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Correlation of polymer wear-debris generation between microscratching and macroscopic wear

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ABSTRACT

The paper investigates the effect of the tip attack-geometry on wear-debris generation of polymers. Microscratching and pin-on-disk macroscopic wear experiments are carried out to establish the correlation between microscratching and macroscopic wear. Results show that no debris found on PET using a conical tip. However, debris were observed on PET using a cubic corner tip. Furthermore, the specific wear rates of tested polymers agree well with Ratner–Lancaster correlation. However, correlation of the wear rate between microscratching and macroscopic wear shows a reverse relationship which suggests that wear mechanisms of polymers between microtribology and macroscopic wear may exist.

1. Introduction

Polymers have been widely applied in various forms such as machinery components, electric and MEMS parts, cosmetics products, artificial joints [1]. However, the failure of these examples has been related to material friction and wear that involve adhesion, abrasion or fatigue in a macroscopic scale [1–4]. Macroscopic wear results from the effects of a large number of asperities that make up a 'rough' surface, whereas microscopic tribology considers such specific effects of individual asperities. Four important microscopic wear mechanisms may be distinguished, including microploughing, microcutting, microfatigue and microcracking [5,6]. Many studies about the polymer surface plasticity and material removal mechanisms using microscratching technique have been reported including PMMA, PET, PTFE, UHMWPE, and PEEK [7–12]. As a consequence, recognition of the importance of polymer tribology has received much attention from scientists and engineers. Total projected areas of wear-debris in microscopic scale using microscratching technique were measured for PET [13]. Furthermore, the correlation of wear-debris generation between macroscopic and microscopic scale has been less reported. The understanding of the microscopic processes leading to wear-particle generation on polymer surfaces may enable predictions of the macroscopic wear performance of that polymer. Sinha et al. used a 90° conical tip to scratch polymer surfaces of PEEK, PMMA, UHMWPE, POM and Epoxy [9,14]. In this work, the authors suggested that for polymers a linear correlation may exist between the amount of wear debris generated by microscopic scratching and the macroscopic specific wear rate as determined in pin-on-disk tests.

As microscratching can readily be performed [8,10,13,15], this and similar correlations would provide new tools for estimating the likely macroscopic wear of a polymer material. Furthermore the question arises if such linear correlations reported by Sinha et al. [9] also hold for other tip geometries and non-orthogonal intersecting scratching. Adam et al. employed a Berkovich tip scratching on PMMA surface with multiple-scratching passes [7]. The formation of pile-ups caused by the attack face of the Berkovich tip, which may be related with the wear-particles generation. In a complex tribosystem, such as an orthopaedic prosthesis a multitude of hard asperities with different geometries and scratching modes act upon a UHMWPE surface. If the microscopic debris generation mechanisms for different polymers are indeed all linearly related to macroscopic wear testing, the isolated measurement of a single microscopic mode of defined asperity geometry on UHMWPE or a new type of polymer surface, could predict the macroscopic wear performance of that polymer as a joint prosthesis component. Thus complex and cumbersome wear simulations for that component may be avoided.

Therefore, the paper presented has aimed to focus on the correlation of wear-debris generation between microscratching and macroscopic wear. Specifically, the effect of the tip attack-geometry on wear-debris generation of polymers has been

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investigated. An isolated asperity is modelled using a scratching tip with a controlled geometry. The tip has micrometre dimensions and moves across the polymer surface under load. Scanning electron microscopy and atomic force microscopy are the prime characterisation techniques. Such experiments thereby may shed light on wear-debris generation mechanisms and correlations between microscopic and macroscopic scale.

2. Experimental

2.1. Semi-automated microscratcher

The semi-automated microscratcher is lab-built with an integrated driving system. The system has been designed, so that controlled microscratching can be carried out in a pre-specified and repeatable way. Important parameters are programmable, including scratching length, scratching velocity, number of scratching passes, the *x*–*y* scratching pattern, and the tip positioning. With the semi-automated microscratcher a series of microscratches can be performed sequentially under the automated control of the positioning software. In order to simulate the possible realistic pathway of asperities in the contact surfaces, several continuous scratching patterns were achieved by this software, including bidirectional scratching, intersecting scratching and square scratching. Details of the microscratch patterns have been introduced in a previous paper [15].

The major components of the semi-automated microscratcher can be seen in Fig. 1(a). They are the sample holder that sits on a movable *x*–*y* stage, the tip holder and the balanced cantilever arm. The scratching tip is mounted under the tip holder. The tips with 4 mm × 4 mm were cleaved along crystal planes over a commercial silicon wafer (p-type). Before each scratching experiment, the tip was cleaned and inspected by SEM. Details of the tip geometry was illustrated in previous publication [16]. Fig. 1(b) gives a detailed view of the mounting of the silicon cubic corner tip beneath the tip holder. The cantilever arm is balanced with an adjustable screw. The dead weight, normal load is applied above the tip holder using calibrated weights. The polymer samples are fixed on the sample holder using double-sided, adhesive carbon tape. The *x*- and *y*-drivers of the motorised linear stage (Zaber T-LSM Series), that moves the sample, have a specified accuracy of better than 0.05 μm and a guaranteed repeatability significantly better than 1 μm.

2.2. Polymer materials

The polymers used in this research are the amorphous polymer PMMA and the semi-crystalline polymers PET, PEEK, PTFE and UHMWPE. All the polymers were purchased from Goodfellow Cambridge Limited (Huntingdon, England). The main mechanical properties of these polymers are listed in Table 1.

The polymers were purchased as sheets and prepared to meet the experimental requirements by cutting to a suitable size and polishing the surface. The polymer samples were cleaned using 96 $% ethanol before experimental use. For PMMA and PET, the original surface roughness was measured as approximately 5 nm, 50 nm, respectively. However, the initial surface roughness of PTFE and UHMWPE is too large to permit reliable microscratching experiments. It has been determined as 482 ± 61 nm and 808 ± 23 nm. Therefore, these latter polymer samples with larger roughness were pre-polished as described in previous publication [15], in order to allow isolation of the morphology effect on the microscratching experiments in micron scale. With polishing the average surface roughness has been dramatically reduced to 80 ± 4 nm and 100 ± 6 nm. For example, the effectiveness of polishing for UHMWPE is demonstrated in Fig. 2. Fig. 2(a) shows the initial 'rough' surface morphology of a UHMWPE sample. On this initial rough surface the machining tracks appear to be of similar order of magnitude as a typical microscratch. Following polishing, Fig. 2(b), microscratching can reliably be performed, as it is shown in Fig. 2(c) and (d).

2.3. Experimental methods

2.3.1. Microscratching

Microscratching experiments were performed with the semi-automated microscratcher for patterns with directional change on the polymers PET, PMMA, PEEK, PTFE and UHMWPE. Silicon cubic corner tips were used in flat-on attack geometry. The applied normal load was 10 mN and the scratching velocity was 50 μm/s. In particular bidirectional, square and orthogonally intersecting scratching were performed. The number of passes was varied from $N=1$ to $N=90$. The detailed microscratching procedures have been introduced and published in previous work [15]. SEM images of the results of these experiments are discussed below in Section 3.

Characterising the cross-sectional geometry of the microscratch in terms of the width d_s, Briscoe et al. [19] have introduced the concept of the scratching hardness of polymers H_s. It allows a

Table 1
Mechanical properties of the polymers used in this project: coefficient of friction μ; normal hardness H_N; ultimate tensile strength σ_u; ultimate strain (elongation at break ε_u). Data from the supplier Goodfellow and the literature [3,7,17–20].

Polymer	μ	H_N (MPa)	σ_u (MPa)	ε_u (%)
PET	0.2–0.4	200	80	50–300
PMMA	0.2–1	300	80	2.5–4
PEEK	0.18	200	70–100	50
PTFE	0.05–0.2	37	27.5	400
UHMWPE	0.1–0.2	32	35	500

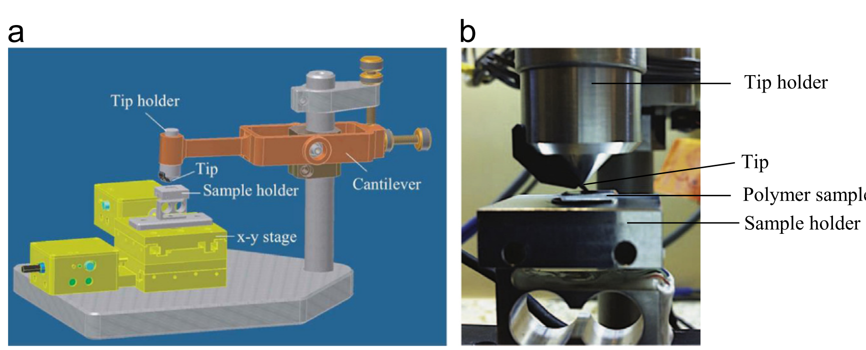

Fig. 1. (a) Schematic drawing of the semi-automated microscratcher including the tip holder for cubic corner tips; (b) a close-up photograph of the sample stage of the semi-automated microscratcher, mounted with the cubic corner tip.