 (2004), pp. 428–435.

(6) Zhang, H., Fukuda, M., Washizu, H., Kinjo, T., Yoshida, H., Fukuzawa, K., and Itoh, S., "Shear Thinning Behavior of Nanometer-Thick Perfluoropolyether Films Confined between Corrugated Solid Surfaces: A Coarse-Grained Molecular Dynamics Study", *Tribology International,* Vol. 93 (2016), pp. 163–171.