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Citation: Journal of Applied Physics 88, 4825 (2000); doi: 10.1063/1.1310187
View online: http://dx.doi.org/10.1063/1.1310187
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/88/8?ver=pdfcov
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A critical look at surface force measurement using a commercial atomic force microscope in the noncontact mode
Topography-induced contributions to friction forces measured using an atomic force/friction force microscope

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(Received 28 February 2000; accepted for publication 19 July 2000)

Most friction studies using an atomic force/friction force microscope, while concentrating on material-induced effects, often present users with conflicting and confusing interpretations of the topography-induced friction forces. It has been generally reported that topography-induced contributions are independent of scanning direction and can be removed by subtracting friction data from forward and backward scans. In this article, we present friction studies on samples with well-defined topography variations and find that the above-given statement is not generally true. At surface locations involving significant changes in topography, the topography-induced contributions to friction forces are found to be different between forward and backward scanning directions. This is explained by the ratchet mechanism of friction and due to the additional torsion generated by ‘‘collision’’ of the tip when traversing up an increase in topography, which is absent in the downward travel. Topography-induced contributions to the friction force always correspond to transitions in the surface slope. Moreover, these contributions will be of the same sign in both Trace and Retrace friction profiles of the friction loop whereas changes due to material effects are in opposite directions. These characteristics of topography-induced friction forces will aid in differentiating them from other effects. © 2000 American Institute of Physics.

I. INTRODUCTION

Atomic force/friction force microscopy (AFM/FFM) is extensively used to study friction of various samples at ultralow loads ranging from micro down to the atomic scales. During friction measurements, the friction signal from both the forward and backward scans (friction loop as shown in Fig. 1) are needed in order to understand the origins of the observed friction forces. It is well known that when an AFM tip is scanned across a sample surface, the measured friction forces (or lateral forces) are generated by both material effects as well as topography-induced effects. However, friction studies in the past, while concentrating on material-induced effects, often present users with conflicting and confusing interpretations of topography-induced friction forces. It has been reported that topography-induced effects are independent of scanning direction and are hence eliminated when subtracting the friction data of the backward scan from that of the forward scan, leaving only material-induced effects. Other studies have attributed correlations between surface topography and friction forces in scanning probe microscopy to variation of van der Waals forces between high and low points on a surface, to influence of local slope of the sample (ratchet mechanism), and to torsion of the cantilever generated by reaction forces and friction forces at locations involving significant surface height change. These effects do explain the variations of friction as a function of topography but appear to be independent of the scan direction and agree with the previous suggestion that the subtraction process will eliminate the topography-induced effects.

In this article, we present friction studies on samples with well-defined topography variations and show that the subtraction process does not generally remove the topography-induced effects. At surface locations involving significant changes in topography, the topography-induced contributions to the measured friction forces are found to be different between forward and backward scanning directions. In order to explain these observations, the physical processes involved with topography-induced friction variations are discussed and dynamic effects are considered in addition to static effects in analyzing these variations. Methods to identify topography-induced effects are identified and differences between these effects and material-induced effects are highlighted.

II. EXPERIMENT

The AFMs used in this study were the commercial Nanoscope III small sample Multimode AFM and the Dimension 3000 AFM, both from Digital Instruments (Santa Barbara, CA). Both these machines allow the simultaneous measurement of topography and friction forces. Standard V-shaped silicon nitride cantilevers with integrated square-pyramidal tips were used. The height of the tip is 4 μm and the cantilever length is 115 μm, with a spring constant of about 0.6 N/m, all the numbers being the manufacturer’s specifications. All scanning was performed in a direction
perpendicular to the long axis of the cantilever beam, which is the norm for friction measurements. The normal load used was 25±5 nN.

Two samples with distinct topographical features were utilized in this study: a silicon sample with 5 μm square pits of depth 180 nm and a pitch of 10 μm, commonly used as a calibration grid for the AFM piezos. The second is a gold-coated ruling with a somewhat rectangular grid with a pitch of 1 μm and a ruler step height of about 70 nm. Each sample is composed of homogeneous material and any friction variations seen during measurements will be purely topography induced.

III. RESULTS AND DISCUSSION

Figure 1 shows a typical friction loop obtained with an AFM/FFM. In this paper, we define left to right (forward) direction as Trace (T) and the right to left (backward) direction as Retrace (R). From Fig. 1 it can be seen that the sign
of the friction signal is reversed for the Retrace scan compared to that of the Trace scan. This is of course due to the reversal of the torque applied to the end of the tip when the scanning direction is reversed. As a consequence when raw friction data are presented, peaks in two-dimensional (2D) friction profiles correspond to high friction for Trace data and low friction for Retrace. This also means that for grayscale images, lighter regions in the Trace friction image correspond to higher values of friction force while in the Retrace image, lighter regions correspond to lower friction force. This must be kept in mind when comparing Trace and Retrace friction data.

Figure 2 shows topography and friction data for the silicon grid obtained in scope mode with a Dimension 3000 (left column) and Multimode (right column). Both the friction data show large variations at the edges of the pit where the topography changes sharply. In addition, the friction data obtained with the Dimension show a large tilt. This is due to cross-talk between the vertical deflection signal and the horizontal deflection signal that arises from misalignment between the trajectory of the reflected laser beam on the photodetector and the photodetector axis.11 This misalignment is negligible in the case of the Multimode whose data shows no tilting of the friction signal. Looking at the subtracted friction data (T−R), two points are clear. First, the subtraction process does not remove the topography-induced effects associated with the pit edges. Second, the effect of detector cross-talk is effectively removed by the subtraction process. Figure 3 shows grayscale and 2D cross sections of topography and friction data for the gold ruler over a 5 μm scan size. The changes in topography in this sample are less severe than that of the silicon grid. Again, it is clear that friction peaks occur at locations of topography variations. It is also clear that the subtraction process does not eliminate these variations.

Figure 4(a) shows topography and friction data for the silicon grid over a 1.5 μm scan size, encompassing a single ruling, obtained using the Multimode. From the 2D traces it is clear that high friction results when the tip traverses up a sharp rise in topography (point A) and low friction results when the tip traverses down a sharp fall in topography (point B). Due to the reversal of sign of the Retrace friction signal with respect to the Trace signal, the friction variations due to topography are in the same direction (peaks in Trace correspond to peaks in Retrace). However, the magnitudes of the peaks in Trace and Retrace corresponding to the same location are significantly different. Rather, the magnitude of the increase in friction force experienced by the tip when scanning up a sharp change in topography is larger than the magnitude of the decrease in friction force experienced when scanning down the same topography change. As a result, subtracting the friction signals still yields a residual peak, which is a topography-induced (T−R) variation. From the grayscale images, it can be seen that this effect occurs at all locations of significant topography change (e.g., the oval-shaped region at the bottom right of the images). Figure 4(b) shows the derivative (slope) of the topography for the corresponding scanning directions. Comparing the slope data to that of friction in Fig. 4(a), a clear correlation can be obtained with transitions in slope corresponding to transitions in friction, which has been reported previously.7-9 This effect has been attributed to the ratchet mechanism of friction,1 which has been used in previous studies to explain microscale friction. When a tip applying a constant normal load W slides over an asperity making an angle θ with the horizontal plane, the lateral or friction force F experienced by the tip varies as a function of surface roughness according to

$$F_u = W(\mu_0 + \tan \theta)/(1 - \mu_0 \tan \theta), \quad \text{sliding up}, \quad (1)$$

$$F_d = W(\mu_0 + \tan \theta)/(1 + \mu_0 \tan \theta), \quad \text{sliding down}, \quad (2)$$

FIG. 3. Grayscale images and representative 2D profiles of surface height and friction forces of a gold ruler. Note that subtracting the friction force data (T−R) does not eliminate topography-induced effects.
where \( \mu_0 \) is the coefficient of friction for the tip–sample material pair, and \( F_u \) is the lateral force experienced by the tip when going up the slope, and \( F_d \) is the force experienced when going down the same slope. A tip therefore experiences higher lateral force when going up a surface slope than when coming down the same slope, which is consistent with the experimental data shown here and elsewhere.\(^7\)–\(^9\),\(^12\),\(^13\) As-sociating \( F_u \) with the Trace direction and \( F_d \) with the Retrace direction, a negative sign will be added to \( F_d \) to account for the sign change associated with reversal of scan direction. Thus subtracting \((- F_d)\) from \( F_u \) [from Eqs. \((1)\) and \((2)\)] is equivalent to the operation of “Trace–Retrace” and will result in

\[
F_u - (- F_d) = 2 W \mu_0 (1 + \tan^2 \theta) / [1 - (\mu_0 \tan \theta)^2].
\] (3)

According to Eq. \((3)\), subtraction of the Retrace friction data from the Trace friction data will not eliminate the topography contribution, namely the \(\tan \theta \) (slope) term, when \(\tan^2 \theta\) becomes comparable to 1. Typically, values of \( \mu_0 \) on the microscale measured with an AFM range between 0.01 and 0.1. The measured values of \(\tan \theta\) for the features studied in this paper, which were obtained from the AFM topography data \((dz/dx)\), were about 0.9 (\(\theta\approx40^\circ\)) for the steps in the gold ruler and about 1.5 (\(\theta\approx55^\circ\)) for the steps in the silicon grid. The ratchet mechanism therefore accounts for a variation of about \(200\%\) of the material-based friction signal \((2 W \mu_0)\) for the features studied here. However, as mentioned before, performing “Trace–Retrace” still yields a residual peak at the asperity located at the lower right-hand side of the grayscale images in Fig. 4. The slope here was found to be about 0.3 (corresponding to \(\theta\approx18^\circ\)), which is closer to values found for steps and asperities found on engineering surfaces. For this value of slope, the subtraction process [Eq. \((3)\)] should almost entirely eliminate the ratchet mechanism effect on the measured friction forces. However, a residual peak is still seen at the edge of the asperity, which corresponds to a \(30\%–40\%\) variation in the friction signal.

FIG. 4. (a) Grayscale images and 2D profiles of surface height and friction forces and (b) grayscale images and 2D profiles of surface slope \((dz/dx)\) across a single ruling of the gold ruler.
This suggests that the difference in lateral force experienced by a tip traversing up and down the same topography feature cannot be attributed solely to the ratchet mechanism.

It is proposed that in addition to the slope effect, the ‘‘collision’’ or impact of a tip when encountering an increase in slope produces additional torsion of the tip leading to higher measured friction force. Consider a tip of finite radius traveling across a surface with a given normal load and scanning velocity. When the tip encounters a surface feature with a considerable increase in slope such as a sharp asperity or surface step, a ‘‘collision’’ or impact can occur between the leading edge of the tip and the surface feature that results in part of the linear momentum of the tip being converted to angular momentum, which leads to torsion of the cantilever. This would be measured as an increase in the friction force signal. In addition, the impact can cause a momentary increase in the applied normal load of the cantilever due to the finite bandwidth of the microscope feedback controller. This would result in an increase in the real area of contact, thereby leading to increased friction force. In some cases, the edge of a step or asperity may come in contact with the side of the tip, which can create an additional torque as soon as the tip is pressed against the step or asperity. Including the term \( F_c \) for the lateral force generated by the above-mentioned effects, Eq. (1) can be rewritten as

\[
F_u = W(\mu_0 \tan \theta)/(1 - \mu_0 \tan \theta) + F_c, \quad \text{sliding up.} \tag{4}
\]

The magnitude of \( F_c \) would be a function of the tip radius, the applied normal load, and the scanning velocity.

On the other hand, when the tip travels down the same feature, there is no event (certainly no ‘‘collision’’ that can cause a decrease in the friction force that is equivalent to \( F_c \) in magnitude. Only the ratchet mechanism affects friction forces during the downward travel. Hence expression (2) remains the same. Performing the subtraction operation of ‘‘Trace – Retrace’’ with \( F_u^* \) and \( -F_d \) results in

\[
F_u^* - (-F_d) = 2W\mu_0 (1 + \tan^2 \theta)/[1 - (\mu_0 \tan \theta)^2] + F_c. \tag{5}
\]

Equation (5) would account for the peaks that occur in a friction profile after subtraction that are correlated to changes in surface slope. At locations with significant changes in slope (\( \tan^2 \theta \) comparable to 1) the topography-induced contribution to the friction signal due to the ratchet effect becomes significant while at locations with small changes in slope, the contribution due to the collision effect becomes significant.

The differences in the magnitudes of the friction peaks when going up and down a sloped region may also be attributed to asymmetry in the tip shape. If this were the case, then the surface slope data for the opposite scan directions would also show differences. Figure 4(b) shows the inverse of the Retrace slope (\(-R\)). Comparing this with the Trace slope shows that the two are almost identical, thus ruling out the possibility of tip shape asymmetry being a major cause in affecting friction signals.

Figure 5 shows a schematic of the friction loop that can be expected when scanning across a sample that presents both a change in material (with different friction properties) and a change in topography. During the Trace scan, the tip encounters higher friction force at region A due to higher friction of the material. Based on the above-mentioned data and discussion, at region B, the tip encounters high friction when scanning up the feature and lower friction when scanning down the feature. In the Retrace scan, the same effects are seen. The change in friction force due to the material effect in Trace and Retrace will be in opposite directions (upwards or downwards). However, the changes in friction due to topography in Trace and Retrace will be toward the same direction. This is one difference between material-induced effects and topography-induced effects on the friction forces. The magnitudes of the friction change due to material effects will be the same in Trace and Retrace but the magnitudes of the topography-induced friction forces at a
given location will be different, as was discussed before. As a result, subtracting the Trace and Retrace friction profiles does not eliminate the topography-induced contributions to the friction forces. However, these contributions can be identified by comparing the friction profiles to the slope profiles. As was shown before, topography-induced transitions in friction correspond to transitions in slope. Material effects in friction forces are independent of transitions in slope. This is another difference between material-induced effects and topography-induced effects in friction forces.

FIG. 6. (a) 2D profiles of surface height, surface slope, and friction force for a scan across the silicon grid pit. (b) Grayscale images of surface height, surface slope, and friction force for the gold ruler.
When comparing Trace and Retrace friction signals, it is important to take into account the sign change in the Retrace friction signal. Figures 6(a) and 6(b) show topography, slope, and friction data for the silicon grid and gold ruler, respectively. The correlations between surface slope and friction forces are clear. The third column shows retrace slope and friction data, which have been inverted (hence labeled as -Retrace). In order to correctly compare directionality effects in friction, the Trace and -Retrace (not raw Retrace) profiles should be compared. From Fig. 6 it is clear that the friction experienced by the tip is quite different when scanned across the sample in different directions, in this case due to the influence of topography. Comparison of Trace and (-Retrace) slope profiles will reveal information of tip shape asymmetry.

IV. SUMMARY

This study focused on understanding topography-induced effects in the friction forces measured using an AFM/FFM. The following points can be made regarding these effects:

1. The changes in the friction force due to topography-induced effects will be of the same sign in both Trace and Retrace friction profiles (peaks in Trace correspond to peaks in Retrace) of the friction loop whereas changes due to material effects are in opposite directions.

2. Topography-induced friction transitions always correspond to transitions in surface slope.

3. The magnitude of the increase in friction force experienced by a tip when traversing up an asperity, step, or similar topography feature is greater than the magnitude of the decrease in friction force experienced by the tip when traversing down the same feature. This is attributed to the ratchet mechanism of friction and to the "collision" force encountered by the tip during the upward movement, which is absent during the downward movement.

4. As a result, subtraction of Trace and Retrace friction profiles will not eliminate topography-induced friction forces. This subtraction operation will, however, remove the effect of detector cross-talk on the measured friction forces.

These characteristics of the topography-induced contributions to measured friction forces in an AFM will be useful when attempting to differentiate these effects from material effects in samples with numerous topographical features (e.g., high roughness). In addition, they aid in understanding the forces experienced by an asperity (AFM tip) when moving over other asperities and similar surface features.

ACKNOWLEDGMENTS

The financial support for this research was provided by the National Science Foundation (Contract No. ECS-9820022). The content of this information does not necessarily reflect the position or policy of the Government and no official endorsement should be inferred. The authors also gratefully acknowledge M. S. Bobji and Anton V. Goldade for helpful discussions during the preparation of this manuscript.

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