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Effects of wear on contact area and dynamic sliding velocity

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ABSTRACT

The effects of the contact area and degree of wear on the sliding friction of polytetrafluoroethylene (PTFE) samples were investigated using an inclined glass plane. The sliding velocity and contact area of the samples were evaluated as functions of the sliding length and angle of inclination. The sliding velocity decreased exponentially as the contact area increased due to the wear of the samples, suggesting that wear is significant in non-lubricated sliding friction with PTFE on glass. The sliding velocity increased toward a maximum during the early stages of sliding, and then decreased in the later stages. The increase in the velocity during the early stages of the experiment can be explained by acceleration due to gravity, and the subsequent decrease is attributed to an increase in the contact area and to the build-up of debris particles due to wear caused by frictional heating of the contact area of the sample.

1. Introduction

Friction is one of the most significant physical phenomena observed in daily life, and thus has been studied since ancient times to elucidate the frictional forces acting at the interface between two solids. For the static case, it is well established that the frictional force F is given by $F=\mu N$, where μ is the coefficient of friction, and N is the contact force at the interface. This equation indicates that F is proportional to N and is independent of the apparent contact area. For the dynamic case, however, many aspects of friction are still not well understood; *e.g.*, F with dynamic friction may result from many different factors, including the contact area, sliding velocity, surface roughness, and temperature, and F should be defined differently with static and dynamic friction. Therefore, the dynamic contact between two sliding solids has been widely studied both analytically and experimentally across various disciplines at the nano- and macroscale [1–4]. Nanoscale investigations over the last decade have shown that factors including the contact force [5–10], contact area [11–15], sliding velocity [7,8,10,16–19], surface roughness [11], temperature [20,21], humidity [16,18,22], and wear [6,23] of the interface are important factors for dynamic friction. However, these effects are not well understood to date.

The dynamic frictional forces during the oblique impact of a golf ball were investigated by evaluating the angular velocity of the ball, the contact force, and the contact area between the ball and a target [24]. The effects of the contact area on the angular velocity were evaluated, and the results indicate that the contact area plays an important role in dynamic friction. These results suggest that the dynamic frictional force F is given by $F=\mu N+\mu\eta\, dA/dt$, where dA/dt is the time derivative of the contact area A, and η is a coefficient associated with the contact area.

Here, we investigate the sliding behavior of PTFE samples on an inclined glass plate with a smooth transparent surface. The sliding friction of PTFE has been studied over the past five decades [25–28], and PTFE has one of the lowest coefficients of friction against any solid, and is widely used as a solid lubricant to reduce friction and wear of sliding components such as bearings, gears and slide plates. Here, we measure the sliding velocity of the PTFE samples as a function of time using a video camera. The contact area between the sample and the glass plate was measured to examine the effect of the wear on the contact area and the sliding velocity.

2. Materials and methods

Fig. 1 shows the test samples for this experiment. The contact surfaces between the sample and the glass plate consisted of three spheres of PTFE (Flonchemical, Japan) attached tightly to a steel disk (outer diameter: 90 mm; inner diameter: 20 mm; and thickness: 9 mm). Two different sizes of the spheres were used to vary the contact area; their diameters were 9.52 mm (3/8 in.) for Sample 1 and 19.05 mm (3/4 in.) for Sample 2. Polycarbonate (PC) sockets were used for Sample 1 to hold the spheres tightly and prevent rotation. The mass of both samples was 410 g. The contact surfaces were cleaned with ethanol before each experiment.

Fig. 2 shows the sliding-test and contact-area measurement on a glass plate at an inclined angle of θ. A smooth transparent glass

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plate (size: $0.3 \times 0.9\ m^2$ and thickness: 5 mm) was mounted on a rigid wooden frame to avoid bending and torsion of the plate. Scale marks were glued on the backside of the glass plate to determine the sliding length of the samples. The glass surface was degreased with ethanol; dust and wear particles were removed using a duster made of polyethylene fibers just before each test. The sliding behavior was recorded using a video camera (Handycam HDR-PJ760V, Sony), and the sliding lengths were determined from the still pictures using an image converter (PlayMemories, Sony). The glass plate was inclined at an angle of $10 < \theta < 20°$. The experiment was conducted at room temperature (*i.e.*, 22 °C) and a relative humidity of about 40%. The sliding tests were performed at least three times for each angle using new contact surfaces, and the result with the median velocity of the three was used as representative. The sliding direction of the samples is indicated in Fig. 1. To minimize the influence of wear debris on velocity, the trajectories of the three spheres did not cross each other in a single experiment.

The apparent contact area between the sample and glass plate was measured under static conditions, as shown in Fig. 2. The sample was mounted on an inclined glass plate with a point force. The contact surface was illuminated perpendicularly with diffusion light from the backside of the glass plate by inserting a small glass plate (size: $12 \times 25\ mm^2$ and thickness: 1 mm). The dark spots resulting from diffuse reflection were recorded at 200 × magnification using a digital microscope (MJ-302, Sato Shoji, Japan). The contact area was evaluated from the diameter of the dark spots. Changes in the contact area were examined by increasing the sliding length at intervals of 0.2 or 0.4 m. The roughness of the contact surfaces was also measured at 1250 × magnification using a surface profile microscope (VF-7500, Keyence).

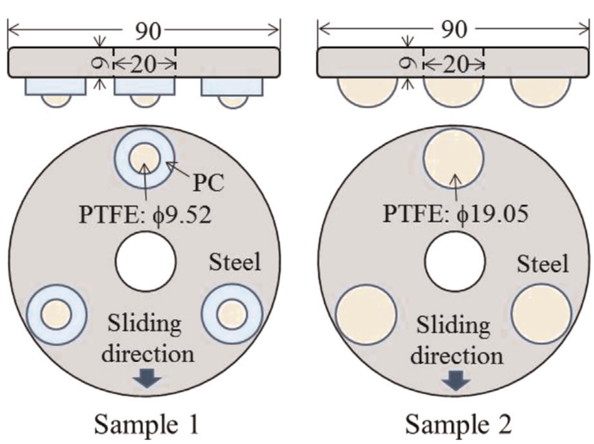

Fig. 1. Test samples for the sliding experiments. Two different sizes of PTFE spheres were used to vary the contact area.

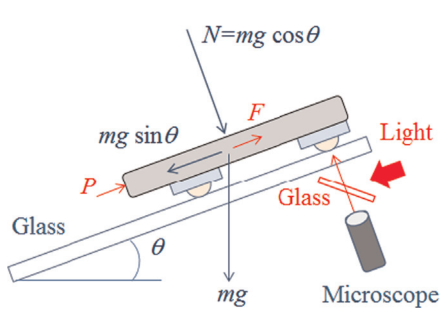

Fig. 2. Sliding tests and contact area measurement at an inclined angle θ.

3. Results and discussion

Fig. 3 shows the sliding length L as a function of time t at an inclined angle $\theta = 15°$. The sliding length L for the two samples increased with time t, and their slopes were larger during the initial stages of sliding and decreased in the later stages. The slope for Sample 2 was smaller than that for Sample 1 for a given t. The L–t curves determined experimentally were quite different from the theoretical ones given by $F = \mu N$, because L is proportional to the square of time, *i.e.*, $L = 1/2(g\sin\theta - \mu N/m)t^2$, where m is the mass of the sample, and g is the gravitational acceleration. This suggests that frictional force is not constant during sliding, and can be related to several factors, including the contact area and sliding velocity.

To minimize data scatter in the evaluation of the sliding velocity, a data-fitting procedure was used based on a least-squares method using the software package Mathematica (Wolfram Research). Measured values of L were expressed as a seventh-order polynomial of t to fit the observed values (see Fig. 3). The sliding velocity v was determined from the first time derivative of the fitted curve $L(t)$ [24].

Fig. 4 shows v as a function of L at $\theta = 15°$; v for the two samples increased in the early stages of sliding and then decreased in the later stages. The maximum values of v were approximately 0.21 m/s for Sample 1 and 0.07 m/s for Sample 2. The value of v for Sample 2 was smaller than that for Sample 1 for a given L. This suggests that the contact area is an important factor in understanding the sliding velocity. Fig. 4 also suggests that there is some similarity between the dynamic sliding friction and Stokes' law, which describes the falling velocity of a small particle in a viscous fluid [29]. The velocity of the sample increased because of acceleration due to gravity during the early stages of sliding, and then approached a constant value because of the frictional force acting on the contact area; this is similar to the behavior with viscous drag acting on a falling particle. However, deceleration behavior occurred in the later stages, which is attributed to the following

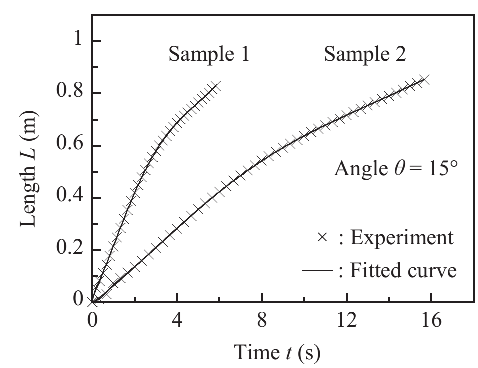

Fig. 3. The sliding length L as a function of time t at an inclined angle $\theta = 15°$.

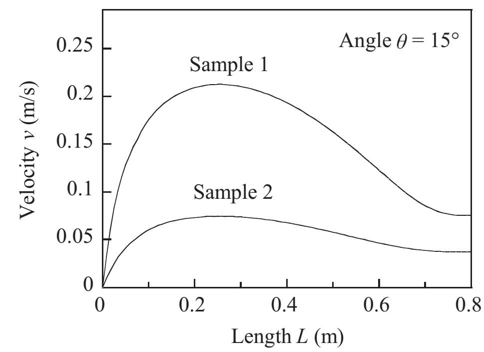

Fig. 4. The sliding velocity v as a function of L at an inclined angle $\theta = 15°$.