Water droplet lubrication between hydrophilic and hydrophobic surfaces

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Abstract. Water droplets, which are stuck to the hydrophilic surface, reduce the friction coefficient when they are slid against the hydrophobic surface. This is because a repulsive force is generated between water and hydrophobic surfaces due to the surface tension of water. In the present experimental system, the water droplets carried the load up to 170mN and showed the coefficient of friction between the surfaces as low as 0.0011. The low coefficient of friction is attributable to the low energy loss during the adhesion hysteresis process of water onto the hydrophobic surfaces. In micro-machine applications, the water droplet lubrication is effective for reducing the coefficient of friction by utilizing the repulsive force between water and the hydrophobic surface.

1. Introduction
When a water droplet is interposed between two hydrophilic plates which are just separated, it sticks them together. This is because the plates easily become wet. In the world of a small-sized machine (micro-machine) the gap between the machine parts, which are usually hydrophilic, are so small that water acts as a glue of the parts and prevents them from sliding. As a result, it interrupts the normal operation and sometimes causes a complete failure of the whole system. As the size of the machine becomes smaller, the water droplet effects become larger.

On the contrary a water droplet on the hydrophobic surface does not stick to the surface and actually drops down from the surface, which can be commonly observed on the grass or leaves. The droplet has a spherical shape and rolls/ slides like a ball. So if it is utilized as a ball bearing between two plates, it will greatly reduce the friction force [1,2]. From this point of view, we interposed the water droplet between two hydrophobic plates and found out that it shows the coefficient of friction as low as 0.0011. In this paper, the origin of friction force will be discussed from the point of view of the adhesion hysteresis loss in loading/unloading processes of the water droplet onto the hydrophobic surface.

2. Friction measurements
2.1. Experimental procedure
The experiments were carried out using a plate on plate sliding system. We sprayed the polytetrafluoroethylene (PTFE) fine particles with the binder and pasted on the glass plates to form hydrophobic surfaces. The contents of PTFE to the binder was changed from 10 to 80%. Fig.1 shows the water droplet on the glass plate and on the hydrophobic surface with various contents of PTFE.
powders. Water wets very well the glass plate whose surface is hydrophilic. On the contrary, water droplet forms a spherical shape and stays on the surfaces which contain PTFE of 10 to 60%. On the surface containing PTFE of 80%, water was hardly trapped on the surface and dropped down. The contact angle of water on the plate with PTFE of 80% was $150^\circ$. To trap the water droplet we masked one or two small areas on the glass during spraying process of PTFE, which became hydrophilic areas after removing the masks.

![Figure 1](image1.png)

**Figure 1.** Water droplet on the surfaces of various PTFE contents

![Figure 2](image2.png)

**Figure 2.** Schematic of experimental setup

2.2. Results and discussion

Fig.3 shows the effect of sliding velocity on the coefficient of friction when a water droplet of 50mm$^3$ was interposed between glass plate coated with various contents of PTFE. The applied load
was 60mN. As the PTFE content increased, the coefficient of friction decreased. The minimum coefficient of friction of 0.0014 was obtained when the sliding velocity was 0.03mm/s. In the case of 80% of PTFE contents, the coefficient of friction gradually increases as the sliding velocity increases. It means that it is in a fluid lubrication mode. The contribution of viscosity to the friction force $F$ is calculated by the following equation.

$$F = S\tau = S\eta \frac{v}{h}$$

where 
- $S$: contact area = 60mm$^2$
- $\eta$: viscosity of lubricant = 1mPa·s
- $v$: velocity = 0.2mm/s
- $h$: lubricant thickness = 0.8mm.

We then have $F=1.5\times10^{-5}$mN. The coefficient of friction is $2.5\times10^{-7}$, which is much smaller than the measured value. It is thus concluded that the viscosity does not contribute principally to the friction force.

![Figure 3. Effect of sliding velocity on the coefficient of friction, Load=60mN](image)

The effect of load on the coefficient of friction of the same plate as in Fig.3 is shown in Fig.4. The sliding velocity was 0.1mm/s. The coefficient of friction decreased with the increase in load, which means that the friction force was almost the same in all the loading conditions. This fact also supports that viscosity has little effect on friction.

Fig.5 shows the effect of the number of hydrophilic area i.e. the number of water droplets, and the effect of load on the coefficient of friction. Two types of surface exhibit the same coefficient of friction.

Fig.6 shows the load carrying capacity of one or two water droplets. As the number of hydrophilic area was doubled, the supporting load was also doubled. The maximum supporting load of this system was 170mN.
Figure 4. Effect of load on the coefficient of friction, Sliding velocity=0.1mm/s

Figure 5. Effect of load and the number of hydrophilic area on the coefficient of friction, Sliding velocity=0.1mm/s

Figure 6. Load-carrying capacity of water droplets interposed between hydrophobic surfaces
To clarify the origin of the friction force, we hypothesized that the friction force was caused by the energy dissipation in the adhesion/separation processes of a water droplet to and from the hydrophobic surface. The dissipated energy is expressed as the hysteresis loss of adhesion [3]. Accordingly, next we carried out another experiment to check whether the hysteresis loss is the main cause for the water droplet lubrication.

3. Adhesion hysteresis measurements

3.1. Experimental procedure

Fig. 7 shows the schematic of the test procedure. In the sliding test, a water droplet slides on the new surface. This means that the water droplet adheres to a new surface at the front end and is separated from the surface at the rear end. On the other hand in the loading/unloading test, the water droplet spreads out to extend the contact area in the loading process followed by the decrease in diameter in the unloading process. The loading/unloading process is equivalent to the sliding process from the viewpoint of changing the contact area. Therefore for the same surface area, we compared the hysteresis loss during loading/unloading processes with the frictional loss due to the sliding process.

![Figure 7. Schematic of sliding and loading/unloading tests](image)

![Figure 8. Repulsive forces in loading and unloading processes generated from water droplet and hydrophilic surface](image)
3.2. Results and discussion

Fig. 8 shows an example of the change in repulsive force associated with the change in the gap between the plates. A water droplet was pressed between the plates until the repulsive force reaches 50mN. In the next step the gap was increased until the repulsive force was decreased down to 5mN. Then the plates were approached again to the original position.

Fig. 8 exhibits that the loading and unloading processes are not reversible; the load – distance curve does not show the same trace. This means that the system has the hysteresis between the two processes.

The same kinds of experiments were carried out for different loading/unloading conditions:

1) 50mN \rightarrow 45mN \rightarrow 50mN,
2) 50mN \rightarrow 40mN \rightarrow 50mN,
3) 50mN \rightarrow 5mN \rightarrow 50mN.

The hysteresis losses for each process are plotted in Fig. 9. The horizontal axis is the change in contact area, which is calculated by dividing the volume by the gap. The hysteresis loss is linearly increased as the change in contact area is increased.

On the other hand, the frictional work is the product of a friction force and a sliding distance. The friction force of 0.425mN was obtained in the sliding conditions: load; 50mN and sliding speed; 0.2mm/s. In this case, the sliding distance was calculated so that the friction area should be equal to the newly wet surface area in loading/unloading test. The calculated values are plotted in Fig. 9. It is apparent that the frictional force is linearly increased as the contact area increases. There is still a difference between the frictional work and the hysteresis loss. However the frictional work and the hysteresis loss increase in parallel, which means that the major contribution to frictional work is the hysteresis loss of adhesion/separation of water droplet to hydrophobic surface.

4. Conclusions

From the results mentioned above, it is clarified that water droplets, when they are interposed between the hydrophobic surfaces, carry the load up to 170mN and show the coefficient of friction as low as 0.0011. The load is supported by the repulsive force resulting from the surface tension of water. The low coefficient of friction is attributable to the low energy loss during the adhesion hysteresis process. In micro-machine applications, the water droplet lubrication is effective for reducing the coefficient of friction by utilizing the repulsive force of the hydrophobic surfaces.
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