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Short Communication

Dynamic sliding friction and similarity with Stokes' law

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ABSTRACT

This study investigated the dynamic sliding friction of polyurethane (PU) rubber samples on an inclined smooth transparent polymethylmethacrylate (PMMA) surface with a thin layer of silicone oil. The sliding velocity increased during the initial stages of sliding and approached a constant value toward the latter stages. To describe the changes in velocity observed, the present study developed an analytical model based on Couette flow with no pressure gradient and indicated that the model could predict important changes in velocity. These findings suggest that dynamic friction force is dependent on both the sliding velocity and the contact area, and that the behavior is similar to that given by Stokes' law, which describes the falling velocity of a particle in a viscous fluid.

1. Introduction

Frictional forces acting at the interface between two solids have been studied for centuries. With static friction, the product of the coefficient of friction and the contact force at the interface determines the frictional force. Dynamic friction, however, is less well understood. Dynamic contact at the interface between two sliding solids has been widely studied, both analytically and experimentally, and features in various disciplines from the nanoscale to the macroscale [1–4]. 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 have been examined to elucidate the frictional forces at the interface. Although these factors are clearly important, the mechanisms for these effects are not well understood.

We have previously reported an investigation of dynamic friction during the oblique impact of a golf ball by evaluating the angular velocity of the ball, together with the contact force and contact area between the ball and the target [24]. The effects of the contact area on the angular velocity were investigated, and the results indicate that the contact area is significant in dynamic friction. We also studied sliding friction of polytetrafluoroethylene (PTFE) samples on an inclined glass plate with a smooth transparent surface [25]. The sliding velocity and contact area of the samples were evaluated as functions of the sliding length and inclined angle to determine the relationships between the contact area and the sliding velocity. The velocity decreased exponentially as a function of increasing contact area, which suggests that the contact area is important in sliding friction.

The present study investigated the sliding friction of PU rubber samples on an inclined smooth transparent PMMA surface with a thin layer of silicone oil. The oil layer was applied to avoid an increase in the contact area during the sliding process due to wear; an increase in the contact area complicates the sliding acceleration and deceleration in a single sliding process [25]. To simplify the sliding behavior, the sliding velocity and contact area of the PU samples were measured on an oiled PMMA surface and characterized as a function of the angle of inclination. The relationships between these factors were identified to investigate the effect of contact area on sliding velocity. In addition, the present study proposed an analytical model to describe these observations, which is based on Couette flow [26] with no pressure gradient.

2. Materials and methods

Fig. 1(a) shows the two test samples used in the experiments. Three PU rubber specimens with a smooth convex surface (Iteck Co., Japan) were attached tightly to a steel disk (with an outer diameter of 90 mm, an inner diameter of 20 mm and a thickness of 9 mm). Two PU specimens with different convex surfaces were used to vary the contact area: Sample 1 was 8 mm in diameter and 2.5 mm thick at the center, and Sample 2 was 9 mm in diameter and 3.5 mm thick at the center. The mass of both samples was 425 g. The contact surfaces were wiped with cotton swabs to remove dust prior to each experiment.

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Nomenclature

A	the contact area
a_c	the diameter of the contact area
c	$c=\gamma A^2$
F	the frictional force
F_d	the dynamic frictional force
g	the acceleration due to gravity
h	the thickness of oil layer
k	$k=mg(\sin\theta-\sin\theta_c)$
L	the sliding length
m	the mass of sliding sample
N	the contact force
P	the point force
t	time
v	the sliding velocity
v^*	the average sliding velocity

Greek symbols

γ	$\gamma=\eta/hA$
η	the viscosity of oil layer
θ	the angle of inclination
θ_c	the critical angle between dynamic and static friction
μ	the coefficient of sliding friction
τ	the shear stress

Fig. 1(b) shows the sliding test and the contact area measurement at an angle of inclination of θ. A smooth transparent PMMA plate that was 5 mm thick and $0.5\times1\ m^2$ was mounted on a rigid wooden frame to avoid bending and torsion of the plate. To determine the sliding distance, scale marks were glued to the reverse side of the plate; the center of the sample was marked as shown in Fig. 1(c). The PMMA surface was sprayed with silicone oil, and wiped with tissue paper to leave a thin layer of oil. A non-solvent-type silicone oil spray (Prostaff Co., Japan) was used, to avoid chemical damage to the PMMA and PU rubber samples. The sliding behavior was recorded using a video camera (Handycam HDR-PJ 760V, Sony Corp.), and the sliding distances were determined from still images using an image converter (PlayMemories, Sony Corp.). The PMMA plate was inclined at angles in the range $20<\theta<45°$. The experiment was conducted at room temperature (i.e., 22 °C) and the relative humidity was about 40%. The sliding tests were performed at least three times for each angle, 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(a). To minimize the influence of the surface change on velocity, the trajectories of the three rubbers did not cross each other in a single experiment.

The contact area was measured under static conditions, as shown in Fig. 1(b). The sample was mounted on an inclined PMMA plate with a point force. The contact surface was illuminated using diffused light from the reverse side of the PMMA plate by inserting a small 1-mm-thick glass plate that was $12\times25\ mm^2$. We recorded a dark spot due to diffuse reflection at a magnification

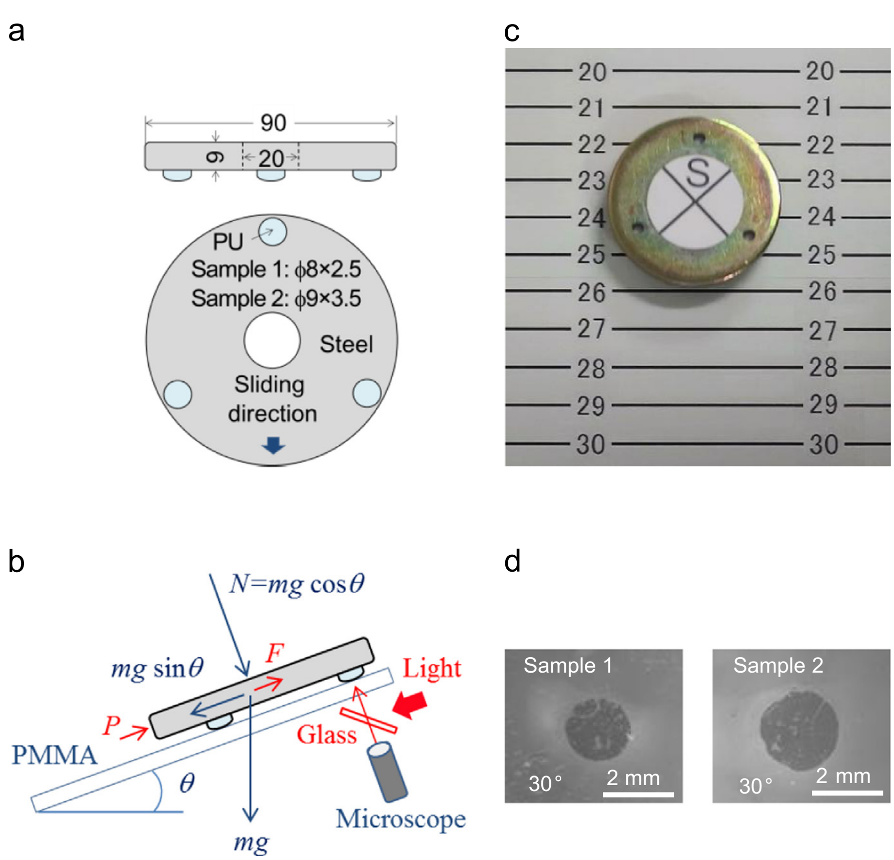

Fig. 1. (a) The two PU samples used in the experiments. The mass of both samples was 425 g. (b) Sliding tests and contact area measurements at an angle of inclination of θ. (c) Measurement method of sliding distance. (d) Measurement method of contact area.