Ultrasound induced lubricity in microscopic contact

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A physical effect of ultrasound induced lubricity is reported. We studied the dynamic friction dependence on out-of-plane ultrasonic vibration of a sample using friction force microscopy and a scanning probe technique, the ultrasonic force microscope, which can probe the dynamics of the tip–sample elastic contact at a submicrosecond scale. The results show that friction vanishes when the tip–surface contact breaks for part of the out-of-plane vibration cycle. Moreover, the friction force reduces well before such a break, and this reduction does not depend on the normal load. This suggests the presence on the surface of a layer with viscoelastic behavior. © *1997 American Institute of Physics.* [S0003-6951(97)04335-0]

The friction force microscope (FFM),[1] has opened a way for the study of nanoscale friction phenomena. In the past years, a variety of tribological phenomena have been investigated.[1–5] Recently, experiments have been carried out in ambient, controlled humidity and ultrahigh vacuum environments to understand the conditions in which a single or a multiasperity contact prevails under these conditions.[6,7] Nevertheless, a full understanding of friction and tribology on the nanoscale is still a long way away. It is difficult to investigate the nature of the tip–surface interaction and differentiate the contribution of various forces since FFM only measures the overall lateral force acting on the tip.

A few years ago, a new scanning probe technique, the ultrasonic force microscope (UFM),[8] was introduced, enabling the modulation of the tip–surface distance on the *ultrasonic* submicrosecond time scale. Using UFM, a direct study of the dynamics of the tip–surface contact can be achieved. As a result of the first observations, it was reported that friction is modified by out-of-plane ultrasonic vibration of the sample.[9] A reduction in friction was observed for a range of materials,[10] but only briefly examined. We propose to investigate this phenomenon by combining FFM and UFM techniques.

The microscope used for the experiments is a commercial multimode atomic force microscope (AFM),[11] modified in order to implement the UFM mode.[8,9] The experiments were carried out by laterally moving the sample back and forth relative to the tip, at a set load, as shown schematically in Fig. 1(a). The lateral length was sufficiently long (20–200 nm) to realize dynamic friction for most of the cycle. The friction force was measured by a lock-in amplifier.[12,13]

In the UFM configuration, the sample glued to a piezoplate is vibrated out of plane at ultrasonic frequency (2–3 MHz in our experiments). The free resonance frequency of the cantilever is more than two orders of magnitude lower than the excitation frequency, and so, although there is some cantilever vibration at that frequency, its amplitude is small compared with the excitation amplitude.[14] Any subharmonic response would occur only at higher excitation amplitudes.[15] The tip–sample distance is, thus, modulated [see Fig. 1(b)]. As shown in Fig. 2, if the ultrasonic amplitude is low (a_0) so that the tip–surface distance is modulated over the linear part of the force F versus distance z curve, $F(z)$, the average normal force over one cycle remains unchanged. If the amplitude is high enough (a_{c1} for a set load F_1) to reach the pull off, the average normal force changes causing an additional cantilever deflection. This change in force strongly depends on the set load and the slope of the $F(z)$ curve. For amplitudes higher than a_{c1}, the tip–surface contact is broken for part of the vibration cycle.[8,16]

In our experiments, we recorded the effect of the ultrasonic amplitude on (i) the friction force and (ii) cantilever deflection. The time interval at which the ultrasonic amplitude increases was chosen longer than the sliding period in (i) and shorter than the AFM z-feedback response in (ii), respectively. Comparing the two measurements, one can relate friction to the modulated tip–surface contact area.

We chose three different flat (on the nanoscale) samples to avoid topographical artefacts: polished (100) silicon wafer, cleaved mica, and optically polished glass. Two different types of cantilevers with the tip have been used: a silicon ultralever (nominal tip radius $R=10$ nm, cantilever elastic constant $k_c=0.24$ N/m) and a silicon–nitride microlever ($R=100$ nm, $k_c=0.05$ N/m).[11] All the experiments have been carried out in an ambient environment ($\cong 23\,°$C, 30% of relative humidity).

Measurements without ultrasound show that the friction force versus load curve is almost linear for all the cantilever–sample combinations used. This suggests that a multiasperity contact is taking place.[6,17]

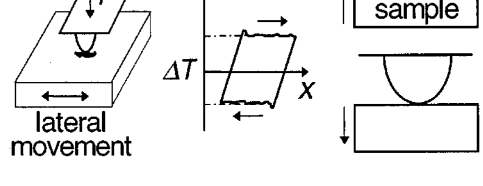

FIG. 1. (a) The tip and the surface slide relative to each other at normal load F. The friction force is proportional to ΔT. (b) The cantilever cannot follow the ultrasonic vibration due to inertia, and the tip–sample distance is modulated.

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