



Nanofriction and nanowear of polypropylene, polyethylene terephthalate, and high-density polyethylene during sliding



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ABSTRACT

Friction and wear studies on the nanoscale are of interest to develop a fundamental understanding of the operative mechanisms and to establish the relationship between nanoscale and macroscale sliding phenomena. Herein, nanofriction of polypropylene, polyethylene terephthalate, and high-density polyethylene was measured with atomic force microscopy and then compared with their macrofrictional behavior using a cylinder-on-disk arrangement at one load and speed. A probe-based scanning nanoindenter was used to investigate wear mechanisms, and nanohardness was measured using a depth-sensing nanoindenter. Results showed that friction at the nanoscale was nanohardness-dependent. In contrast, macrofriction was dependent instead on surface roughness. The three polymers exhibited lower values of nanofriction than macrofriction, possibly because of less plowing. The polymer with higher nanohardness also showed higher wear resistance.

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1. Introduction

A polymer is a macromolecule composed of smaller subunits of monomers. From the manufacturing perspective, products made from polymers can be molded, pressed and cast, so that it is feasible to produce various designed shapes with lower cost compared to metals or ceramics [1–4]. Also, the light weight of products made from polymers allows reduction in transportation costs. Because of these advantages, it is easy to find applications using polymers in daily life. For example, they are used in bottles, contact lenses, intraocular lenses, fabrics, artificial joints, mobile phones, serving bowls, toys, nanolubricants, insulators, and functional coatings with flexibility, hydrophobicity, and/or transparency [2,5–8]. Among polymers, polypropylene (PP), polyethylene terephthalate (PET), and high-density polyethylene (HDPE) are commonly used polymers. Polymers are used on nanoscale as well as macroscale. Friction and wear emerge as a crucial factor for designing products made from polymers when their applications include sliding surfaces. For example, the friction of PP textiles should be designed considering the human tactile sense. Controlling friction also is important for the roll-to-roll process, which is the process of creating electronic devices on a roll of flexible polymer foil. The roll-to-roll process is a widely used method for fabricating transparent and flexible PET substrates for electronic

devices. Wear also affects the optical performance of transparent films and the life of artificial joints made of HDPE. Therefore, their friction and wear from macro to nanoscale should be studied.

Friction occurs because of surface interactions during moving contact. The dominant friction mechanisms include adhesion and deformation. Based on classical theory of adhesion, friction force F is a product of the real contact area and the effective shear strength of contacts, which is given as [9–11]:

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

and friction coefficient μ is given as

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

$$\mu = A_r \tau / W \quad (3)$$

where A_r is the real contact area, τ is the effective shear strength of contacts, and W normal load. The real contact area is inversely proportional to the mechanical properties and surface roughness. In order to understand friction, measurements of mechanical properties of contacting surfaces and surface roughness on the micro/nanoscale should be performed. In addition, if one surface is rougher or harder than the other surface, the contribution of plowing to friction may also be important [11]. The surface asperities on the harder material plow grooves in the softer material via plastic deformation. The dimensions of plowed grooves are orders of magnitude larger than those of the asperities on either sliding surfaces.

The study of friction and wear behavior on the nanoscale can be used to understand friction and wear on the macroscale because

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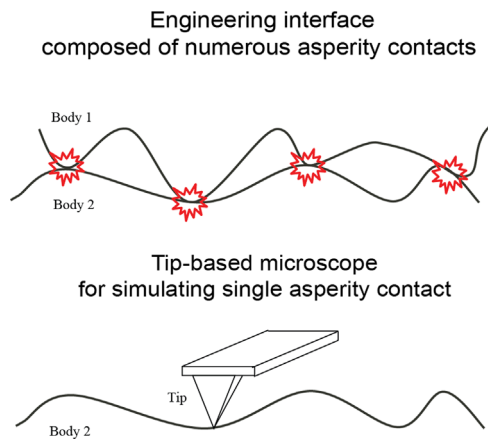


Fig. 1. Macroscale contact composed of numerous asperities, and single-asperity contact made by tip-based microscope. The tip-based microscope allows simulation of a single asperity contact.

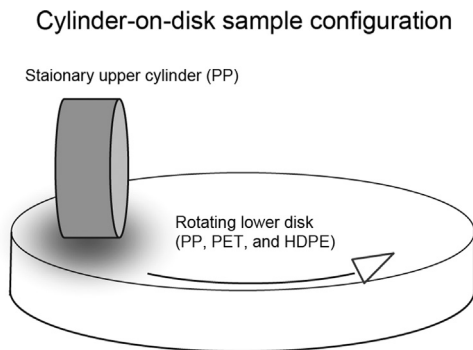


Fig. 2. Schematic of a cylinder-on-disk configuration. PP was used as a stationary upper cylinder. PP, PET, and HDPE were used as rotating lower disks.

macroscale contact is composed of asperity contacts on both the microscale and the nanoscale [12,13]. During sliding, friction and wear are affected by interaction with all asperity contacts, which makes the understanding of friction mechanisms difficult. It is desirable to study a single asperity contact to develop a fundamental understanding of friction mechanisms. Tip-based microscopy allows simulation of single-asperity contact, as shown in Fig. 1 [11,13]. For studying friction on the micro/nanoscale, an atomic force microscope (AFM) can be employed [13]. Wear resistance on the nanoscale can be evaluated using a probe-based scanning nanoindenter [14]. As mentioned above, evaluation of wear resistance is important for the durability desired in industrial products.

In the present study, nanofriction tests for PP, PET, and HDPE samples were performed. By comparing their frictional properties, surface roughness, and nanomechanical properties, the major contributor for nanofriction is studied. Macrofriction measurements were made using a macroscale tribometer, and the results were then compared to nanofriction results. Nanowear tests were performed to evaluate wear resistance. Various loads and sliding cycles were used to observe gradual changes in surface roughness profiles of worn surfaces. Based on changes in surface roughness profiles, wear mechanism is discussed.

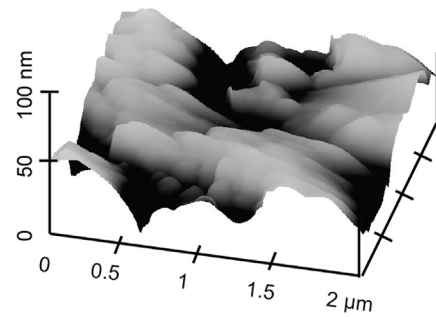
2. Experimental details

2.1. Samples

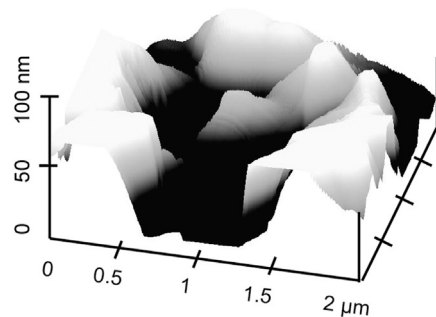
The samples were fabricated as follows. The PP sample was fabricated by injection molding, the PET sample by injection

Surface Roughness Profiles

PP (RMS = 55.8 nm, P-V = 294 nm)



PET (RMS = 85.1 nm, P-V = 705 nm)



HDPE (RMS = 12.5 nm, P-V = 161 nm)

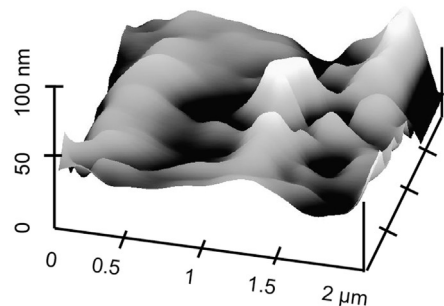


Fig. 3. Surface roughness profiles, RMS, and $P-V$ distance of PP, PET, and HDPE obtained with an AFM for a scan size of $2\ \mu\text{m} \times 2\ \mu\text{m}$. RMS roughness results, in descending order, are PET > PP > HDPE.

Table 1
Hardness and elastic modulus of PP, PET, and HDPE.

	Measured values at contact depth of 350 nm		Reference-bulk values	
	Hardness (MPa)	Elastic modulus (GPa)	Hardness (MPa)	Elastic modulus (GPa)
PP	65.1 ± 13.9	1.23 ± 0.18	60–110 ^{a,b}	0.9–1.6 ^{a,b}
PET	107.7 ± 31.8	2.12 ± 0.14	31–180 ^{a,b}	1.8–5.2 ^{a,b}
HDPE	87.7 ± 18.7	1.70 ± 0.13	54–215 ^{c,d}	0.7–1.4 ^{c,d}

^a Van Krevelen and te Nijenhuis [21].

^b Anonymous [22].

^c Mark [2].

^d Anonymous [23].

stretch blow molding (ISBM), and the HDPE sample by extrusion blow molding (EBM). These processes were employed to prepare samples in a disk shape, which is a convenient shape to fabricate. Each disk had a diameter of 76.2 mm. The disks were 0.55, 3.18, and 0.1 mm thick for PP, PET, and HDPE, respectively. For the

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