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Friction from nano to macroforce scales analyzed by single and multiple-asperity contact approaches

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ABSTRACT

Understanding friction and wear at different force and length scales is an interesting aspect in tribology. The variety of processes that make friction such a complex phenomenon includes mechanical, chemical and atomic interactions, each operating at their own time, length, and force scale.
Extending local tribological information obtained from a single-asperity contact study (e.g. by lateral force microscopy LFM experiments) to contacts with multiple-asperity interactions is a challenging task. In this work, we analyze the localized friction recorded during a single-asperity LFM experiment, and compare it with that of multiple-asperity sliding contacts. Such a detailed study is relevant for miniature contacts which prevail in microelectromechanical systems of devices. In this work, the friction loops (i.e., tangential force versus displacement curves) obtained from nano to macroforce and different length scales were used to understand the scale effects of friction. Experiments were performed in reciprocating sliding conditions with a ball-on-flat configuration on diamond-like carbon and titanium nitride coatings.
With decreasing contact size and stiffness of the measuring equipment, the effect of roughness is strikingly evident. The effect of surface roughness is clearly visible on the recorded friction loops as fluctuations, which were later attributed to geometrical and adhesive components. Based on our observations, a simple contact model was proposed to describe the nature of localized friction in single and multiple-asperity configurations during a sliding pass. The existing friction model for smooth and chemically interacting surfaces was extended to rough surfaces and it was found that most of the existing experimental claims could be explained as special cases of the proposed model.

1. Introduction

The dependence of friction on force and length scales on rough surfaces has been studied for some time [1,2]. Although force and length scale effects of friction were theoretically studied [3–5], the experimental data is rather limited [6]. Previous researchers have compared nanoscale friction measurements with the macroscopic data [6–8]. Ruths et al. studied force and length scale effects on friction using LFM and SFA [6]. Despite 6 orders of magnitude difference in the contact radii and contact pressures, Ruths et al. reported a similar coefficient of friction with the two techniques on atomically smooth chemically inert surfaces [6]. A scale dependence of friction on rough surfaces was also studied by Bhushan et al. [7] and Liu et al. [8]. Both studied friction on a variety of materials and reported higher coefficients of friction at high normal forces in N range than at nN normal forces (LFM experiments). The observed difference was attributed to the variation in the friction mechanisms such as adhesion dominated effects at nanoscale compared to plastic deformation and wear dominated processes at macroscale. Comparing nanoscale friction data obtained in LFM with the macroscopic friction data is tricky because, in LFM friction arises when a single-asperity surface slides over multi-asperity surface while, at macroscale friction is a consequence of collective asperity interactions (in turn dependent on the effective surface roughness of the surfaces). Thus, the mechanisms of friction when scaling up from a single-asperity to multiple-asperity contact sliding could change, which is not thoroughly addressed in the literature.

The aim of this work is to improve the understanding of friction between rough surfaces when the apparent contact size varies from few nm^2 up to hundreds of μm^2. As the surface roughness is a length scale dependent parameter [9], its effect on friction is also studied systematically. This investigation is carried out on industrially relevant coatings like diamond-like carbon (DLC) and titanium nitride (TiN). Such an investigation would surely help in linking friction measured

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Table 1
Details of force sensor stiffness and counterbodies used in the different test equipments

Equipment	Stiffness of the force sensor (N/m)	Load range (N)	Counterbody diameter (m)	Provider	Counterbody material
AFM/LFM	0.15	10^{-9}	$40 \cdot 10^{-9}$	Veeco® Instruments, Switzerland	Si_3N_4
Microtribometer	100	10^{-6}	$2 \cdot 10^{-3}$	Ceratec®, Netherlands	
	1000	10^{-3}	$5 \cdot 10^{-3}$		
Macrotester	$5 \cdot 10^{6}$	10^{0}	$5 \cdot 10^{-3}$		

at nanoscale (single-asperity observations) with the one measured at macroscale (multiple-asperity contacts).

2. Experimental

In this work, friction is investigated by analyzing friction loops during a reciprocating sliding test under unlubricated conditions. A friction loop is obtained by plotting friction force against sliding distance for each sliding cycle [10]. Such friction loops can be recorded in equipments ranging from conventional reciprocating testers to atomic force microscopes. Friction loops with AFM/LFM were previously used to study phenomena like atomic stick slip, energy dissipation in the contact, and to differentiate friction signals arising from either topography or microstructural differences [11–15].

2.1. Test methods

An atomic force microscope equipped with lateral force microscopy technique (Nanoscope III, Digital Instruments, USA), a microtribometer (MUST® Falex Tribology NV, Belgium), and a macroreciprocating tester (MTM fretting tester, K.U. Leuven) were used for this investigation thus enabling the coverage of large force and length scales. In order to have a similar chemistry of the tribocouple, silicon nitride (Si_3N_4) was used as counterbody material in all the equipments. The details of the counterbodies used and the stiffness of the force sensors used in the above equipments are summarized in Table 1. The average surface roughness of the counterbody used in microtribometer and macrotester was 5 nm.

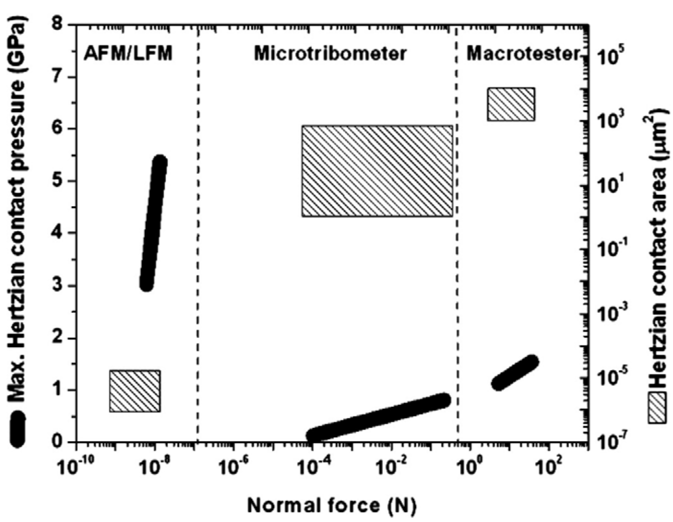

Fig. 1. Overview of contact parameters in the case of DLC and TiN coatings sliding against Si_3N_4 balls in the three test equipments (all experiments in ambient air at 23 °C, 50% RH).

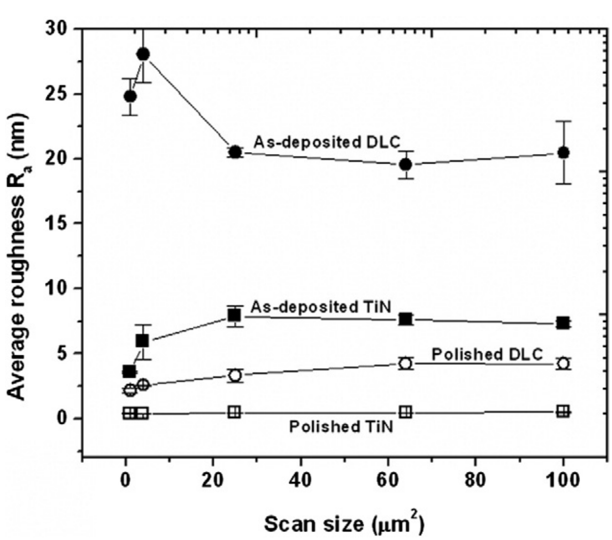

Fig. 2. Average surface roughness (R_a) recorded on DLC, TiN, and Si with contact AFM over different scan sizes using 40 nm Ø Si_3N_4 counterbody.

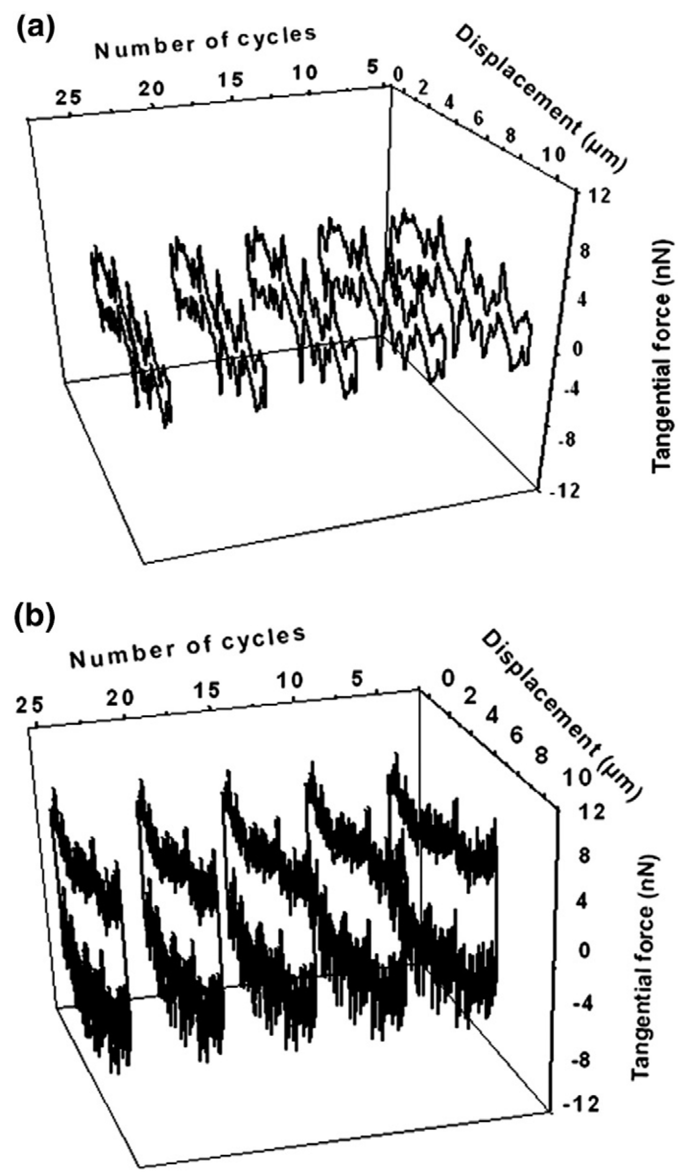

Fig. 3. Evolution in friction loops during first 25 sliding cycles recorded in LFM: (a) as-deposited DLC at 50 nN, (b) as-deposited TiN at 20 nN normal force sliding against 40 nm Ø Si_3 N_4.