

The sliding friction of thermoplastic polymer composites tested at low speeds

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Abstract

An investigation of the tribology of three commercialized thermoplastic polymer composites based on polytetrafluorethylene, polyethylene terephthalate and polyamide, which are considered to be used as sliding bearings in nanopositioning, is carried out by a microtribometer in a speed range of 5–1000 $\mu\text{m/s}$. Deionized water and acetone plus methanol are used in surface cleaning. By using a steel sphere as counterface, the reciprocating sliding friction is measured in dry and with water as lubricant for a variety of running conditions and correlated with surface analysis techniques including scanning electron microscopy and energy-dispersive spectroscopy. The tribological performance of polymer composites is highly depending on the surface conditions. When they are cleaned with water, the friction is independent of materials and a master curve of friction force versus normal load is observed. After cleaning with acetone plus methanol, the friction turns materials dependent. The high Young's modulus is found to be beneficial for the formation of a thin transfer film, which is crucial to obtain a low and stable coefficient of friction. The low yielding strength results in a thick transfer film, which causes large fluctuations in the friction coefficient. Two kinds of velocity weakening of friction are observed from all composites, the one with a mild linear decrease of friction with logarithmic increase of speed in lubricated sliding and the other with a sharp decrease of friction in the speed range of 20–100 $\mu\text{m/s}$ in dry sliding. The results are discussed with the potential applications of these polymer composites in nanopositioning.

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1. Introduction

Partially crystallized thermoplastic polymers, such as polyamide (PA), polyethylene terephthalate (PET) and polytetrafluorethylene (PTFE), have found wide applications in precise engineering as bearings and couplings because of their low adhesion and low friction. There is also an increased interest in applying such polymers in nanopositioning — the means of controlling motion at nanometre scales, a key enabling technology in high-tech fields such as semiconductor test and measurement, photonics alignment and microlithography [1–3].

The performance of nanopositioning is limited by, to a large extent, the friction-caused positioning errors, in particular when direct-drive mechanisms are employed. The absence of a transmission mechanism combined with the existence of nonlinear

friction, notably the stick–slip, often creates problems such as tracking errors in the positioning control [4]. Therefore, designs with non-friction components, such as piezo drivers and flexure stages are preferred. Such designs are widely adopted and exhibit a positioning range (linear stroke) of less than a few millimetres. However, the advancing of the semiconductor industry drives nanopositioning to have a linear stroke at the same scale of current microelectronics device technology up to several hundred millimetres. To accomplish this, bearings must be used to cover a wide working distance, and the friction and wear of the bearings must be minimized.

PTFE possesses low coefficient of friction, low stick–slip and high levels of anti-adhesive properties, which make it a potential candidate for bearing materials for nanopositioning. Unfortunately, PTFE has the following drawbacks: low Young's modulus, high viscoelasticity and poor wear resistance. Low Young's modulus, and thus the low stiffness and high deflections can result in high static positioning errors. High viscoelasticity may result in rate-dependent friction, which can cause dynamic

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positioning errors when the speed changes. The Young's modulus of PTFE can be reinforced by introducing hard fillers such as calcium silicate, glass fibres, nanoparticles to form composites [5–7]. Other fillers such as bronze, lead, carbon nanotubes, graphite, molybdenum and tungsten disulfide have also been introduced as solid lubricants to improve wear resistance while retaining low coefficient of frictions [8,9]. The tribological performance of such PTFE composites, both in the form of bulk materials [7,9–11] and in the form of coatings [8,12,13], has been widely investigated. The results demonstrate that hard fillers can improve or degrade the wear resistance of composite depending on the characteristics of the filler material such as its shape, concentration, and the interface between the filler and the matrix.

PTFE is also frequently used as fillers to form composites. If the matrix is a polymer, the composite is sometimes termed as polymer compound. Such compounds have been tested in various conditions [8,14,15]. An improved wear resistance and a reduced coefficient of friction are usually observed. We notice that most of these tests are performed at relative high operating load and high running speed. These operating conditions are quite different to the requirements of nanopositioning, especially when approaching the targets with accuracy down to nanometres. In this case, the positioning stage normally runs at very low speed at micrometers per second ($\mu\text{m/s}$). This work evaluates the friction behaviour of commercially available polymer composites based on PTFE, PET and PA, respectively, in similar running conditions of nanopositioning, i.e. at low running speed, low working load, and under direct-drive. The aim is to shed light on the relationship between friction and the key operating parameters of nanopositioning such as running speed, working load and cycles of running.

2. Experimental details

2.1. Materials and characterization

High strength polymer composites with trade names of ZX100, ZX530 (Deinhammer GmbH) were selected for testing. Such composites used for bearings are usually provided as semi-finished products that are directly used as bearings or attached to the existing bearings surfaces. In both cases, no further surface processing is required except for some conditional cleaning. ZX100 is a PET based composite with $-10\text{ wt.}\%$ high elastic rubber-like filler in it. The PET matrix is chiefly amorphous while the rubber-like filler balls ($-1\ \mu\text{m}$ diameter) distribute homogeneously in PET. It has been reported that the bonding at the interface between PET and the filler is mainly chemical, i.e. a new compound is created. As a result, the properties of ZX100 are different to that of PET and the filler [16]. ZX530 is also called super PTFE compound with PTFE as a main component. As a comparison, PA12G, a polyamide composite with $30\text{ wt.}\%$ glass fibre (Schneeberger GmbH) is also selected for testing. Some typical properties of the materials to be tested are summarized in Table 1 [16,17]. The surface roughness of these polymers was usually in the range of $1\text{--}3\ \mu\text{m}$ in terms of root-mean-square (RMS), though some macroscopic waviness from processing was also observed. Such waviness was

Table 1
Typical properties of the tested polymer composites [16,17]

	ZX530	ZX100	PA12G
Density ρ (kg/dm^3)	1.51	1.3	1.39
Young's modulus E (GPa)	1.38	2.5	5.9
Compressive yielding strength $\sigma_{0.2\%}$ (MPa)	55	87	105 ^a
Hardness H358/30 (MPa)	136	136	–
Thermoexpansion coefficient α (293 K, $\times 10^{-5}/\text{K}$)	3.5	8	11
Thermal conductivity c (W/m K)	0.25	0.24	0.23

^a Tensile strength.

easily avoided in our measurements by adjusting the testing positions. Chromium steel (100Cr6) spheres (grade 5, RMS 50 nm, 3 mm diameter) were employed as a counterpart in the tests. An environmental scanning electron microscope (SEM, XL30 LaB6 ESEM, FEI) with an integrated energy-dispersive spectrometer (EDS, with S-UTW-window) was used to determine the morphology and composition of wear scars and wear debris. The surface roughness of the specimens was determined by a high precision mechanical stylus profilometer (Ambios XP-2).

2.2. Experimental setups and procedures

Tests were performed using a precision microtribometer based on piezo driver and optical fibre sensors. Details of principle, theory and accuracy of the microtribometer are described by Scherge and Gorb [18] and by Liu et al. [1,19]. It consists of three basic units: reciprocating piezo actuator, force transducer and fiber-optic sensors. A moving table directly mounted on the piezo was employed as a specimen carriage. The force transducer is a double leaf spring, whose spring constants can be adjusted by variation of materials, length and width of the beams. The specimen was fixed on the specimen carriage while a steel sphere was mounted on the tip of the double leaf spring. Once the sphere and specimen were in contact with a certain normal load, sliding friction was initiated from the reciprocating motion of the moving table driven by piezo. The normal load and friction force were obtained by measuring the deflection of the double leaf spring in normal and lateral direction by fibre-optical sensors, respectively, then multiplying by the spring constants. The actuator is directly driven by a voltage amplifier with input signal generated by commercial software (Basalt, Tetra), which can achieve a maximum stroke of 1 mm and a speed range of $1\text{--}2000\ \mu\text{m/s}$. The same piezo stroke of $500\ \mu\text{m}$ and a speed range of $5\text{--}900\ \mu\text{m/s}$ were employed in all the tests. A spring made from stainless steel with spring constants of $3845\ \text{N/m}$ in lateral direction, and $1097\ \text{N/m}$ in normal direction was employed in this work. With this spring, we can readily measure both the normal load (L) and friction force in the range of $0.05\text{--}1.0\ \text{N}$. All the tests were performed in ambient environments with humidity of 40% r.h., and temperature $296\ \text{K}$ approximately.

The polymer composites underwent cleaning procedures for 5 min in deionized water (1), and 5 min in acetone plus 5 min in methanol in an ultrasound bath (2), prior to dry sliding tests. The specimens cleaned with procedure (2) were also tested

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