

Mechanisms of static and kinetic friction of polypropylene, polyethylene terephthalate, and high-density polyethylene pairs during sliding

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ABSTRACT

Polymeric materials are widely used in household applications. During use, sliding surfaces are worn out and the interfacial properties change affecting friction. Consequently, understanding of friction mechanisms of polymeric materials with changing interfacial properties is important. In this study, the effect of various speed, load, and dwell time conditions on friction of polypropylene (PP), polyethylene terephthalate (PET), and high-density polyethylene (HDPE) pairs is studied. Roughness, debris formation, and mechanical properties are measured to understand friction behavior. Static and kinetic friction exhibits dependence on surface roughness which affects mechanical interaction of asperities and real contact area. Static friction increases with dwell time due to creep.

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1. Introduction

Polymeric materials are widely used in household applications including toothbrushes, shower doors, shopping bags, clothes buttons, toys, serving bowls, ski boots, mobile phones, and plastic bottles. It is hard to imagine daily life without use of products fabricated from polymeric materials. These products should be designed considering comfort as well as performance. If the products include sliding interfaces, friction becomes an important factor in comfort design. Consequently, understanding of friction mechanisms of polymeric materials is important.

Friction is governed by the surface interaction in moving contact. Based on classical theory of adhesion, friction force F is given as [1,2]

$$F = A_r \tau \quad (1)$$

and friction coefficient μ is given as

$$\mu = F/W \quad (2a)$$

$$= A_r \tau / W \quad (2b)$$

where A_r , τ , and W are the real contact area (sum of area of contact asperities), the effective shear strength of contacts, and applied normal load, respectively. Macroscale contact is composed of surface asperity contacts on micro/nanoscale. The real contact area is

inversely related to mechanical properties and surface roughness. In order to understand interfacial contact, mechanical properties of contact surfaces and surface roughness on micro/nanoscale should be measured.

Interfacial properties which affect friction can vary during sliding dependent upon contact conditions. Typically, a change in surface roughness, formation of tribo-film, and wear debris are ascribed to the change in interfacial properties [3,4]. In polymeric materials, creep is prominent. Therefore, friction can be affected also by the time of stationary contact, called dwell time, due to an increase in real contact area [5]. Hence, contact conditions such as sliding speed and dwell time as well as applied normal load are important. Numerous experiments of friction of polymeric materials have been carried out for several decades under various contact conditions [3,4,6–11]. For example, Shooter and Tabor reported friction of polytetrafluoroethylene, polymethyl methacrylate, polyvinylchloride, polyethylene, and nylon sliding at the load range from 10 to 100 N changes with sliding distance [12]. Friction can also depend on applied load and speed [1,2,4,8,10]. Because of the effect of temperature-dependent mobility of polymer segments, significant speed effects can be observed near the glass transition temperature. When measuring friction under lower temperatures than the glass transition temperature, the speed effects are less pronounced [7,13]. An increase in dwell time can increase static friction as a result of an increase in real contact area by contact creep [4,5]. An increase in friction with dwell time has been reported by many researchers [4,5,14–16].

In the literature reviewed above, researchers have studied the effect on friction of load, or speed, or dwell time individually.

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However, in real systems, such as the household applications listed above, every use affects interfacial properties, resulting in changes in friction over time. Bowl/cover, buckles of ski boots, and bottle/cap pairs may be used after they are stored under various storage conditions. These examples indicate that even the same products can exhibit different frictional behavior dependent upon contact history. Consequently, contact history should be considered as a design factor in household applications. Therefore, it is important to study simulated real system conditions in order to understand the compounded effects of changes in interfacial properties, such as change in surface roughness, creep, wear debris formation, which occur simultaneously during sliding.

In the present study, polypropylene (PP), polyethylene terephthalate (PET), and high-density polyethylene (HDPE) samples were prepared because they are commonly used polymeric materials. Also, various contact conditions including load, speed, and dwell time were applied before measuring friction in order to simulate the contact history of household applications. Static and kinetic friction of sliding pairs of PP on PET, PP on HDPE, and PP on PP were measured using a macroscale tribometer. The nanoindentation technique was employed to measure hardness and elastic modulus in order to elucidate frictional behavior [17]. The wear mechanism was investigated by observing worn surfaces with an optical microscope and measurement of the change in surface roughness. Creep tests were carried out both on macro/nanoscale using a macroscale tribometer and nanoindentation in order to understand the dwell time effect on static friction. Speed and load effects are elucidated based on wear mechanisms. The relationship between the dwell time effect on static friction and the results of macro/nanocrep tests is demonstrated.

2. Experimental details

2.1. Samples

PP was injection molded in molten state about 350–400 °C. PET, clear plastic was injection stretch blow molded (ISBM) in rubbery state about 150–170 °C. PET is biaxially oriented responsible for high strength. HDPE was extrusion blow molded (EBM) in near molten state. Root mean square (RMS) roughness and size of samples are tabulated in Table 1.

2.2. Friction measurement

CETR-UMT-2 (Bruker), shown in Fig. 1(a), was used to measure static and kinetic friction. It provides a range of speeds from 0 to 3000 rpm and loads from 0 to 20 N. Temperature and humidity can be controlled. A force sensor, which senses both normal and friction forces, provides feedback to a vertical carriage controller that controls vertical position to provide a constant load during the experiment. It mounts directly to the vertical and lateral carriage. The position of the vertical and lateral carriage (y- and z-position) can be adjusted during the experiment by PC-based motor-control. In the case of the y-position, manual adjustment is feasible, setting the sliding radius at

Table 1
RMS roughness and size of samples.

	Roughness (μm)	Thickness (mm)	Diameter (mm)
PP (stationary upper cylinder)	0.08	6.35	19.05
PET (rotating lower disk)	0.08	0.55	76.2
PP (rotating lower disk)	0.10	3.18	76.2
HDPE (rotating lower disk)	3.10	0.10	76.2

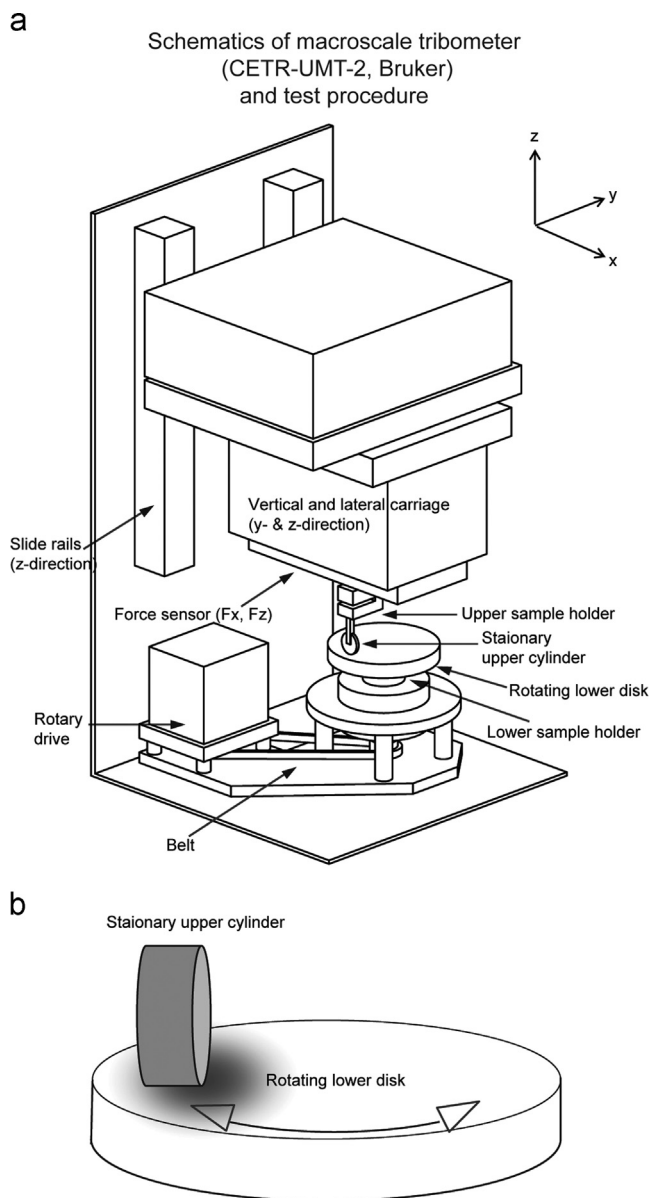


Fig. 1. Schematics of (a) macroscale tribometer (CETR-UMT-2, Bruker), (b) and test procedure. The stationary upper cylinder slides on the rotating lower disk for 3 cycles (step 1), sits during dwell time (step 2), and then friction is measured (step 3).

which the stationary upper cylinder contacts the rotating lower disk. Both upper and lower samples were fixed by clamping, using screws and pads to the upper and lower sample holder, respectively. The upper sample holder included a suspension allowing the stationary upper cylinder to follow the z-direction variations of the rotating lower disk during experiment. The rotary drive provides rotating motion for the lower disk [18].

The cylinder-on-disk configuration was chosen as shown in Fig. 1(b) because cylinder and disk are convenient shapes to fabricate from polymeric materials. Friction of PP upper cylinder on PET lower disk, PP upper cylinder on HDPE lower disk, and PP upper cylinder on PP lower disk were measured. In order to clamp PET and HDPE on sample holder, they were affixed on to steel disk by using cyanoacrylate adhesive (Scotch-Weld Instant Adhesive CA50 Gel, 3M).

The experimental procedure consists of three steps, shown in Fig. 1(b). In step 1, the disk sample was rotated for 3 cycles at various operating conditions. In step 2, sliding motion was stopped

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