MEASUREMENT AND CONTROL OF FRICTION UNDER MICROLOAD CONDITIONS

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SUMMARY
Friction force between a silicon wafer and a diamond pin is measured under microload conditions, and the effects of surface forces on friction force are investigated experimentally. Furthermore, friction properties on a vibrated surface are examined under low normal load. Time averaged friction coefficient varies drastically by changing frequency or amplitude of applied vibration, which shows the possibility of active control of microscale friction by means of vibration. In case the surface forces cannot be neglected compared to the normal load, peculiar changes in friction depending on sliding velocity and vibration frequency are observed. In order to explain these results, a new meniscus model considering a tangential component of meniscus force is proposed.

Keywords: microtribology, friction, surface force, meniscus force, active control, vibration

1 INTRODUCTION
On sliding surfaces of micromechanical elements, surface forces, such as van der Waals force, electrostatic force, and meniscus force, become dominant compared to normal load. The surface forces have a significant influence on friction force.

In recent years, many studies on surface forces and friction force under low normal load have been carried out actively. Ando et al. [1] made it clear that the surface forces act as an additional normal load, and friction coefficient calculated by dividing the friction force by sum of the normal load and the surface forces remains constant under low load conditions. As for the meniscus force, static and dynamic behavior of nano-meniscus bridge was investigated [2] and it was found that the ratio of elastic force to viscous force varies depending on the modulation frequency.

In this study, friction forces under microload conditions are measured to clarify the effect of surface forces on friction. Furthermore, friction characteristics on a vibrated surface are examined and active control of friction by means of vibration is discussed.

2 EXPERIMENTAL APPARATUS

Figure 1 shows a schematic of the friction tester developed in this study. The friction force between a silicon wafer and a diamond pin is measured. The silicon wafer is set on a x-y elastic stage and driven by two piezoelectric actuators for loading and sliding on the diamond pin. The wafer can be oscillated by another piezoelectric actuator attached just behind the wafer. Vibration in a direction of x, y, or z is generated by setting a PZT oscillator in each direction. The coordinate system is defined as shown in Figure 1. The x axis is parallel to the sliding direction. The y axis is at right angles with the sliding direction in the sliding plane. The z axis is perpendicular to the sliding surface. The friction force and normal load are measured by two sets of double cantilever springs whose deflections are detected by capacitive displacement sensors. The resolutions of friction force and normal load are 0.28 µN and 0.25 µN, respectively. The friction tester is put in a constant humidity cell that enables to set relative humidity at any value from 15% to 90%. Silicon wafers coated with hydrophobic PFPE lubricant, which is widely used for magnetic disks, are also used in order to change the surface energy.

3 EXPERIMENT

3.1 Effect of Adhesion Force

Figure 2 shows the relationship between normal load and friction force when no vibration is applied and relative humidity is 50%. Friction force increases linearly with normal load. However, the line does not intersect the origin of the graph, and friction force is generated even under negative load. This is because an adhesion force between sliding surfaces is acting as an additional normal load. The adhesion force increases with relative humidity due to the adsorbed water on the sliding surfaces [3]. When the relative humidity is 50%, the adhesion force is estimated to be about 15 µN from the intersection between friction curve and x axis shown in figure 2. By coating the silicon surface with hydrophobic PFPE lubricant, both the friction coefficient and the adhesion force are reduced.
3.2 Effect of sliding velocity

When the sliding surface is oscillated, the relative sliding velocity increases with amplitude and frequency of the vibration. In order to examine the effect of relative sliding velocity, friction force without surface oscillation is measured at various sliding velocities.

Figure 5 shows the variation of friction force with the sliding velocity. Friction force increases with sliding velocity below 20 µm/s, while it slightly decreases above 20 µm/s. The sliding velocity characteristics are peculiar under low normal load and can be explained by newly proposed meniscus model shown in figure 6. The meniscus bridge of adsorbed water is deformed laterally with increasing sliding velocity and the direction of meniscus force is inclined. The tangential component of the meniscus force increases the friction force directly, while the normal component and other adhesion forces increase normal load and affects the friction indirectly. The angle of inclination increases with increasing sliding velocity, and has a maximum at 20 µm/s. Thus the friction force increases with the sliding velocity up to 20 µm/s.

3.3 Effect of Vibration

The friction forces between a diamond pin and a silicon wafer which is oscillated in various directions are measured under low normal load. On a oscillated surface, time-averaged “apparent” friction force is reduced. The reduction mechanism is as follows: Vibration parallel to the sliding direction causes the periodical change of the relative sliding direction when the amplitude of the velocity is larger than the sliding speed, and the direction of the friction force is also
reversed periodically. When vibration in \( y \) direction is applied, the direction of relative sliding and friction force change continuously along the sliding path. The change in friction force direction causes the reduction of averaged friction force. In the case of vibration perpendicular to the sliding plane, normal force is fluctuated and sliding surfaces are separated periodically when the inertial force is larger than normal load. This results in the reduction of time-averaged friction force.

Figure 6: Deformation of meniscus bridge by sliding.

Figure 7 shows the experimental results and theoretical predictions when the vibration parallel to the sliding direction is applied. The experimental conditions are shown as Case A in Table 1, in which the adhesion force is relatively small compared to the normal load.

Figure 7: Changes in frictional coefficient by vibration in the direction of sliding.

The friction coefficient \( \mu \) is normalized by \( \mu_0 \), the value when no vibration is applied. The normalized friction coefficient varies over a wide range from 1 to 0 with increasing amplitude and frequency. The results indicate that the friction coefficient can be controlled actively under microload conditions by changing the frequency or amplitude of applied vibration. The experimental results agree well with the theoretical predictions.

Figure 8 shows the variation of friction coefficient with amplitude when vibration in \( z \) direction is applied under conditions of “Case B” shown in Table 1, in which the adhesion force is comparable to the friction force. Pull-off force on the vibrating surface is also shown in figure 8. The results show that the measured friction force decreases with the amplitude above 2 nm, while the calculated one is constant at the amplitude below 5 nm. The pull-off force becomes almost zero at the amplitude of 2 nm, which seems to have significant influence on decrease in friction coefficient.

Figure 8: Relationship between friction force and pull-off force with surface vibration in \( z \) direction.

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Table 1: Experimental conditions

<table>
<thead>
<tr>
<th>Case</th>
<th>Tip radius of diamond pin</th>
<th>Relative humidity</th>
<th>Normal load</th>
<th>Sliding velocity</th>
<th>Frequency of applied vibration</th>
<th>Amplitude of applied vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10 ( \mu ) m</td>
<td>50 %</td>
<td>120 ( \mu ) N</td>
<td>4.12 ( \mu ) m/s</td>
<td>0 - 200 Hz</td>
<td>0.1-0.5 ( \mu ) m</td>
</tr>
<tr>
<td>B</td>
<td>100 ( \mu ) m</td>
<td>50 %</td>
<td>100 ( \mu ) N</td>
<td>10.0 ( \mu ) m/s</td>
<td>0 - 3000 Hz</td>
<td>1 – 5 ( nm )</td>
</tr>
</tbody>
</table>

Figure 9 shows the variations of friction force and pull off force with frequency when in-plane vibrations in directions of \( x \) and \( y \) are applied. The amplitude of the vibration is 2 nm. Frequency characteristics of the friction forces and the pull-off force are similar to one another. At frequencies of 800 Hz and 1400 Hz, the friction forces and the pull-off force are reduced remarkably. If the adhesion forces act in normal direction, the effect of the adhesion forces on friction could be small because friction force is calculated by multiplying adhesion force by friction coefficient. Therefore the results suggest that the tangential component of adhesion force acts directly as an additional friction force. The proposed meniscus model shown in figure 10 gives a consistent explanation of the experimental results. In this model, the meniscus bridge is inclined during sliding, and the meniscus force acts not only as an additional normal load, but also as an...
additional friction force, while other adhesion forces act only as an additional normal load. The pull-off force on a vibrated surface corresponds to the normal component of the adhesion force. Frequency characteristics of tangential and normal meniscus forces are considered to be similar to each other. Moreover, tangential meniscus forces acting during vibrations in x direction and y direction have almost the same effects on friction force because both vibrations are in the sliding plane. Therefore, the friction forces and the pull-off force shown in figure 9 are considered to be reduced at the same frequency.

The experimental results show that the reduction of friction force by means of vibration under low load conditions is caused by two factors: the fluctuation of sliding direction or normal load, and the change in the tangential component of the meniscus force depending on frequency.

4 CONCLUSION

The effects of surface forces on a frictional force were investigated experimentally under low load conditions. Moreover, the friction force on a oscillated surface in various directions was measured and the possibility of friction control by means of vibration was discussed. The results are summarized as follows:

(1) Adhesion forces act as an additional normal load.

(2) Friction coefficient calculated by dividing friction force by sum of normal load and adhesion forces does not change under load conditions.

(3) Friction force increases with sliding velocity below 20 µm/s, and decreases slightly above 20 µm/s.

(4) Friction force and pull-off force on the vibrated surface show similar characteristics of frequency and amplitude.

(5) A new meniscus model considering tangential component of the meniscus force which increases the friction force directly is proposed. This model gives a consistent explanation of all experimental results.

(6) Under microload conditions, vibration of a sliding surface changes not only the time-averaged friction force but also the tangential component of the meniscus force depending on frequency, which can be utilized for active control of friction.

5 REFERENCES

