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PRE-SLIDING TANGENTIAL DEFLECTIONS CAN GOVERN THE FRICTION OF MEMS DEVICES

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ABSTRACT
We have measured pre-sliding tangential deflections (PSTD) between micromachined surfaces of up to 200 nanometers in length before the static friction event using a polysilicon nanotractor[1] actuator [1,2]. The detailed PSTD structure is resolved by a one-nanometer-resolution in-plane optical metrology we have developed, and may be a manifestation of discrete asperity-asperity interactions leading to an effective spatial distribution of friction coefficients. Results indicate a dependence on surface treatment, with a perfluorinated eight-carbon chain monolayer coating showing substantially different PSTD than an eighteen-carbon chain hydrocrabon monolayer. This behavior may qualitatively be related to variations in dynamic versus static friction. We present a simple phenomenological model that captures some of the behavior of PSTD, and suggest some possible microscopic interpretations.

INTRODUCTION
Surface micromachining fabrication techniques are used to construct a wide range of microactuators for microelectromechanical systems (MEMS) applications. When micron-scale structural materials come into contact, their response may be dominated by frictional effects and therefore rubbing surfaces are often avoided in MEMS actuators. Conversely, we can take advantage of friction to achieve high-performance actuation characteristics at the microscale [1]. The actuator we have developed, which features large force (up to several milliNewtons), large travel range (±100 μm) and precise positional control (50 nm steps), is called the "nanotractor". We can also employ the nanotractor to obtain detailed information on friction of contacting MEMS surfaces.

NANOTRACTOR DESCRIPTION AND OPERATION
The nanotractor is a polycrystalline silicon surface-micromachined MEMS actuator [1] that consists of two frictional clamps spanned by an actuation plate, as seen in Figure 1. Through an appropriately-phased sequence of clamping voltages, we can walk the nanotractor in 50 nm steps against the tangential force of a linear suspension spring. The clamping force, acting normal to the surface, is applied electrostatically and is borne mechanically by equipotential rubbing counterfaces. The upper counterface is called the friction foot. Knowing the geometry of the parallel plate clamping electrodes and the clamping voltage, we determine the normal force F_c (from 0 to 6 mN in these experiments). The large apparent contact area of the friction feet (4800 μm^2), enables us to obtain a large friction signal.

The suspension spring, shown in Figure 1, is linear due to its fixed-guided geometry, has an in-plane spring constant calculated to be 4.5 N/m and has an out-of-plane spring constant calculated to be 3.6 N/m. The in-plane spring constant was verified through a resonant frequency measurement on the nanotractor. This spring serves both to center the nanotractor and to present an in-plane restoring force to the nanotractor. Before initial operation, the clamps are suspended 2 μm above the surface.

[1]This actuator was previously called an "inchworm" in refs. [1] and [2]. The "Inchworm®" trademark is owned by EXFO Burleigh Products Group Inc in the field of electromechanical actuators.

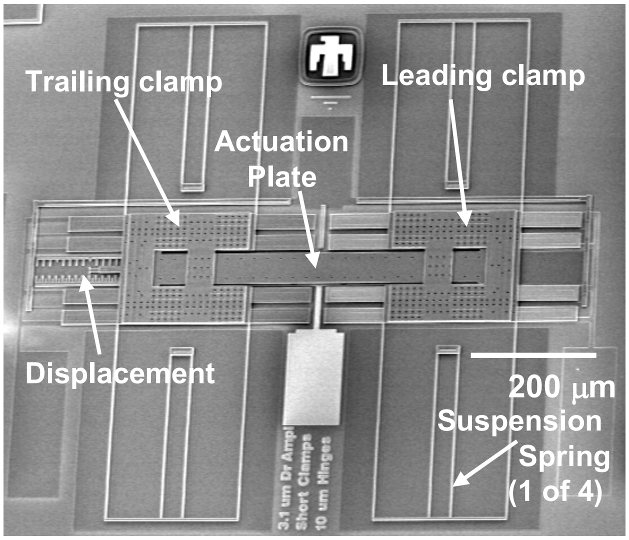

Figure 1 An SEM image of a nanotractor.

COATINGS

We can use the nanotractor to study the performance of low-energy hydrophobic monolayer coatings on MEMS devices. Hydrophobic coatings are used to greatly reduce release and in-use stiction [3] and may have advantageous effects on friction and wear, and ultimately on MEMS reliability. For the work presented here, we have used an eight-carbon chain, vapor-deposited, tridecafluoro-1,1,2,2-tetrahydrodecyltris(dimethylamino)silane (FOTAS) [4] and an eighteen-carbon chain, solution-deposited octadecyltrichlorosilane (OTS) [5]. These coatings have been seen to reduce both the coefficient of static friction and adhesion in previous studies [1].

STATIC FRICTION TEST

To carry out a static friction test, we first walk the nanotractor out against the suspension spring to a large distance, e.g., 40 μm. Then, the leading clamp is fixed in place with a large voltage (i.e., large normal force), while the trailing clamp and plate are released. We then step down the voltage (force) in the leading clamp while recording the position of the nanotractor (see Figure 2).

As long as the static frictional force at the clamp interface is large enough to balance the tangential force of the load cell, we expect the nanotractor to remain fixed in place. When the frictional force drops just below the tangential force, we expect the nanotractor to start sliding. Figure 3 shows the results of a measurement of position as a function of normal force for a FOTAS-coated nanotractor. Indeed, it remains fixed in position until the normal force is sufficiently low that a jump occurs. At that point, the frictional force is exactly balanced by the tangential force corresponding to the critical static friction event.

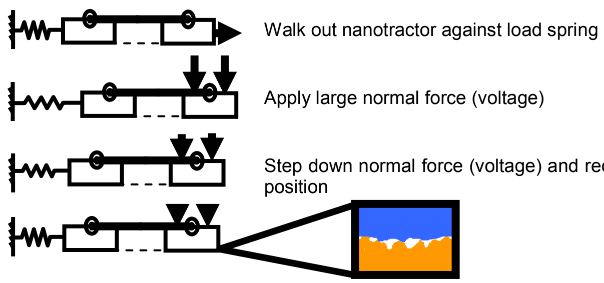

Figure 2 Schematic diagram showing a nanotractor static friction test.

Each such event can be converted into a tangential force (from position using the spring constant) and a normal force F_c (from voltage using the geometry of the electrodes). We can then fit these points with a modified version of Amontons' law if we allow the normal force to include an out-of-plane restoring force from the suspension spring ($k_z z$), a gravitational mass term (mg), i.e., $F_N = F_c + k_z z + mg$. Including a surface attraction term F_{adh},

$$F_s = \mu_s\left(F_c + mg - k_z z\right) + \mu_s F_{adh} \qquad (1)$$

Thus, by a best fit to the data over all the jumps, we can determine both the coefficient of static friction and the contribution of adhesion. We also measure the true dynamic friction coefficient by a technique that has been described elsewhere [2].

PRE-SLIDING TANGENTIAL DEFLECTIONS

We have developed an optical metrology that allows us to measure in-plane displacement with one nanometer resolution [6]. When we observe in detail the position of the nanotractor during the friction test, we see that it is not actually fixed in position, but that it slides over about 200 nm before the gross sliding event. Such deflections have been observed in macroscopic systems, and are referred to as pre-sliding tangential deflections (PSTD) [7-11]. The phenomenon is usually reported for metals that are heavily deformed at their contacting asperity junctions. The stable tangential deflections are thought to be associated with increasing contact area before the static friction limit is reached [7]. At sufficiently small displacements, the number of contacting asperities governs reversible "elastic" tangential compliance [8] while a much longer "plastic" regime exists before the static friction limit is reached [9]. Such μm-scale deflections have also been observed for ceramic materials such as ZrO_2, Al_2O_3 and SiC [10]. For our microactuator, which walks with 40 nm steps, this 200 nm PSTD is critically important in any application where precise positional control under tangential loading is desired.

Figure 4 shows a magnified portion of the position versus voltage curve of the FOTAS-coated nanotractor (the data in the dotted circle of Fig. 3). We observe that substantial slipping (170 nm) occurs before the gross sliding event, and we can observe fine structure in the PSTD behavior. For this coating we find a static coefficient of friction of 0.31 ± 0.01 and a dynamic coefficient of friction of 0.265 ± 0.005. The difference between static and dynamic friction leads to the emergence of a few large gross slip events (of many μm) as seen in Figure 3, and allow a clear separation of the gross slip and the much smaller PSTD events. We can thus unambiguously attribute the fine structure seen in Figure 4 to PSTD.

We have made similar static friction measurements on an OTS-coated nanotractor. Figure 5 shows the complete friction test curve for one such measurement.

As seen by comparing to Fig. 3, the OTS and FOTAS coatings behave very differently. For this coating we find a static coefficient of friction of 0.102 ± 0.002 and a dynamic coefficient of friction of 0.10 ± 0.01 after averaging over several measurements. The uncertainties reflect averaging over multiple tests similar to Fig. 5. Although the uncertainty in static friction coeffecient is small, there is larger scatter in adhesion force, which is important but will be discussed elsewhere. Because the static and dynamic as seen in Figure 5. This makes the separation between gross sliding and PSTD less clear. However, a magnified portion of the OTS curve (Figure 6), shows that we can still pick out individual PSTD events, also revealing PSTD on the order of 200 nm.

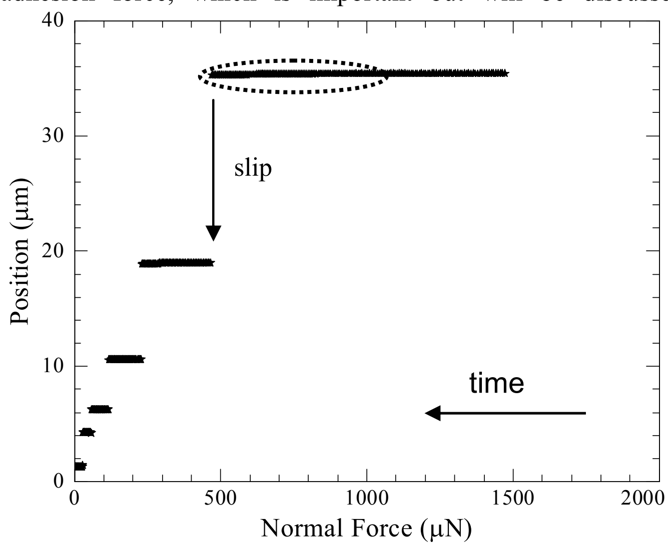

Figure 3 A static friction test from a FOTAS coated nanotractor (data in dashed oval is magnified in Fig. 4).

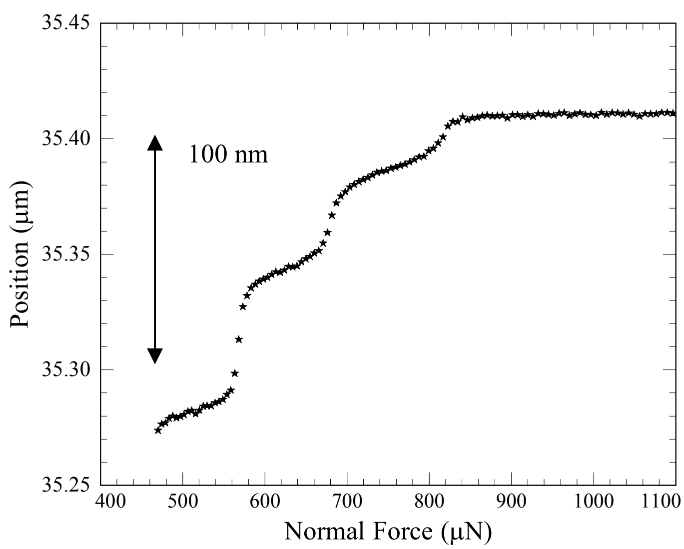

Figure 4 A magnified portion of Fig. 3 (as indicated by dashed oval) from a FOTAS coated nanotractor.

SIMPLE NUMERICAL MODEL

We can qualitatively capture some of this behavior with a simple numerical model. We let the local effective friction coefficients on the surface vary spatially with a Gaussian distribution centered about the measured value. The transition from static to dynamic friction is set by a minimum sliding distance transition parameter. Upon sliding, we let the dynamic friction coefficient also vary spatially with a Gaussian distribution.

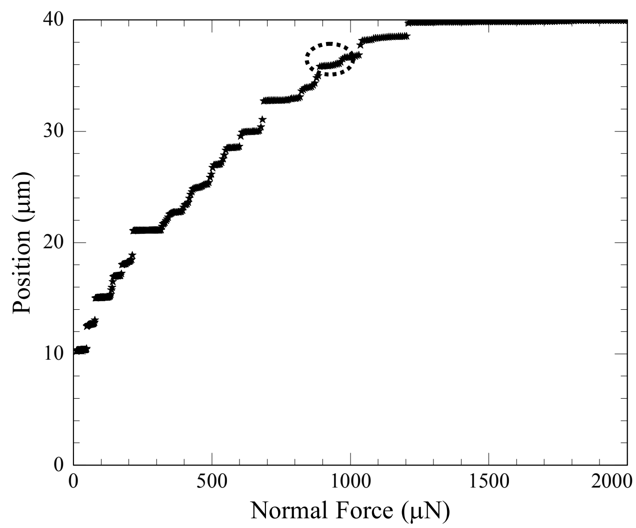

Figure 5 A static friction test from an OTS coated nanotractor (data in dashed oval is magnified in Fig. 6).

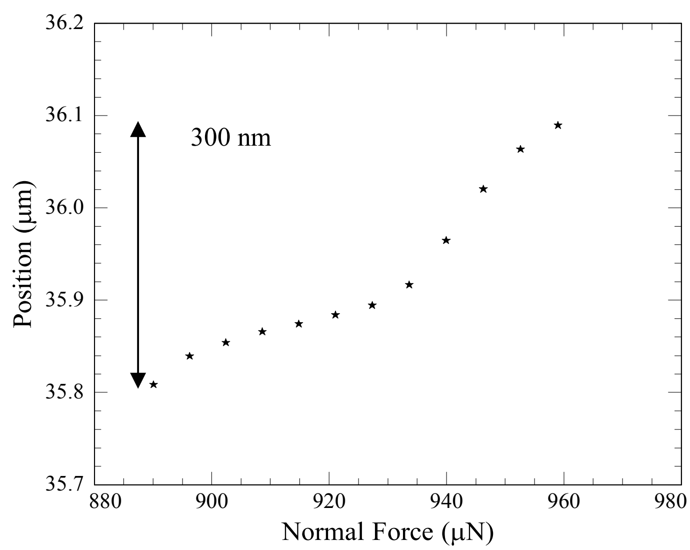

Figure 6 A magnified portion of a Fig. 5 (as indicated by dashed oval) from an OTS coated nanotractor.

In Figure 7, we have used the experimental values of static and dynamic friction and a transition static to dynamic transition length of 120 nm to simulate the large-scale behavior of an OTS-coated nanotractor. We again see that the distance after gross sliding is small due to the static and dynamic friction coefficients being similar. In Figure 8, we see that a magnified portion of the Fig. 7 curve contains PSTD-like behavior, with a similar distance of about 250 nm. Thus, we infer that PSTD may be due to local surface variations which may lead to a spatially varying frictional force. Essentially, as the nanotractor moves along, local maxima in surface friction will stop the slipping after small travel distances. Eventually as the normal force is continually lowered, there will be no local maximum large enough to stop the slipping, and a large jump in position will occur. Using appropriate parameters, we can also simulate the behavior of the FOTAS-coated nanotractor.

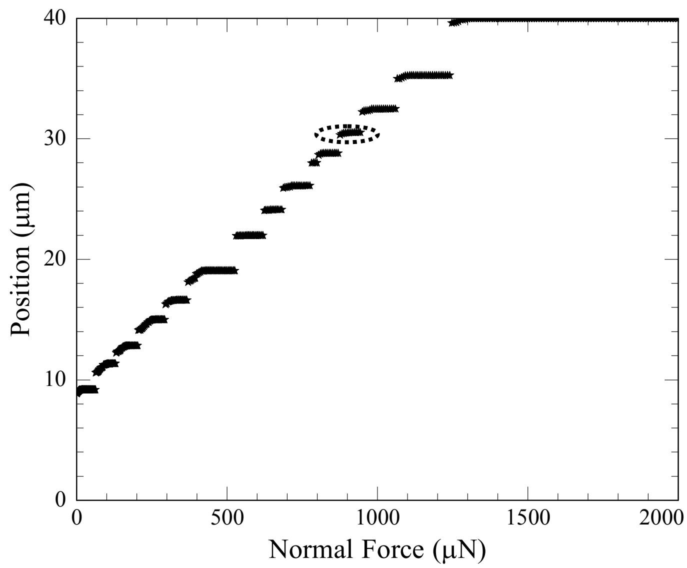

Figure 7 A simulation of a static friction test for an OTS coated nanotractor.

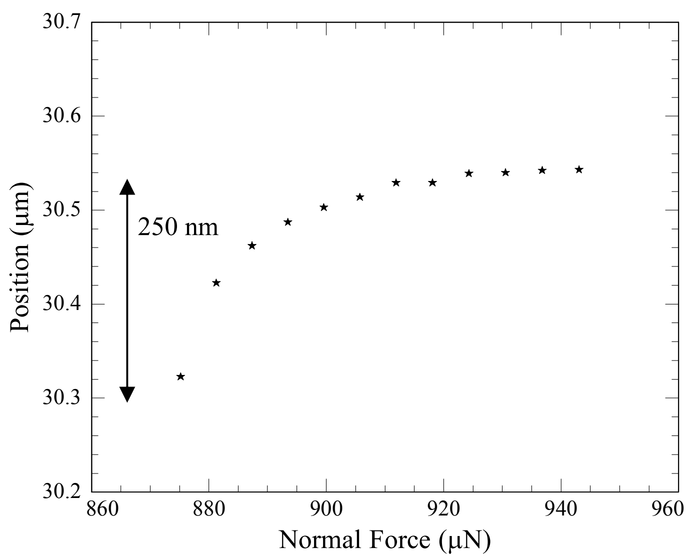

Figure 8 A magnified portion of Fig. 7 (as indicated by dashed oval) for an OTS coated nanotractor.

CONCLUSIONS

We observe that pre-sliding tangential deflections (PSTDs) of up to 300 nanometers occur before the static friction event in a polysilicon surface micromachined device. This is very large relative to positioning requirements in applications such as optical MEMS, and thus it is important to characterize and to understand in more detail. Preliminary results indicate a dependence on surface treatment, with an FOTAS-coated sample showing PSTD with more fine structure that an OTS-coated sample. Additionally, as static and dynamic friction become similar, we find the distinction between gross sliding and PSTD begins to vanish. We have presented a simple phenomenological model that captures some of the behavior of pre-sliding tangential deflections and suggests that local surface variations may be responsible for the PSTD.

ACKNOWLEDGMENTS

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