CONTACT GEOMETRY EFFECTS ON FRICITION IN MEMS PROBE ARRAYS

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ABSTRACT

This paper examines the friction and wear properties between a laterally unconstrained slider and an array of AFM-like probe tips. Specifically, it focuses on how variations in the actual number of contacts and contact geometry (varied by tip wear) influence the friction forces. Results show that the steady state friction coefficient increases dramatically as the number of contact points increases. Additionally, initial variations in the friction forces due to rapid tip wear become steady after sliding distances greater than 1 mm. These results combined with SEM images of the tip wear imply that the wear rate becomes minimal as the contact pressure is reduced to approximately 20 MPa.

INTRODUCTION

Friction and wear are important aspects of the performance and reliability of many MEMS devices such as atomic force microscopes (AFMs), probe data storage devices, and tip based nano-fabrication [1-3]. The magnitude of the friction force affects the ability to control and position an actuator, which is critical when atomic resolution and rapid movement are needed. In addition to creating debris, tip wear can dull a sharp tip, reducing the density of bits stored in a data storage device or increasing the minimum feature size in a tip-based fabrication device [1,3]. Thus, understanding the contributing parameters to friction forces and wear is critical to the design and reliable operation of MEMS structures that include contacting and sliding surfaces.

Friction involves a complex combination of material properties, environmental conditions, sliding conditions, and contact properties. Although relatively simple relationships for friction have been established at the macro-scale, surface forces such as van der Waals forces, electrostatic forces, and capillary forces must be accounted for when considering friction at the micro- and nano-scale [4-7].

One of the most common methods for examining friction at the nano-scale is the single point scanning probe microscope [6,7]. This method correlates the reaction of an AFM cantilever as it is slid across a surface to the friction forces. This method has been instrumental in understanding many of the atomistic origins of friction forces. Typical results for a silicon tip sliding on a silicon surface produce a friction coefficient of 0.05 [7]. Commercial tribology testers are another common method to measure friction and adhesion forces at micro-scale contacts. These experiments

typically yield friction coefficients that are an order of magnitude larger than the nano-scale scanning probe results [7]. Other commonly used methods to measure friction forces include *in situ* methods where friction forces are a part of the device operation [8]. Although these methods mimic how actual MEMS devices will respond to friction forces, very few careful studies have been performed on statistically significant sample sets.

The experimental method used in these experiments represents a unique approach to examine the friction forces between an array of nano- to micro-scale contact points and a flat surface. Friction forces are calculated from the relative motion of a slider as it moves over the array of tips. First presented in [9], this method has been refined and automated to produce statistically significant results. The contacting and sliding surfaces mimic MEMS probe arrays such as those used for probe data storage and tip based nano-fabrication. Figure 1 shows an example of the AFM-like tips that are used to contact the flat surface of a slider. The sharp tips represent the asperities in contact between two surfaces where the total number of contact points can be controlled. Depending on the material properties and loading conditions, these probe arrays can have many more actual contact points than two nominally flat surfaces contacting each other [5].

EXPERIMENTAL SETUP

Based on the previously published method [9], friction forces are measured between a laterally unconstrained slider and an array of upward pointing tips as shown in Figure 2. A horizontal shaker laterally actuates the array allowing only friction forces at the contact points to move the slider. The array is mounted to the shaker's stage using a stainless steel "fence." This fence constrains the total motion of the slider to remain over the array, but its opening is large enough to allow 95 μ m of free motion in the lateral directions (see Figure 3). This entire setup is placed in a vacuum chamber capable of achieving pressures of 2e-5 torr (2.7e-3 Pa).

Figure 1. SEM images of a row of cantilevered probe tips that serves as the contact points for the friction experiments and a close up image of a single tip.

Figure 2. Schematic of friction test setup with the slider sitting on top of the probe array.

Figure 3. SEM image and schematic of the slider sitting on top of an array surrounded by the stainless steel fence.

An accelerometer attached to the shaker's stage measures the lateral motion applied to the array by the shaker. Additionally, a differential laser Doppler vibrometer (LDV) provides a non-contact method for measuring the relative motion of the slider on top of the array. As shown in Figure 2, the reference laser of the LDV is focused on the shaker's stage and the other laser is focused on the edge of the slider.

The tip arrays used in these experiments consist of pyramidal single crystal silicon tips (20 nm initial radius of curvature) made by a combination of isotropic etching and oxidation sharpening. Each tip is located at the end of a rectangular cantilever. To compensate for variations in tip height and increase the probability that all the tips contact the slider, the compliance of the cantilever is tuned to deflect 300-400 nm under the normal load of the slider. SEM images showing that each tip in the array is worn confirm the assumption that the slider contacts all the tips in the array. Arrays with 3, 100, 196, and 289 tips are analyzed in this paper.

The slider that sits on top of the arrays provides the normal force between the two surfaces and a controlled, nominally flat surface for the tips to slide across. The slider is a 2 mm x 2 mm x 0.3 mm polished single crystal silicon chip with a RMS surface roughness of 0.3 nm. The slider's dimensions allow it to slide freely on top of the array of probe tips spanning a 1.6x1.6 mm² area (see Figure 3) and sufficiently reflect the LDV laser back to the emitter. To minimize the total mass and the distance between the center of mass and the sliding surface, a 1.8x1.8 mm² square is etched to approximately 210 μm from the top surface.

RESULTS AND DISCUSSION

The forces that act on the slider include the slider's weight (mass times gravity) and the normal forces at the contact points in the vertical direction and friction forces in the horizontal direction. Thus, the nominal normal force at each contact is approximately equal to the total weight divided by the number of tips. A moment created by the friction forces acting a distance from the center of mass can vary the normal forces across the array up to ±5% from the nominal normal force per tip. In addition, non-uniform tip height can lead to variations in the normal force at each tip. Table 1 lists the nominal normal force per tip for the arrays used in these experiments and the corresponding dynamic friction coefficients.

Figure 4 shows a sample of the accelerometer and LDV measurements and the corresponding friction analysis for a single release and slide event. The slider acceleration is the obtained by numerically differentiating the relative velocity and adding it to the shaker acceleration. Automation of the actuation, measurement, and analysis has allowed for investigation of over 20 different arrays in varying environments and over 4000 individual release events producing statistically significant results.

Table 1. Average loading and friction parameters for the arrays of various number of contact points.

Number of Tips	Slider Mass	Nominal Force per Tip	Dynamic Friction Coefficient
3	.99 mg	3.7 μN	0.61
100	1.34 mg	120 nN	1.27
196	1.22 mg	67 nN	1.77
289	1.12 mg	34 nN	2.75

Figure 4. Analysis of an individual release and slide event for a slider on a 100-tip structure at 1.9e-5 torr. The release and dynamic acceleration correspond to the static and dynamic friction coefficients when the acceleration is divided by gravity.

The labels in Figure 4 show the key events that correspond to the friction forces. The release event is where the slider overcomes the static friction force and begins to move relative to the array (Equation 1). After a brief transition period, the dynamic friction governs the subsequent motion of the slider (Equation 2). As shown in the figure, the dynamic friction is averaged to a constant value. Since only friction forces are acting in the lateral direction, the sum of the friction forces at each contact is equal to the inertial force of the slider.

$$\sum F_{f,static} \leq m_s a_{release} \quad (1)$$

$$\sum F_{f,dynamic} = m_s a_{dynamic} \quad (2)$$

The dimensionless friction coefficient is used to compare the friction values obtained from the various arrays and sliders used in these experiments. The friction coefficient is the friction force normalized by the total normal force, which simplifies to the measured acceleration of the slider divided by gravity as shown below:

$$\mu = \frac{F_f}{F_n} = \frac{m_s a_{meas}}{m_s g} = \frac{a_{meas}}{g} \quad (3)$$

FRICITION VARIATION WITH CONTACT NUMBER

Friction measurements between a MEMS probe array and a flat surface present a unique situation where the total number of contact points can be controlled. The number of contact points affects the total contact area between the two surfaces and the capillary forces. The attractive capillary forces originate from the pressure created by the curvature of the liquid meniscus acting over the area of the meniscus. The contact geometry of the probe tips leads to a liquid meniscus forming around every contact point. Thus, the attractive capillary forces will increase linearly with the total number of contact points [4].

Although the experiment is run in a vacuum chamber at low pressures, thin absorbed films of water continue to exist on the surfaces [4,5,10]. To normalize the effects of the capillary forces, all of the probe arrays and sliders were subjected to the same conditions leading up to the friction experiments. To maintain a clean sliding surface, the sliders are stored in deionized water and dried with nitrogen before mounting on top of the probe array. The probe array is stored at room temperature in a nitrogen dry box until the slider is mounted to it. Once mounted, the array and slider are installed in the vacuum chamber and pumped down to a base pressure less than 2×10^{-5} torr.

The relationship between the total number of contact points and the dynamic friction force is shown in Figure 5. Despite the fact that parameters such as actual contact area do not necessarily vary linearly with the number of contact points, the linearity of Figure 5 indicates that the capillary forces play a significant role in the friction forces even at low pressures.

Figure 5. Increasing friction with the number of contact points. Each point on this plot is the average of 200 individual sliding events after steady friction behavior is reached.

FRICITION VARIATION WITH CONTACT GEOMETRY

In addition to the role that the number of contact points plays in friction, small geometric changes of the tips also significantly affect the friction and adhesion forces. As the tips wear, the total contact area increases. The results shown in Figure 6 indicate that there is a large initial variation in the friction force as the slider moves for the first 20-200 μm . High contact pressures combined with tangential friction forces at the sharp tips result in large shear stresses and rapid wear. This rapid wear continues until the contact area is sufficient to sustain the contact stresses of the slider moving on top of the tips.

Figure 6. Friction coefficients as a function of the total sliding distance. Each data point represents the average dynamic friction coefficient of an individual sliding event. The large initial variation of the friction coefficient levels off to a constant value after sufficient sliding distance indicating that tip wear no longer significantly changes the friction force.

After the rapid initial change in friction force, a steady friction coefficient is reached as the slider moves longer distances. Figure 6 shows that after the inspection of the initial wear of the tips, the friction coefficient stabilizes to constant friction values with a standard deviation of less than 0.09 (100 tips and up). The standard deviation for the 3-tip array is larger since the slider positioning plays a significant role in the distribution of the normal force per tip. The stability of the friction force as the slider moves longer distances indicates that the effects from tip wear have become minimal.

Tip wear causes the tip to flatten, which increases the surface area and changes the friction coefficient. Figure 7 shows SEM images highlighting the geometric changes of the tips at various distance intervals. An increase in the total contact area due to wear serves to lower the total contact pressure on the tips. Although the slider placement on the tips can cause damage, the sharpness of tips after the slider is placed and removed without sliding is shown in column (a) of Figure 7 and the minimal geometry change from column (b) to column (c) shows that the initial sliding is responsible for the majority of the tip wear.

WEAR AND CONTACT PRESSURE

The wear rate of the tips is related to the total shear stress at the tip. This shear stress is a combination of the contact stresses acting in the normal direction and the lateral stresses from the friction forces. As the number of contact points increases, the combination of the decreased normal load per tip and the increased total contact area reduces the contact pressure at each tip. Thus, as shown in Figure 7, larger contact pressures (fewer number of tips) result in greater amounts of wear per tip. Figure 8 compares the resulting wear lengths, defined as the diagonal of the flat area created as the pyramidal tip is worn, after the friction forces have reached steady values versus the total number of contact points. The average contact pressure, the slider weight divided by the average total contact area, when the tip wear rate becomes minimal is 20 ± 10 MPa for all of the arrays.

Figure 7. SEM profiles of tips indicating amount of wear after initial placement with no sliding (a), after initial sliding of less than 1 mm (b), and after extensive sliding > 2 mm (c).

Figure 8. Averaged individual tip wear versus the number of contact points. The wear length in this case is the diagonal measured across the flat of the worn tip.

CONCLUSIONS

This work takes a careful look at the friction and wear properties between a MEMS probe array with varying number of contact points and flat surfaces. The results from this work show that the unique nature of multiple probe tip contacts causes large variations in the friction force with the number of contacts. Since the probe tips are located at the end of compliant cantilevers, the actual number of contact points for probe arrays can be much larger than typical flat surfaces in contact. Thus, the total friction

forces for applications such as probe-based data storage and tip based nano-fabrication can be significantly larger than flat contacting surfaces.

The findings of this work show that tip wear rate reaches a minimum value for a given contact pressure. In addition to the contact numbers, contact properties, and contact pressures discussed here, friction forces and wear depend on many other parameters including the material properties and additional environmental conditions. Generally, lower contact pressures result in less detrimental effects of wear, but other methods of improving the reliability of sliding surfaces exist including the use of different materials or controlled environments. Further investigations into these areas are needed to enhance the understanding of friction and wear at the micro- and nano-scale and improve the reliability of MEMS applications with contacting and sliding surfaces.

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