Wear 376-377 (2017) 766–770

Contents lists available at ScienceDirect

Wear

journal homepage: www.elsevier.com/locate/wear

Dynamic sliding friction of pencil leads on dry and oiled glass inclines

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ARTICLE INFO

Article history:
Received 19 September 2016
Received in revised form
10 January 2017
Accepted 12 January 2017

Keywords:
Analytical model
Dry and oiled surfaces
Dynamic sliding friction
Effect of mass
Pencil leads
Sliding velocity
Wear particles

ABSTRACT

The present work studied the dynamic sliding friction of pencil lead samples on inclined dry and oiled smooth glass plates. Four types of samples with different masses and lead hardnesses (4B and 4H) but identical diameters were used to vary the contact surface conditions. The results showed that the sliding velocity for a given angle increased as the mass of the sample increased; the velocity also increased as the hardness increased from 4B to 4H. To interpret the velocity change, the present study used an analytical model, which suggested that wear particles play a significant role in the dynamic friction on both dry and oiled surfaces.

1. Introduction

Sliding friction is an important factor in various disciplines, and many studies have examined the forces that develop at the interface between two solids. The following three empirical laws have been established as elementary properties of sliding friction: the frictional force is directly proportional to the contact load; the force is independent of the apparent contact area; and the dynamic friction is independent of the sliding velocity. These laws are valid under static situations, but are inappropriate under dynamic conditions. Therefore, the dynamic contact problem has been widely studied from analytical and experimental perspectives at nanoscale to macroscale levels [1–4]. Over the last decade or so, nanoscale studies have shown that several factors have significant effects on dynamic friction, 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 interface wear [6,23]. However, these effects are still not entirely understood.

Our previous studies [24–27] of dynamic friction yielded several findings. First, the angular velocity of a golf ball during oblique impact depends on the time derivative of the contact area [24]. Second, the contact area of polyurethane (PU) rubber samples has a significant effect on the sliding velocity on oiled inclines [25]. Third, the sliding velocity of polytetrafluoroethylene (PTFE) samples on dry inclines decreases as the contact area increases due to wear [26]. Comparison with analytical models suggested that contact area and sliding velocity are key factors in lubricated sliding friction [25], while the wear of the contact surface also plays a significant role in non-lubricated sliding friction [27].

The present work studied the dynamic sliding friction of pencil lead samples on inclined smooth dry and oiled glass plates. Blau and Gardner [28] conducted sliding tests of pencil lead samples on paper and suggested that the static and kinetic friction coefficients for pencil lead depend on the lead hardness. The present work examined four types of samples with different masses and lead hardnesses, but identical diameters, to vary the contact surface conditions. The sliding velocities were determined as a function of the incline angle, and the effects of mass and hardness were examined as a function of change in velocity. Pencil lead samples were used to avoid changes in contact area because of wear. Therefore, sliding velocities were measured under a constant contact area condition and were characterized as a function of the sliding distance of the samples. These factors were assessed to establish the effects of mass and hardness on velocity. This work also applied the analytical model proposed in our previous work [25,27] to interpret the changes in velocity.

2. Experimental and analytical procedures

2.1. Materials and methods

Fig. 1(a) illustrates the four test samples. Mechanical pencil leads were used as the contact surfaces of the samples by tightly

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http://dx.doi.org/10.1016/j.wear.2017.01.046
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Nomenclature

A	the 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 critical angle between dynamic and static friction for samples having clean surfaces
θ_c'	the critical angle between dynamic and static friction for samples having worn surfaces after sliding
τ	the shear stress

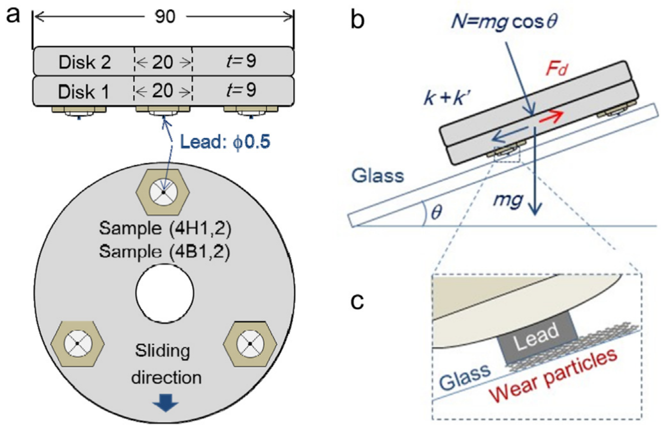

Fig. 1. (a) The four test samples. Mechanical pencil leads were used as the contact surfaces by tightly attaching them to one or two steel disks. The masses of the samples with one and two disks were 465 and 830 g, respectively. Two types of leads with different hardnesses (4B and 4H) but identical diameters (0.5 mm) were used to vary the contact surface condition. (b) Sliding test on dry and oiled surfaces at an inclined angle θ. A smooth transparent glass plate was mounted on a rigid wooden frame to avoid bending and torsion of the plate. The glass plate was inclined at an angle $6<\theta<12°$. (c) Lead tip of the sample and the built-up film of debris particles caused by wear during the sliding process on a dry surface.

attaching them to one or two steel disks (outer diameter: 90 mm; inner diameter: 20 mm; thickness: 9 mm). The masses of the samples with one and two disks were 465 and 830 g, respectively. Two types of leads with different hardnesses (4B and 4H) but identical diameters (0.5 mm) were used to vary the contact surface condition; the leads were 4B for Sample 4B and 4H for Sample 4H. Different from standard pencil leads, the mechanical pencil leads were mainly composed of nanoparticles of graphite and uniformly-dispersed nanodiamonds to reduce the internal friction of the particles (Uni Nano Dia; Mitsubishi Pencil Co., Japan). The diameters of the nanoparticle graphite and diamonds were smaller than 100 and 50 nm, respectively [29].

Fig. 1(b) illustrates the sliding test on a smooth glass plate (size: 0.3×0.9 m^2; thickness: 5 mm). Roughness was measured on the glass surface. A profile measurement microscope (VF-7500; Keyence Corp., Osaka, Japan) was used to determine surface roughness at ×2,500 magnification with a measuring pitch of 0.01 μm and a measuring range of 5 μm in the z direction. The average roughness (Ra) of the glass surface was about 0.04 μm. Sliding tests were performed on two different surface conditions: first, the glass surface was degreased with ethanol and dust was removed using a duster made of polyethylene fibers immediately before every test. The lead tips of the samples were also cleaned with a mini vacuum cleaner before each experiment. Second, the glass surface was sprayed with silicone oil and wiped with tissue paper to leave a thin layer of oil. Sliding tests were performed after 12 hours later to minimize the time change of micro air bubbles trapped in the oil layer [25]. The glass plate was inclined at an angle $6<\theta<12°$ to study the sliding velocities of the samples in a single sliding process.

A video camera (Handycam HDR-PJ 760 V; Sony Corp., Japan) and an image converter (PlayMemories; Sony Corp.) were used to record the sliding behaviors of the samples and to make the still pictures of the sliding process, respectively [25]. The sliding tests were performed at room temperature (22 °C) under ambient relative humidity (48%). The tests were conducted at least three times for each angle and the median velocity of the three tests was taken to be representative. The sliding direction of the samples is indicated in Fig. 1(a). To minimize the influence of wear debris on velocity, the trajectories of the three leads did not cross each other in a single experiment. Fig. 1(c) illustrates the lead tip of the sample and the built-up film of debris particles on a dry surface.

2.2. Analytical model

Detailed analyses of the proposed model for dynamic friction have been described previously [25,27]. Briefly, the lubricated friction model assumes that the contact area A is constant during sliding on an oiled layer with thickness h and viscosity η, and the dynamic frictional force is given by $F_d=\tau A$, where τ is the shear stress at the interface. Expressing $\tau=\eta v/h$ with the Couette flow shear stress [30], the dynamic friction can be expressed as follows:

$$F_d = c_t v = \gamma A^2 v, \qquad (1)$$

where $c_t=\gamma A^2$ and $\gamma=\eta/hA$. The units of c_t are Pa s m and those of γ are Pa s m^{-3}.

Eq. (1) can also be used for non-lubricated friction, assuming that η and h are related to the viscosity and thickness of the built-up film [27], as illustrated in Fig. 1(c). The model also assumes that the critical angle between dynamic and static friction depends on the value of c_t; consequently, the driving force of the sample is a function of c_t.

The sliding motion of the sample is expressed as $m\, dv/dt = -(F_d - k)$, 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 critical angle for samples with clean surfaces. When c_t in Eq. (1) changes with time t, the sliding motion is given by:

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

It is assumed that $v dc_t/dt \sim c_t k'/m$, where $k'=mg\,(\sin\theta_c-\sin\theta_c')$ and θ_c' is the critical angle for samples having worn surfaces after sliding. The value of k in Eq. (2) is related to the driving force of the sample in the initial stages of sliding. Thus, the value of k' can be