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An analytical model for dynamic sliding friction of polytetrafluorethylene (PTFE) on dry glass inclines

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ABSTRACT

An analytical model was developed for the dynamic sliding friction of polytetrafluoroethylene (PTFE) samples on a dry glass surface as a function of the angle of inclination. The analytical expression was derived as a function of the contact area and the built-up film of debris particles caused by wear, and was compared with the velocities experimentally determined from the samples as a function of the sliding length. The velocity greatly increased in the initial stages of sliding, reached a maximum value in the middle stages, and then significantly decreased in the later stages. The model predicted all of the important qualitative features of the velocity change and suggested that the increase in the velocity in the initial stages of sliding can be explained by acceleration due to gravity, whereas the decrease in the middle and late stages was attributed to increasing contact area and the build-up of debris particles.

1. Introduction

Sliding friction acting at the interface between two solids has been studied for centuries. It is well established that the static frictional force is given by the product of the coefficient of friction and the contact force at the interface. The following fundamental laws have been established. First, frictional force is independent of the apparent area of the contact surfaces; second, the frictional force is proportional to the normal force acting at the interface; and third, the frictional force is independent of the sliding velocity of the contact surfaces. These laws are appropriate under some conditions, but are not valid in other cases, especially in dynamic situations. To understand the physical meaning, the contact between two sliding solids has been widely studied both analytically and experimentally, from the nano- 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 underlying these effects are not well understood.

Our previous studies [24–26] investigated the effect of contact area on dynamic friction under different conditions and revealed the following. First, regarding the oblique impact of a golf ball, the time derivative of the contact area can play a significant role in understanding the spin generation of the ball [24]; second, regarding the sliding friction of polytetrafluoroethylene (PTFE) spheres on an inclined, dry glass surface, the sliding velocity decreased exponentially as the contact area increased due to sample wear [25]; and third, regarding the sliding friction of polyurethane (PU) rubber samples on an inclined, oiled polymethylmethacrylate surface, the contact area was an important factor in the sliding friction on the oiled surface [26].

Comparison of experimental results with analytical models has suggested that the contact area and the sliding velocity are important to understanding the dynamics of lubricated sliding friction. This study proposed an analytical model for the dynamic sliding friction of PTFE samples on an inclined, smooth, dry glass surface (Fig. 1(a)). The analytical expression for the sliding velocity was derived as a function of the contact area and the built-up film of debris particles caused by wear of the sample (Fig. 1(b)). To understand the observed changes of the velocities, the analytical expression was compared with the velocities determined from two samples having different contact areas.

2. Model analysis

As a basic equation for dynamic sliding friction, we employed an analytical model proposed in a previous study to describe the sliding behavior of PU rubber samples on an inclined, oiled surface [26]. In the analysis, the following assumptions were made: First, the dynamic frictional force is given by $F_d = \tau A$, where τ is the shear

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Nomenclature

A	the contact area
a_c	the diameter of contact area
c_t	$c_t = \gamma A^2$
F	the frictional force
F_d	the dynamic frictional force
g	the acceleration due to gravity
h	the thickness of film
k	$k = mg(\sin\theta - \sin\theta_c)$
k'	$k' = mg(\sin\theta_c - \sin\theta_c')$
L	the sliding length
m	the mass of sliding sample
t	time
v	the sliding velocity

Greek symbols

γ	$\gamma = \eta/hA$
η	the viscosity of film
θ	the angle of inclination
θ_c	the breakaway angle for samples having fresh surfaces
θ_c'	the critical angle between dynamic and static friction for samples having worn surfaces
τ	the shear stress

stress acting on the contact area A between the rubber and oil layers. Second, Couette flow [27] with no pressure gradient is appropriate for the shear stress $\tau = \eta v/h$, where η and h are the viscosity and the thickness of the oil layer, respectively. Thus, the dynamic frictional force can be represented by Eq. (1):

$$F_d = c_t v = \gamma A^2 v, \tag{1}$$

where $c_t = \gamma A^2$ and $\gamma = \eta/hA$, which is a parameter related to the ratio between the viscosity and the volume of the oil layer. This parameter is important in understanding the dynamics of lubricated sliding friction. The units of c_t are Pa s m and those of γ are Pa s m^{-3}.

The PU rubber samples on an inclined, oiled surface indicated that the sliding velocity increased in the initial stages of sliding, and approached a constant value in the later stages, because the contact area during the sliding process was constant [26]. The PTFE samples on an inclined, dry surface, however, indicated that the sliding velocity increased in the initial stages of sliding, reached a maximum value in the middle stages, and then decreased in the later stages, probably because of the increased contact area and the build-up debris particles at the interface [25].

The present analysis also used Eq. (1) to describe the dynamics of the sliding friction of PTFE samples on a dry glass surface, and assumed that γ was associated with the viscosity and the volume of the built-up film composed of wear particles on the contact area (Fig. 1(b)). The sliding motion of the sample is given by $mdv/dt = -(F_d - k)$, where m is the mass of the sample, $k = mg(\sin\theta - \sin\theta_c)$, g is the gravitational acceleration, and θ_c is the breakaway angle for samples having fresh surfaces. When c_t in Eq. (1) changes with time t, the sliding motion is expressed as Eq. (2):

$$\frac{d(c_t v)}{dt} = -\frac{c_t}{m}(c_t v - k) + v\frac{dc_t}{dt}. \tag{2}$$

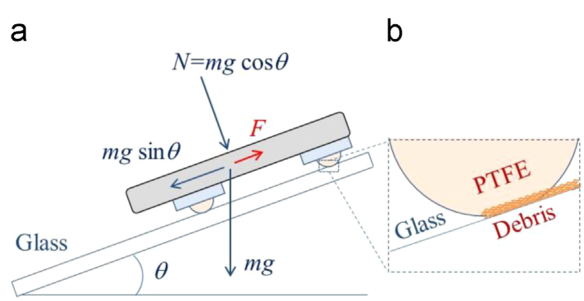

Fig. 1. (a) Polytetrafluoroethylene (PTFE) samples on a dry glass surface with an angle of inclination of θ. The three PTFE spheres were tightly attached to a steel disk. Two samples having different sizes of the spheres were used to vary the contact area. The mass of both samples was 410 g. (b) Built-up film of wear debris at the interface between the PTFE and glass surfaces during sliding.

This analysis assumed that $vdc_t/dt \approx c_t k'/m$, where $k' = mg(\sin\theta_c - \sin\theta_c)'$ and θ_c' is the critical angle between the dynamic and static friction for samples having worn surfaces after sliding. The value of k in Eq. (2) is associated with the driving force of the sample in the initial stages of sliding. Thus, the value of k' can be related to the variation of the driving force due to the increased contact area and the built-up debris particles at the interface after sliding.

Using $c_t V = c_t v - (k + k')$, Eq. (2) can be rewritten as Eq. (3):

$$\frac{d(c_t V)}{dt} \approx -\frac{c_t}{m}(c_t V). \tag{3}$$

Using separation of valuables and integrating Eq. (3) with respect to t, we obtain Eq. (4):

$$\log(c_t V) \approx -\frac{1}{m}\int c_t dt. \tag{4}$$

For a given angle, it is assumed that c_t follows Eq. (5):

$$c_t = \gamma A^2 = c_0 + c_s(t/t_0)^n, \tag{5}$$

where c_o, c_s, and n are constant values and t_o is unit time introduced for dimensionless time t/t_o. Substituting Eq. (5) into Eq. (4) and integrating with respect to t for $v = 0$ at $t = 0$, the sliding velocity is given by Eq. (6):

$$v \approx \frac{(k + k')}{c_t}\{1 - \exp(-pt)\cdot\exp(-qt^{n+1})\}, \tag{6}$$

where $p = c_o/m$ and $q = c_s/m(n+1)t_o^n$. Eq. (6) indicates that v decreases with increasing c_t for a given t.

3. Experimental procedures

The experimental procedures are described elsewhere [25]. Briefly, 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; 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. A smooth transparent glass plate (size: 0.3×0.9 m^2; 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