# On the Appearance of Molecular Effects in Different Tribological Systems

Hiroshige MATSUOKA<sup>1</sup>, Takahisa KATO<sup>2</sup> and Shigehisa FUKUI<sup>3</sup>

<sup>1</sup> Department of Applied Mathematics and Physics, Faculty of Engineering, Tottori University

4-101 Minami, Koyama, Tottori 680-8552, JAPAN

Tel & Fax: +81-857-31-5759, e-mail: hiro@damp.tottori-u.ac.jp

<sup>2</sup> Institute of Mechanical Systems Engineering, Tsukuba East Center, AIST

1-2-1 Namiki, Tsukuba, Ibaraki 305-8564, JAPAN

Tel: +81-298-61-7165, Fax: +81-298-61-7277, e-mail: kato.t@aist.go.jp

<sup>3</sup> Department of Applied Mathematics and Physics, Faculty of Engineering, Tottori University

4-101 Minami, Koyama, Tottori 680-8552, JAPAN

Tel & Fax: +81-857-31-5324, e-mail: fukui@damp.tottori-u.ac.jp

# 1. Introduction

Machine elements are being downsized in recent years with the advance of micromachining technology. In accordance with this downsizing, the separation between surfaces that move relative to each other becomes smaller and smaller. The surface forces, e.g., van der Waals force<sup>[1]</sup>, meniscus force<sup>[2]</sup> or structural force<sup>[3]</sup>, have relatively large effects in the microelectromechanical systems (MEMS), powder systems, colloidal systems and so on. Therefore, knowledge concerning the characteristics of surface forces is considered to be indispensable as the basis of key technologies in the near future<sup>[4-6]</sup>.

In this study, a surface force apparatus (SFA) - type setup which can accurately measure the surface forces between solid surfaces in an atmosphere-controlled chamber has been developed. The surface forces including the nanomeniscus forces in the undersaturated vapor of several kinds of liquids<sup>[7]</sup> and the hydrodynamic film thickness of liquid lubricant under shear<sup>[8]</sup> were measured using this apparatus and the appearance of molecular effects in these tribological systems is discussed. 2. Experimental Section

Apparatus. Figure 1 shows the main part of the SFA-type apparatus. The solid surfaces (A and B) are in a crossed cylinder configuration which is equivalent to a plane and sphere configuration. The cylindrical surface A is supported by a double cantilever spring which is used to measure the normal force between the solid surfaces. The spring constant of the double cantilever spring is 1270 N/m; the normal force can be obtained by measuring the deflection of this spring. The deflection is measured by displacement sensors No. 1 and 2 which are high resolution noncontact capacitive displacement sensors. Since the resolution of the displacement sensors is less than 1 nm, the resolution of the normal force detection is about 1 µN. The cylindrical surface B is supported by a rigid arm.

Cleaved mica is glued by epoxy resin on a cylindrical glass lens whose radius of curvature, R, is 8.5 mm.

The main unit is mounted on stages: Cylinder A is on an elastic stage which is driven by a piezoelectric actuator and can realize fine movement in the x direction; Cylinder B is on a microstage for coarse movement.

The assembly is located in a vacuum chamber in which the vapor pressure of a liquid can be controlled. The complete apparatus is located on a vibration isolation system in a clean booth.

Properties of specimens. In this study, mica is used as the solid specimen and several kinds of liquids are used. The properties of these specimens are shown in refs. [7] and [8]. 3. Results of Nanomeniscus Force Measurements

Examples of the nanomeniscus force measurement are shown in Fig. 2. Under dry conditions  $(p/p_{1} = 0.0)$ , the surface forces denoted by the big black dots agree well with the theoretical value predicted by the JKR theory<sup>[9]</sup>, (dotted line in Fig. 2). It is found that the surface forces gradually change from those under dry conditions to a constant asymptote with increasing relative vapor pressure. In the case of water, the surface force gradually increases whilst in the other cases



Fig. 1 Main part of SFA-type apparatus



Fig. 2 Results of nanomeniscus force measurements

they decrease. This is because the surface energy of water is greater than that of mica while the surface energies of other liquids are lower than that of mica and because the mica surface is hydrophilic. It is also found that the constant values of the surface forces in the region of high relative vapor pressure correspond to the macroscopic meniscus forces generated by the Laplace pressure of each liquid, which means that the nanomeniscus forms at the interface and shows macroscopic bulk characteristics for relative vapor pressures above a certain value. The relative vapor pressures at which the nanomeniscus force begins to deviate from the macroscopic prediction are different for each liquid.

The critical Kelvin radii<sup>[7, 10]</sup>  $r_{Kc}$ , *i.e.*, the nanomeniscus radii at which the nanomeniscus force begins to show the macroscopic bulk characteristics are investigated and the results are shown in Fig. 3. It is found that the critical Kelvin radii of linear chain alkanes are proportional to the carbon number n, the critical Kelvin radii of cyclic alkanes are nearly equal to the effective molecular diameter, and in the case of polar liquids, the critical Kelvin radii are very large compared to their effective molecular diameter.

### 4. Results of Ultrathin Liquid Film Thickness Measurements

Figure 4 shows the results of ultrathin hydrodynamic film thickness measurements under shear ( $100 \mu$ m/s). Octamethylcyclotetrasiloxane (OMCTS) whose shape of molecule is spherical was used as a liquid lubricant. The discretization of the film thickness begins to appear at about 8 nm which corresponds to eight times the effective molecular diameter of OMCTS (about 1 nm). Almost same phenomenon was observed in the case of cyclohexane whose shape of molecule is semispherical and whose effective molecular diameter is about 0.6 nm. This phenomenon is due to the structural force. The discretization was not observed when *n*-hexadecane whose shape of molecule is linear was used as a lubricant. **5. Comparison of Results of the Two Tribological Systems** 

In the case of confined liquid and immersed solid surface in liquid, *i.e.*, the ultrathin liquid film thickness measurements, the molecular effect appeared at about eight times the effective diameter of confined spherical molecule and the effect was not observed with respect to linear molecule, while in the case of nanomeniscus force measurements, the molecular effect appears at 4 - 6 times the effective molecular diameter for linear chain alkanes, about 2 times for cycloalkanes. These results show the different tendency between the deferent experimental systems. We consider that this fact comes from whether the system has free surface of liquid or not, in other words, the liquid is perfectly confined between solid walls or not.

#### 6. Summary

The authors developed a SFA - type setup, which can accurately measure the surface forces between solid surfaces in an atmosphere-controlled chamber. The surface forces including the nanomeniscus forces in the undersaturated vapor of several kinds of liquids and the film thickness of liquid lubricant were measured using this apparatus. It is found by comparing the experimental results that the appearance of molecular effects in these tribological systems has different tendency. The authors considered that this difference is due to the free surface of liquid.

The more detailed data and discussion will be presented at the conference.



Fig. 4 Results of ultrathin liquid film thickness measurements

### Acknowledgment

The authors thank Mr. Shin Inagaki and Mr. Syunsuke Takeya for their help of the development of the apparatus.

## References

- [1] Lifshitz, E. M., Soviet Physics, JETP, 2, 73-83, 1956.
- [2] McFarlane, J. S. and Tabor, D., Proc. Roy. Soc. London, Ser. A, 202, 224-243, 1950.
- [3] Horn, R. G. and Israelachvili, J. N., J. Chem. Phys., **75**, 1400-1411, 1981.
- [4] van Alsten, J. and Granick, S., *Phys. Rev. Lett.*, **61**, 2570-2573, 1988.
- [5] Georges, J. M., Millot, S., Loubet, J. L., and Tonk, A., J. Chem. Phys., 98, 7345-60, 1993.
- [6] Johnston, G. J., Wayte, R., and Spikes, H. A., *STLE Trib. Trans.*, 34, 187-194, 1991.
- [7] Matsuoka, H., Kato, T., and Fukui, S., Langmuir, to be published; Proc. Intnl. Trib. Conf. Nagasaki 2000, I, 733-737, 2001.
- [8] Matsuoka, H. and Kato, T., *IMechE J. Eng. Trib.*, Pt. J, **211**, 139-150, 1997.
- [9] Johnson, K. L., Kendall, K., and Roberts, A. D., Proc. Roy. Soc. London, Ser. A, 324, 301-313, 1971.
- [10] Israelachvili, J. N., Intermolecular and Surface Forces, 2nd ed., Academic Press, 1992.