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Description	

Friction Coefficient between Rubber and Solid Substrate

-Effect of Rubber Thickness-

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Abstract

The frictional coefficient μ between Poly(dimethyl siloxane) (PDMS) rubber and glass plate with PDMS lubricant is measured for various thickness of rubber sample. The friction coefficient of thick sample is shown to be an order of magnitude larger than that of thin sample. The phenomenon is interpreted as the transition from the hydrodynamic lubrication to the boundary lubrication.

KEYWORDS: sliding friction, PDMS, rubber, hydrodynamic lubrication, boundary lubrication

Introduction

The friction is a phenomena taking place between the surfaces of two sliding bodies, and it is usually considered to be controlled by surface property only. Recent studies, however, have shown that this is not true for soft materials such as rubbers or gels: the friction of soft matters involves the bulk effect.[1-6)] Persson et al.[1-3)] has shown that the viscoelastic deformation of the soft materials can be the major part of the energy dissipation associated with the friction. Brochard et al.[4-6)] showed that the deformability of the soft material affects the wetting and dewetting process strongly, and therefore affect the lubrication effect.

Most of the previous works on the friction of soft matters are done for the lubricants which cannot dissolve in the soft matter. On the other hand, the effect of lubricant which can dissolve into the soft matter is also interesting as it is a simple model of lubrication in our joints: the low friction in joints is brought by the soft hydrogels which includes a large amount of water.[7)] Such studies have been done extensively by Gong et al.[8-11)] using hydrogels.

In the previous works, the thickness of the sample was kept constant. On the other hand, if the friction of soft material has the origin of the bulk properties, it will depend on the thickness of the sample, but this has not been studied.

In this paper, we shall study the thickness dependence of friction between PDMS rubber and glass substrate under the situation that both the absorption and lubrication are effective. We shall describe the phenomena and give a simple interpretation.

Experiment

We measured the sliding friction between glass plate and poly(dimethyl siloxane, PDMS) rubber swollen with PDMS oil which plays a role of lubricant.

The PDMS rubber was made from (PDMS) solution by mixing the liquid state Silpot 184 (Dow Corning Toray Co., Ltd., Japan) with the liquid state Catalyst Silpot 184, the weight ratio being 10 to 1. After mixing, the PDMS solution was de-aired promptly by vacuum pump and polymerized between the silicon wafers set in parallel with various gap lengths (0.5, 1, 2, 3, 5 [mm]) at 60˚C for 12 hours. After the polymerization, the sheet-shaped PDMS rubbers having various thicknesses were obtained. The sheet-shaped PDMS rubber was immersed into a large amount of PDMS oil (KF-96-10CS, $Mw=1.1\times10^3$, Shin-Etsu Chemical Co., Ltd., Japan) for a week to be in swelling equilibrium (swelling degree is about 1.5). The swollen PDMS rubber was cut off in disk shape of radius about 10 [mm] for friction measurements.

The friction was measured by rheometer (HAAKE MARS, Thermo Electron Corp., Germany) at a steady state mode. The set-up is shown in Fig. 1. The rubber was fixed onto the top parallel plate by a small amount of adhesive agent. The bottom plate was a glass-made Petri-dish filled with a small amount of PDMS oil which plays the role of lubricant. The top plate was brought into contact with the bottom plate until the normal load N_f reached the preset value. The top plate was then rotated with a rotation speed Ω, and the torque M [Nm] acting on the top plate was measured.

In this experimental setup, the sliding velocity varies along the radial direction, and therefore the shear stress varies as well. We therefore took characteristic shear stress $\overline{\tau}$ which is the stress that gives the torque M if the shear stress is uniform: $\overline{\tau}$ is calculated by

$$M = \int_0^a dr 2\pi r^2 \overline{\tau} = \frac{2\pi}{3} a^3 \overline{\tau} \qquad (1)$$

The normal stress P is given by $P = N_f / \pi a^2$, and the friction coefficient μ was estimated by

$$\mu = \frac{\overline{\tau}}{P} = \frac{3M}{2aN_f} \qquad (2)$$

The torque M was measured as a function of the rotating speed Ω of the upper plate under various initial normal stress P= 9.6, 22, 32 [KPa]. The Ω was increased step wisely from 0.1

[r.p.m.] to 1000 [r.p.m] with measuring torque for 300 seconds at each rotation speed. Fig.2 shows an example of the experimental data. At low sliding velocity, the torque osicillated due to the slip-stick phenomena. When this happens, the average of the torque was used to calculate the friction coefficient. For other case, the steady state value of the torque was used to calculate the friction coefficient μ.

Results

Fig. 3 shows the friction coefficient μ plotted against the rotation speed for various PDMS thicknesses (0.68, 2.5, 6.3 [mm]). The figure also shows the sliding velocity $V=a\Omega$ at the outer rim of the sample.

Fig. 3a is a result of thin sample (0.68 [mm] in thickness). It is seen that the friction coefficient μ of this sample remains small ranging between μ~10^{-2} and 10^{-1} when the sliding velocity varies from 10^{-3} [m/s] to 10^{1} [m/s]. The friction coefficient remains to be high for various normal stresses P (9.6, 16, 22 [KPa]).

Fig. 3c shows the result of thick sample(6.3 [mm] in thickness). The friction coefficient at low rotation speed is about the same as that of the thin sample, but at high rotation speed, the friction coefficient μ becomes much larger than that of Fig.3a.

Fig. 3b shows the result of intermediate thickness (2.5 [mm]). It is seen that for this sample, the friction coefficient depends on the normal stress: The friction coefficient at low normal stress (9.6 [KPa]) shows the same behavior like Fig. 3a, while the friction coefficient at normal stress of 22 [KPa] and 32 [KPa] is significantly larger, about the same as that for the Fig. 3c.

These results indicate that friction of PDMS rubber mainly shows 2 states, the state of low friction, where μ is of the order of 10^{-2}, and that of high friction where μ is of the order of 1. Which of these two states is realized depends on the normal load, sliding velocity and the sample thickness. Our experiment indicates that for thick sample, the friction tends to be high, while for thin sample, the friction becomes low.

Fig. 4 shows the friction coefficient μ plotted against the sample thickness H for various normal stresses P at given sliding velocity V. The figure indicates that the system transforms from the low-friction state to high friction state as the sample thickness increases.

Interpretation

We now discuss why the friction between the rubber and substrate transforms from the low friction state to high friction state as the sample thickness increases. Consider that initially there is a lubrication layer of thickness e as it is shown in Fig. 1. As long as such lubrication layer exists, the friction is determined by the viscosity of the lubricants, and is small. Such state is called the hydrodynamic lubrication. On the other hand, if the rubber absorbs lubricant and contact with the glass plate directly, the friction becomes large. Such state is called the boundary lubrication.

Now suppose that a part of the rubber, of region of radius R, absorbs the lubricants and touches the substrate as it is shown in Fig. 5. Then the system will gain a free energy $F_{surf} \approx -R^2 S$, where S is the spreading coefficient defined by:

$$S = \gamma_{SR} - (\gamma_{SL} + \gamma_{LR}) \tag{3}$$

where γ_{SR}, γ_{SL} and γ_{LR} stand for the solid/rubber, solid/liquid and liquid/rubber interfacial tensions, respectively. In our system S is considered to be negative since it is observed that the rubber sticks on the glass plate when we leave the rubber on the glass plate for a long time. On the other hand, the state shown in Fig. 5 will cost the elastic energy of the rubber. Since the characteristic strain is e/H, the elastic energy of deformation can be written as

$$F_{elas} = G\left(\frac{e}{H}\right)^2 \left(R^2 H + R H^2\right) \tag{4}$$

The term R^2H stands for the volume of the cylindrical region, and RH^2 the volume of the outer shell shown in Fig.5. Thus the total free energy is written as

$$F=\left(-|S|+G\frac{e^2}{H}\right)R^2+Ge^2R=-|S|\left(1-\frac{H_c}{H}\right)R^2+Ge^2R \qquad (5)$$

where

$$H_c\approx\frac{Ge^2}{|S|} \qquad (6)$$

If $H<H_c$, F is always positive and the configuration shown in Fig. 5 is energetically unfavorable. In this case, the lubrication layer exits between the rubber and substrate, and therefore the friction remains small. On the other hand, if $H>H_c$, F becomes minimum at certain value of R: the free energy of the system is reduced if certain part of the rubber touches the substrate directly. In the case, the lubrication layer is lost, and the friction becomes high. One can roughly estimate the critical thickness H_c. Taking the initial lubrication layer thickness e~3μm, the spreading coefficient S~10^{-2}N/m, and the elastic modulus G~10^6Pa, one gets H_c~10^{-3}m. This indicates that the above transition can occur in a few millimeters range. This is consistent with our results shown in Fig. 4.

Discussion

We observed that the friction coefficient between rubber and glass increases more than 1 order in magnitude when the thickness of rubber increases. (We believe that this is the first report for such effect though our literature search is limited to scientific journals.) We interpreted the phenomena as the transition from the hydrodynamic lubrication to boundary lubrication. Our explanation is not complete: it does not explain why the critical thickness H_c depends on the normal stress P, and why the friction depends on the sliding velocity.

In our interpretation, we are assuming that the initial thickness of the lubrication layer e is a given quantity. Although e is a changeable quantity, we assumed that it is about the same. This is because it takes an extremely long time for the thin liquid film to change the thickness, and as long as we follow the same procedure to prepare the sample setting, the thickness of the initial lubrication layer is expected to be the same. This assumption, however, has to be checked.

Although there are many open questions, we believe that our explanation captures an essential feature of the thickness dependence of friction between rubber and solid substrate. The explanation is based on the simple fact that with the increase of rubber thickness, the rubber tends to be stretched more easily and tends to touch the substrate directly. We are now conducting experiments to check this conjecture.

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Figure Captions

Figure 1.

The experimental setup to measure the sliding friction. The swollen PDMS rubber having thicknesses H and radius a is fixed to the upper parallel plate by adhesive agent. The plate is brought into contact with bottom glass plate filled with PDMS oil until the normal load N_f reaches a certain value. The top plate is then rotated with a rotation speed Ω keeping its vertical position held fixed, and the toque acting on the rotating parallel plate is measured. The lubricant thickness e is exaggerated in the drawing

Figure 2.

The frictional torque M [μ Nm] (■) acting on the PDMS rubber in the system shown in Fig.1 is plotted against time when the rotation speed Ω [r.p.m.] (○) is changed step wisely. The rubber thickness is 0.68 [mm] and the normal stress is 9.6 [KPa]. Stick-slip behavior is observed for the rotation speed less than 50 [r.p.m.]. When the stick-slip behavior is observed, the average torque is taken to calculate the friction coefficient.

Figure 3. The sliding friction coefficient μ of PDMS rubber having various thicknesses are plotted against the rotation speed (or the sliding velocity). The sample thickness is (a) 0.68mm, (b) 2.5mm and (c) 6.3mm. Different symbols denote different initial normal stress, circles (●):9.6KPa, squares (■): 22KPa, triangles (▲): 32KPa.

Figure 4. The friction coefficient between PDMS rubber and glass substrate in the presence of lubricant is plotted against the thickness of PDMS rubber. Different symbols denote different initial normal stress, circles (●):9.6KPa, squares (■): 22KPa, triangles (▲): 32KPa. The sliding velocity V is 10^{-2} [m/s].

Figure 5. Schematic illustration of the high friction state: a certain region of size R is touching with the bottom plate, while the other part is separated from the bottom plate by lubrication layer.

Figures

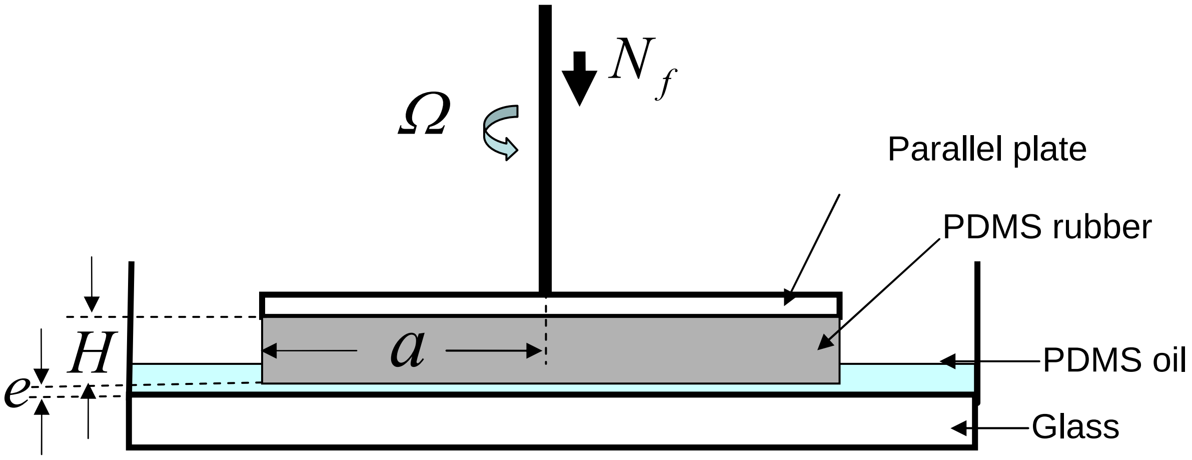
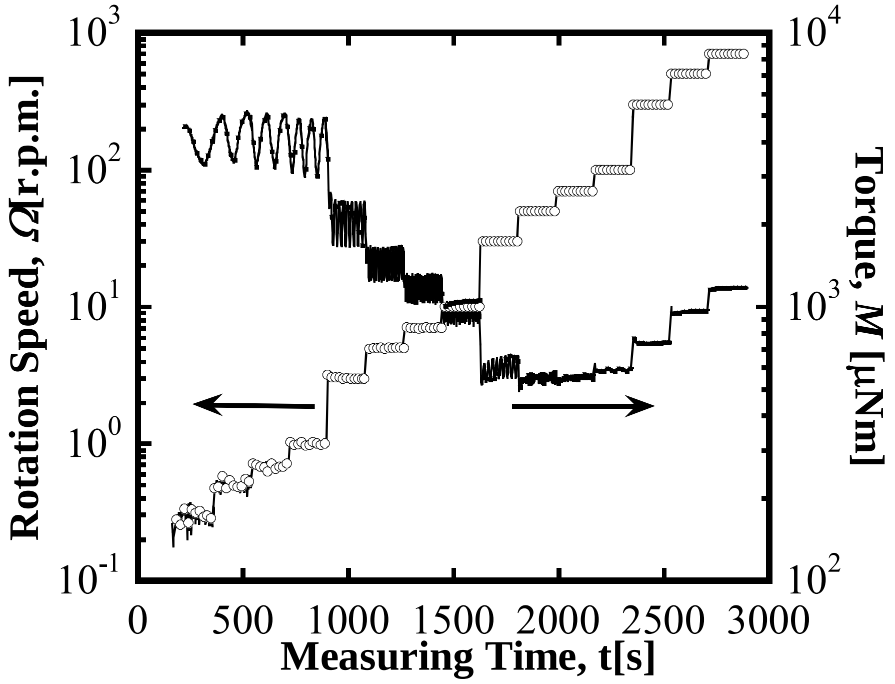


Figure 1. KANEKO et al.



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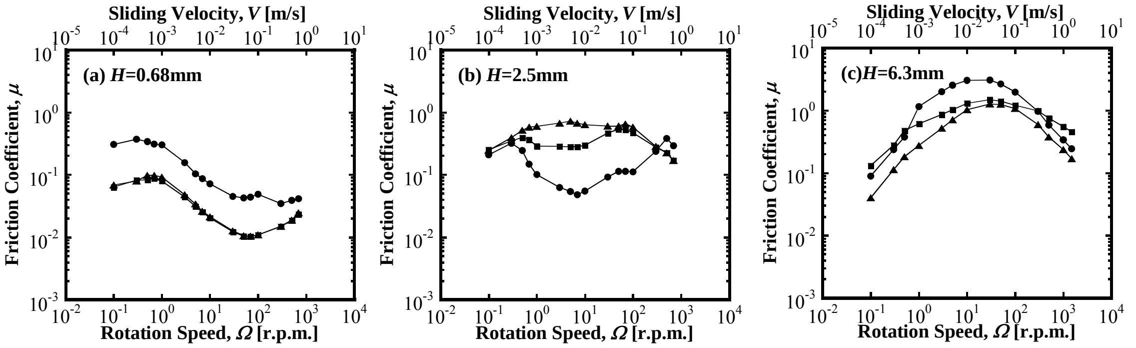

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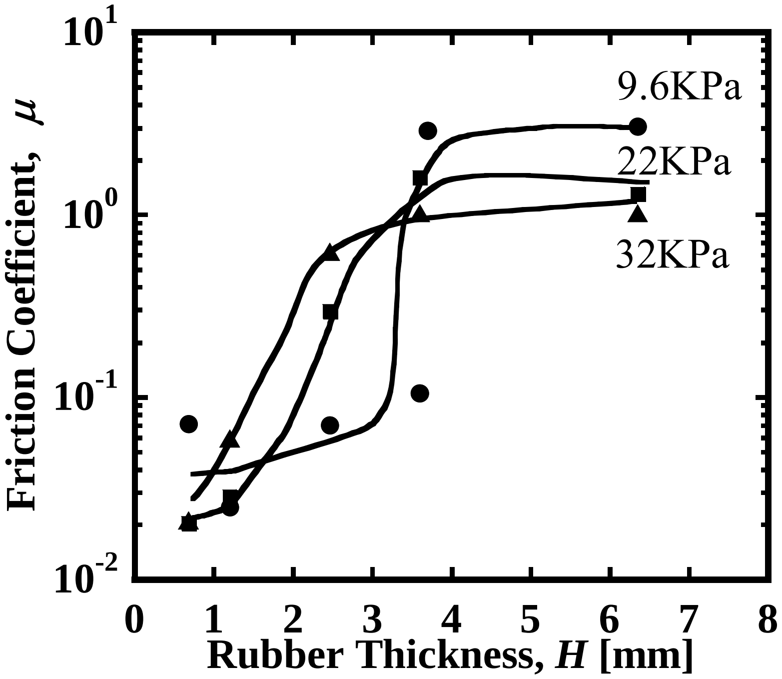

Figure 4. KANEKO et al.

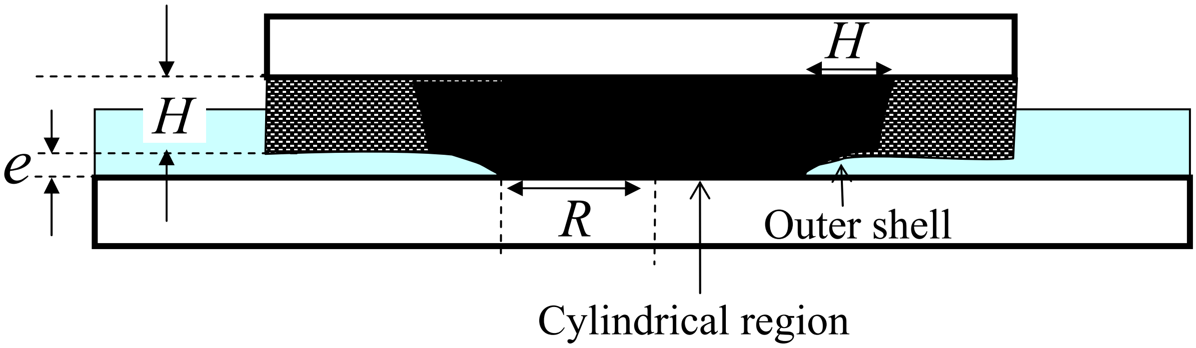

Figure 5. KANEKO et al.