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Final LDRD Report Tribological Studies of Microelectromechanical Systems

Shannon J. Timpe, Bonnie R. Antoun, Kyriakos Komvopoulos, Michael T. Dugger

Prepared by
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Final LDRD Report
Tribological Studies of Microelectromechanical Systems

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Abstract

Understanding and controlling friction in micromachine interfaces is critical to the reliability and operational efficiency of microelectromechanical systems (MEMS). The relatively high adhesion forces and friction forces encountered in these devices often present major obstacles to the design of reliable MEMS devices. Using surface micromachining, arrays of microstructures are being designed and tested to examine the adhesion characteristics, static friction behavior, and dynamic friction response. Emphasis is also being given to the control and actuation of the test structures and the modeling of the dynamic response and contact mechanics at the interface. Specifically, the purpose of the research is to fabricate and test MEMS devices in order to obtain insight into the effect of surface topography, material properties, surface chemical state, environmental conditions, and contact load on the static and dynamic characteristics of the contact interface.

Polysilicon micromachines have been designed for the purpose of studying the tribological properties of microelectromechanical systems (MEMS). A device for

characterizing interfacial adhesion and a device for characterizing friction have been developed at the University of California at Berkeley. These devices were used to develop and understanding of the physics controlling the interfacial behavior that is critical to the reliability and efficiency of micrometer-scale devices. All research activities were conducted at the University of California at Berkeley by Shannon Timpe, awardee of the Excellence in Engineering Fellowship that was established with this LDRD project. Shannon Timpe successfully completed his research project and published several relevant papers on this topic. Shannon also received his M.S from UC Berkeley in May 2004 and his Ph.D. from UC Berkeley in May 2007.

ACKNOWLEDGMENTS

The authors would like to acknowledge support for this work that was provided through an Excellence in Engineering Graduate Fellowship awarded to Shannon Timpe at the University of California at Berkeley from Sandia National Laboratories' Campus Executive LDRD Program.

CONTENTS

FIGURES

Nomenclature

DOE	Department of Energy
F	Force
LDRD	Laboratory Directed Research and Development
MEMS	Microelectromechanical systems
p	Contact pressure
RH	Relative Humidity
SNL	Sandia National Laboratories
τ	Shear stress
μ	Coefficient of friction

1. INTRODUCTION

Increasing demands for smaller feature sizes in microelectronics have increased the impact of surface forces on microdevice reliability. To understand the origins and evolution of these surface forces, it is necessary to develop specialized microstructures and experimental techniques for accurate characterization of the interfacial phenomena occurring at the nano-/microscale. For this purpose, unique microdevices fabricated with surface micromachining were designed and tested to examine interfacial phenomena encountered under typical conditions of microelectromechanical systems (MEMS).

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2. RESEARCH OVERVIEW

The static adhesion force was examined under controlled loading and environmental conditions using the microdevice shown in Figure 1. Both van der Waals forces and capillary forces were found to contribute to the magnitude of the adhesion (pull-off) force at the inception of surface separation. These attractive forces intensified with the increase of the apparent contact pressure due to plastic deformation at asperity contacts. An enhancement of the contribution of the capillary forces to the total adhesion force was encountered with the increase of the relative humidity.

The effect of electrical activation on the adhesion behavior at MEMS contact interfaces was examined with the adhesion testing device in Figure 1. At low interfacial voltages, the insulating native oxide layer prevented significant asperity damage. However, increasing the interfacial voltage produced a transition behavior characterized by dielectric leakage and higher adhesion forces, attributed to both thermal effects (i.e., thermal expansion and fusion of asperity contacts) and electrical effects (i.e., charge trapping in the oxide surface layer). At relatively high interfacial voltages, high current flow across the contact interface promoted interfacial bonding, resulting in permanent surface adhesion. The obtained results illustrate the interdependence of microscale electrical, thermal, and adhesion phenomena at MEMS contact interfaces. The effect of electrical activation on adhesion was examined in the context of the predominant electrical and thermal phenomena occurring at the contact interface.

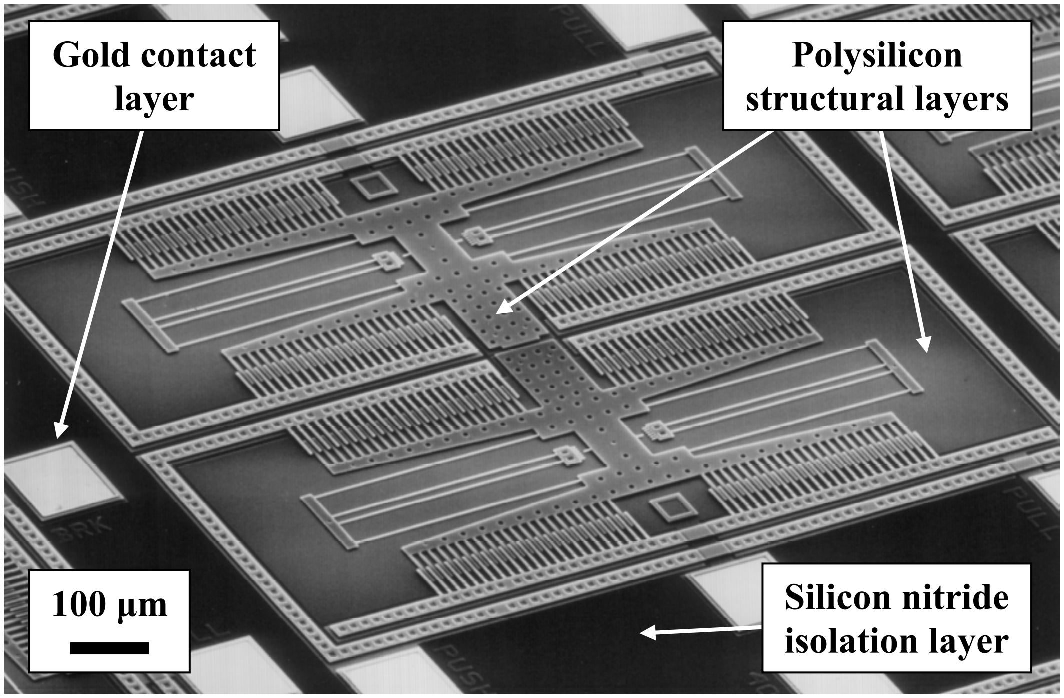

Figure 1. Scanning electron microscope image of the sidewall adhesion testing device used to examine the adhesion properties under controlled environmental and loading conditions.

Using the device shown in Figure 2, the measured adhesion force was coupled with static friction measurements to define the true coefficient of friction, which includes both external and internal force components of the total normal force. It was found that the true coefficient of friction is independent of environment and contact load, as shown in the data (see Figure 3) obtained at ambient pressures ranging from 760 – 10^{-3} torr, temperatures ranging from 35 - 120°C, and relative humidity ranging from ~0 – 95%. The exploration of the true friction coefficient revealed the partial elastic recovery of contacting asperities, resulting in an observable difference between in-contact adhesion force and pull-off force.

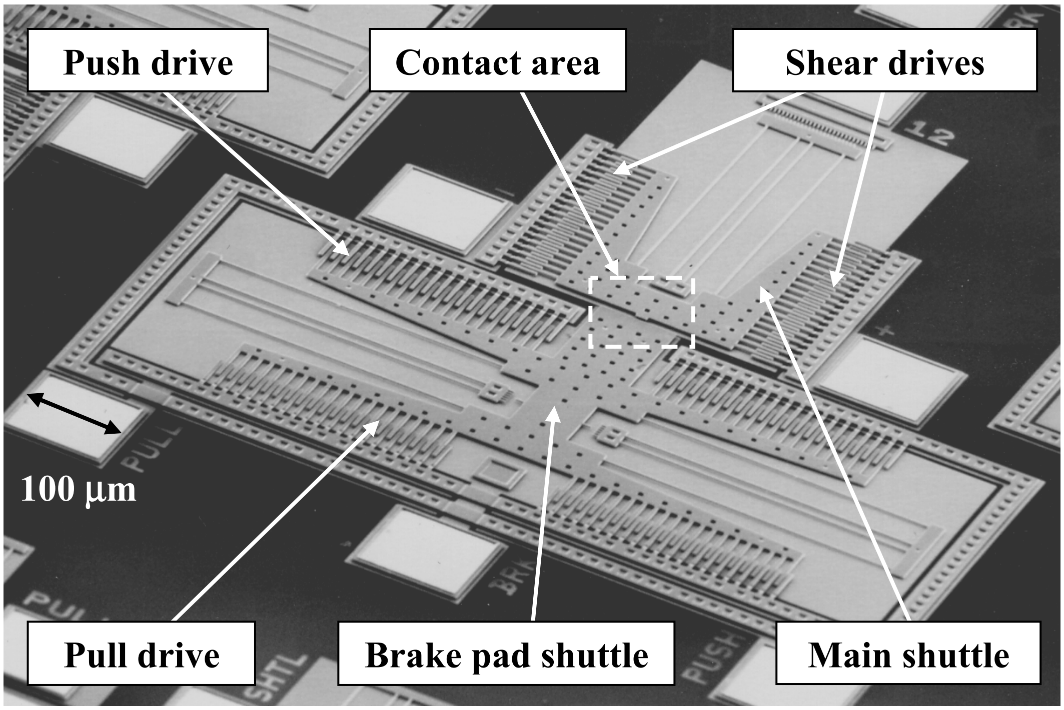

Figure 2. SEM micrograph of the friction testing surface micromachine used to perform friction and adhesion experiments showing the two comb-driven shuttles that come into contact along their sidewall surfaces.

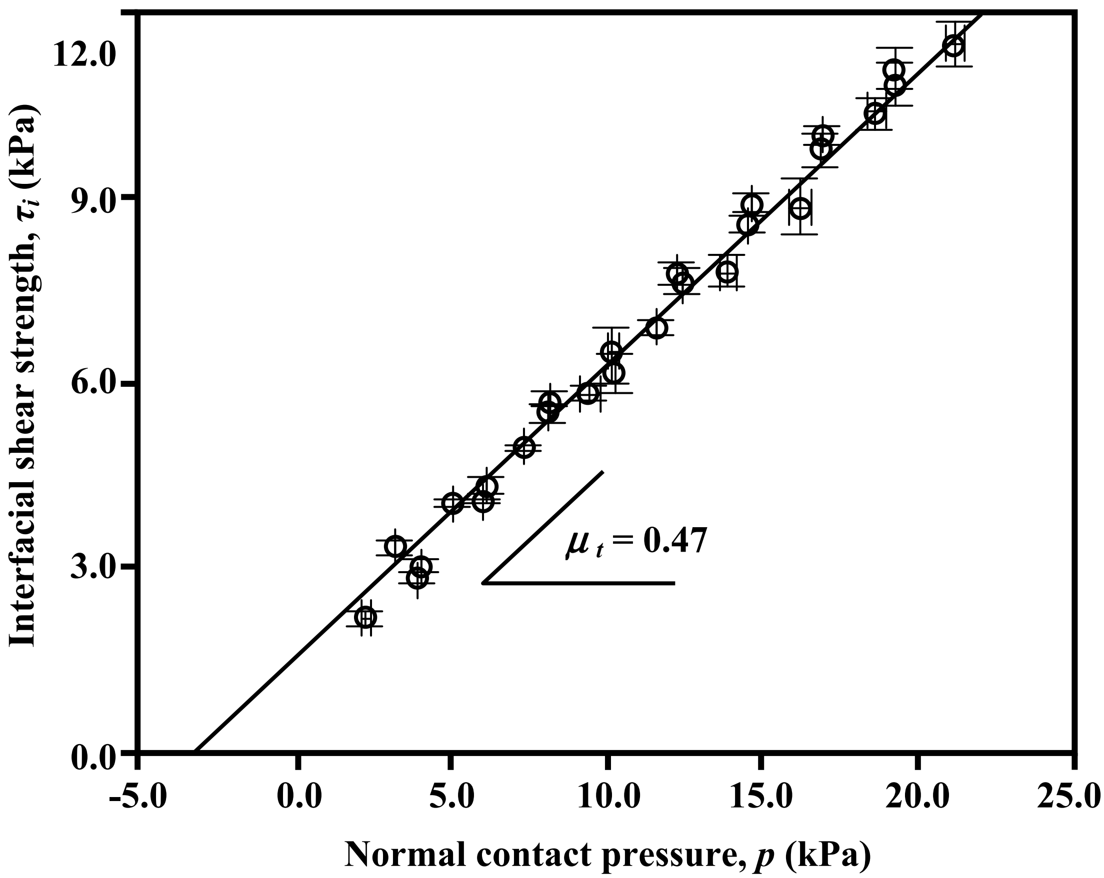

Figure 3. Interfacial shear strength versus normal contact pressure several environmental conditions. Data points represent averages of ten experiments and error bars indicate one standard deviation above and below the corresponding average values.

Dynamic sliding contact experiments were performed to determine the critical parameters affecting device lifetime. The development of wear debris was examined and the observations were compared to the evolution of critical interfacial properties including the adhesion force, static friction force, and dynamic friction force. In this study, microscale stick-slip phenomena were observed *in situ* as shown in the device sliding waveforms of Figure 4. In the dynamic friction experiments, the two distinct wear patterns depicted in Figure 5 were seen for devices experiencing nominally identical conditions. The first wear pattern lead to the development of large-scale wear debris and surface deformation with minimal increase in the adhesion force. The second wear pattern showed no visible wear debris, but resulted in a dramatic increase in the measured adhesion force. By examining the evolution of the relevant tribological forces and theoretical failure envelopes (see Figure 6), device failure in dynamic sliding contact was attributed to the development of excessive static friction at stop points of dynamic oscillation.

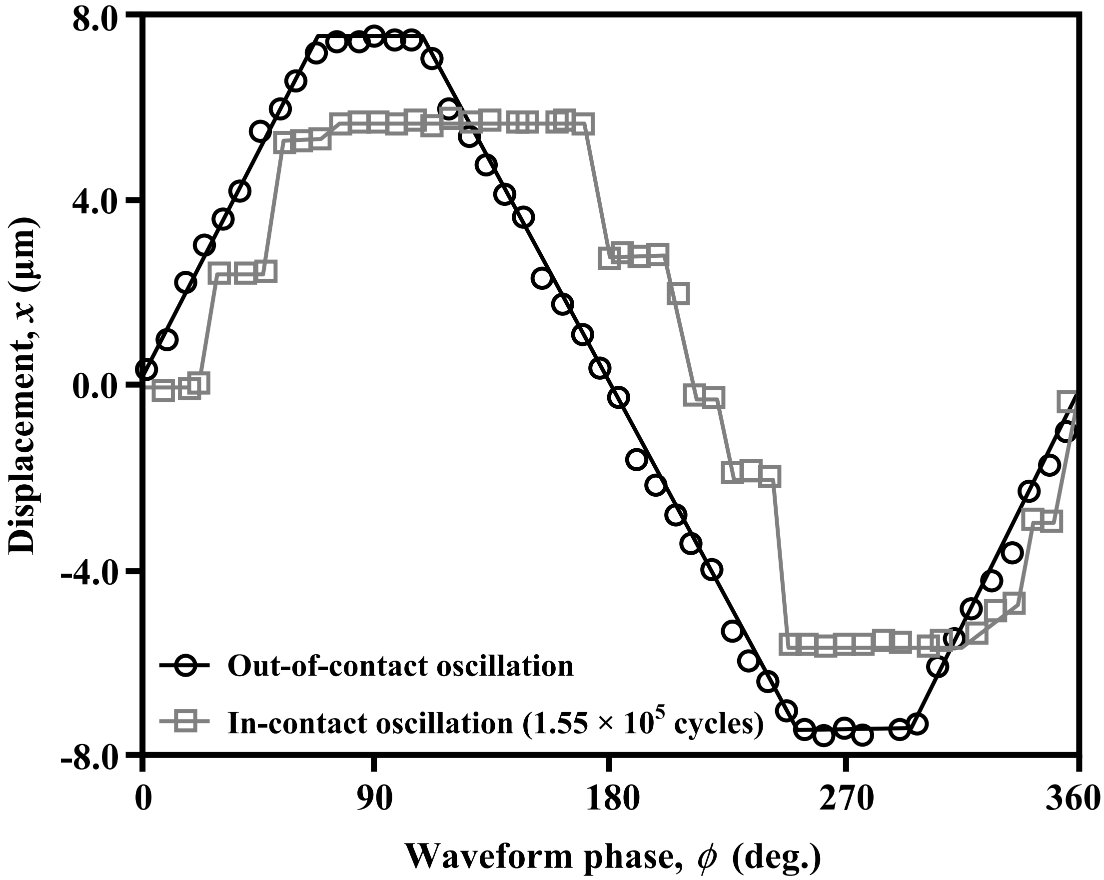

Figure 4. Shear displacement as a function of the voltage waveform phase for out-of-contact (free) oscillation and in-contact (sliding) oscillation after the accumulation of 1.55 × 10^5 sliding cycles revealing the occurrence of several stick-slip instances throughout the motion range.

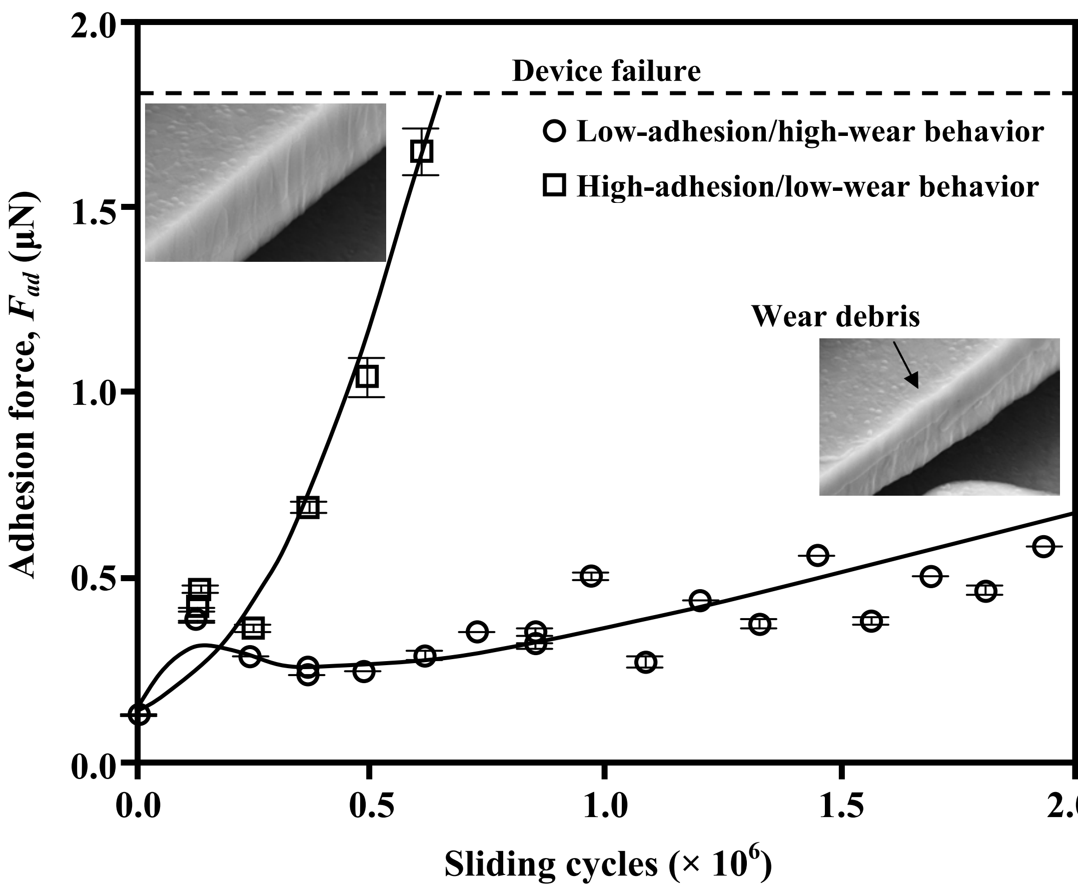

Figure 5. Adhesion force versus number of sliding cycles of micromachines characterized by low-adhesion/high-wear and high-adhesion/low-wear behaviors. Data points represent averages of five experiments and error bars indicate one standard deviation above and below the corresponding average value.

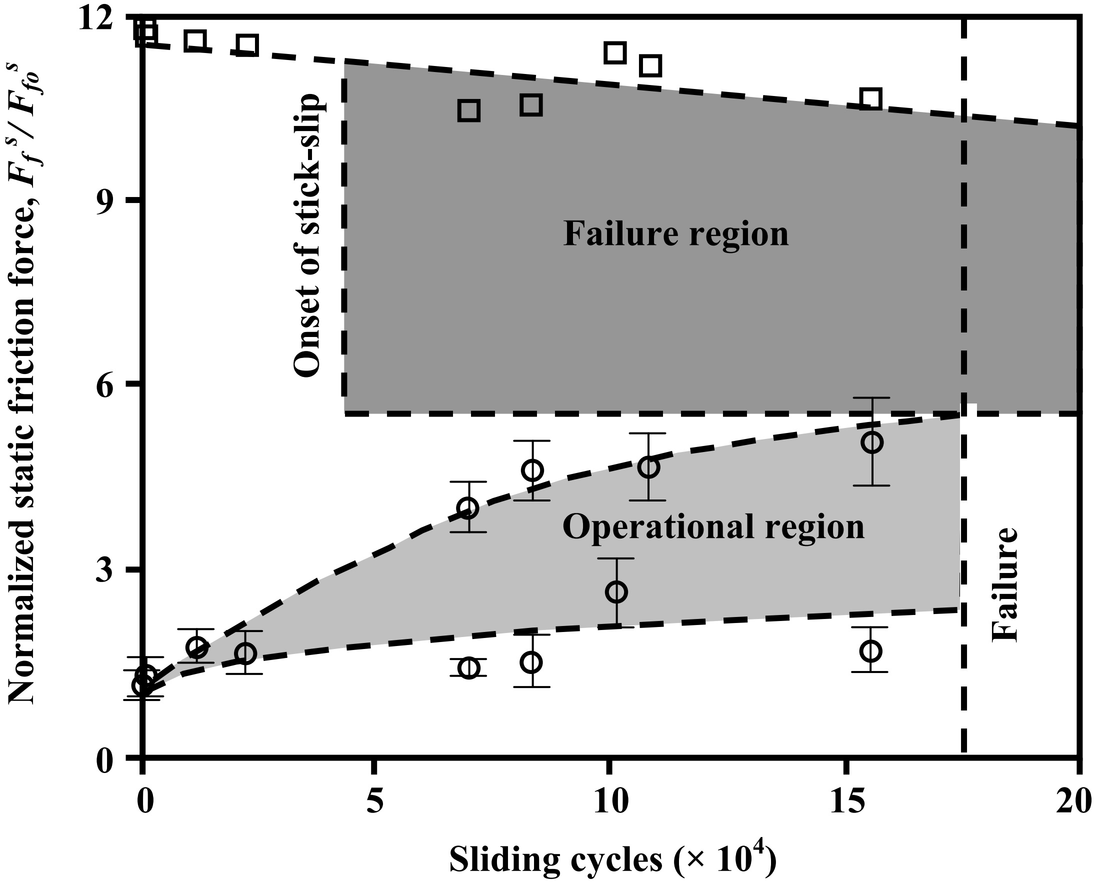

Figure 6. Normalized static friction force versus sliding cycles. A binary behavior of the static friction force occurs with the onset of stick-slip at ~5 × 10^5 sliding cycles which defines the operational region. Failure occurs when the upper limit of the static friction force intersects the lower boundary of the failure region.

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3. CONCLUSIONS

Under this research, a thorough and complete method for evaluating the dominant tribological mechanisms in microelectromechanical systems was defined and executed under controlled conditions. Insight into the critical surface phenomena influencing adhesion, static friction, dynamic friction, and wear was gained. The current methodology provides a means for determining the basic parameters that are significant in the development of contact-mode MEMS technology.

A list of publications resulting from this research, throughout the duration of the University of California at Berkeley Excellence in Engineering Fellowship, is included in the next section.

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Research Publications

1. S. J. Timpe, *An Experimental Study of Sidewall Adhesion in Microelectro-mechanical Systems,* Master of Science Thesis, University of California, Berkeley, CA, 2004.

2. S. J. Timpe and K. Komvopoulos, "An Experimental Study of Sidewall Adhesion in Microelectromechanical Systems," *Journal of Microelectromechanical Systems*, **14(6)**, pp. 1356-1363 (2005).

3. S. J. Timpe and K. Komvopoulos, "The Effect of Adhesion on the Static Friction Properties of Sidewall Contact Interfaces of Microelectromechanical Device," *Journal of Microelectromechanical Systems*, **15(6)**, pp. 1612-1621 (2006).

4. S. J. Timpe & K. Komvopoulos, "Electrical Effect on the Adhesion Force at MEMS Contact Interfaces," in *Proceedings of the STLE/ASME International Joint Tribology Conference*, October 23-25, 2006, San Antonio, TX, USA

5. S. J. Timpe, *Experimental Examination of the Tribological Properties of Microelectromechanical Systems*, PhD Dissertation, University of California, Berkeley, CA, 2007.

6. S. J. Timpe and K. Komvopoulos, "Effects of Electrical and Thermal Phenomena on the Evolution of Adhesion at Contact Interfaces of Electrostatically Activated Surface Microstructures," *Applied Physics Letters*, **90**, pp. 093510-1 – 093510-3 (2007).

7. S. J. Timpe and K. Komvopoulos, "Microdevice for Measuring Friction and Adhesion Properties of Sidewall Contact Interfaces of Microelectromechanical Systems," *Review of Scientific Instruments*, **78**, pp. 065106-1 – 065106-9 (2007).

8. S. J. Timpe, "Mechanical and Environmental Degradation of Self-Assembled Monolayer Coatings for Microelectromechanical System," in *Proceedings of the STLE/ASME International Joint Tribology Conference*, October 22-24, 2007, San Diego, CA, USA.

9. M. A. Philippine, S. J. Timpe, and K. Komvopoulos, "Evolution of Interfacial Adhesion Force in Dynamic Micromachines due to Repetitive Impact Loading," *Applied Physics Letters*, **91**, pp. 063102-1 – 063102-3 (2007).

10. S. J. Timpe, K. Komvopoulos, M. T. Dugger, "Microscale Friction Phenomena in Oscillatory Sliding Contacts," *Journal of Applied Physics*, **102**, pp. 123503-1 – 123503-8 (2007).

11. S. J. Timpe, D. A. Hook, M. T. Dugger, & K. Komvopoulos, "Levitation Compensation Method for Dynamic Electrostatic Comb-Drive Actuators," accepted *Sensors and Actuators A. Physical*, 2007.

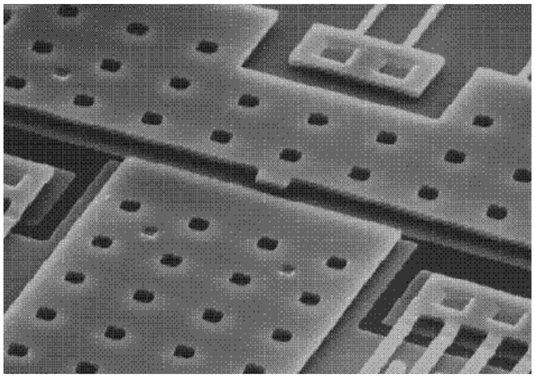
APPENDIX A: PHD DISSERTATION EXIT SEMINAR

A detailed overview of the results obtained during the course of the fellowship is presented in this appendix. This presentation was given by Shannon Timpe as his PhD dissertation seminar exit presentation at the University of California at Berkeley on April 18, 2007.

University of California at Berkeley — Shannon James Timpe

Experimental Examination of the Tribological Properties of Polysilicon Microdevices

Shannon James Timpe



PhD Dissertation Semianr

April 18th, 2007

PhD Dissertation Seminar

University of California at Berkeley — Shannon James Timpe

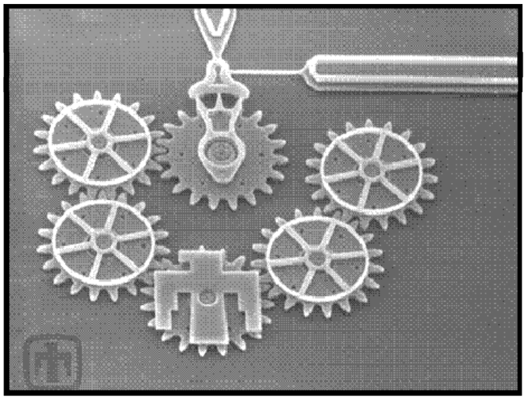
Topics

- Introduction and Motivation
- Device Descriptions
- Static Adhesion Measurements
- Static Friction Measurements
- Dynamic Sliding Measurements
  - Changes in Tribological Properties
  - Examination of Wear
- Conclusions and Acknowledgements

PhD Dissertation Seminar

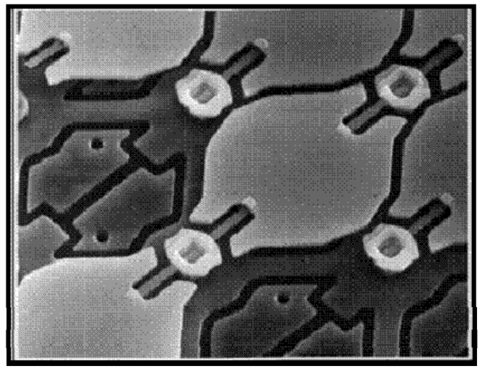
Project Motivation

Contacting Surfaces



Sandia National Laboratories
Gear System

Texas Instruments Digital Micromirrors

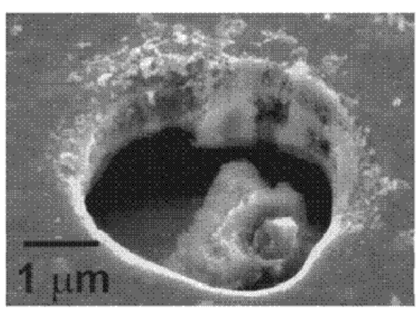


University of California at Berkeley — Shannon James Timpe

Project Motivation

Reliability of Microelectromechanical Systems

- Surface properties influence some of the major failures in MEMS:
  - Adhesion forces
  - Friction failure
  - Wear at the contact interface



Sandia National Laboratories
Micromotor Damage

PhD Dissertation Seminar

Project Motivation

Force Scaling Law

Scaling up to Macroscopic Applications:

- Inertial forces become *large* faster
- Surface forces often become negligible

Surface Forces α L^2

Inertial Forces α L^3

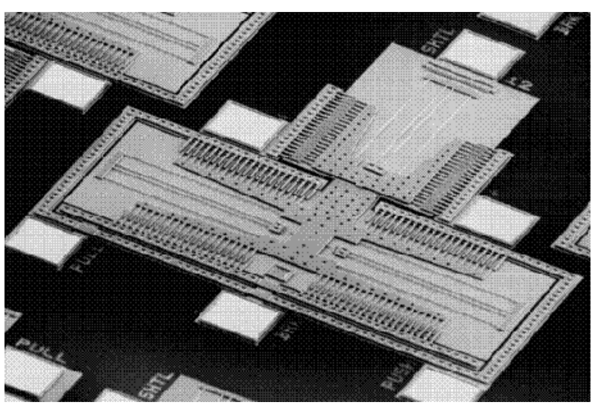
Scaling down to MEMS Applications:

- Inertial forces become *small* faster
- Surface cannot be neglected

University of California at Berkeley — Shannon James Timpe

Research Purpose

Design and test innovative microstructures in order to develop an understanding of tribological phenomena in microelectromechanical systems



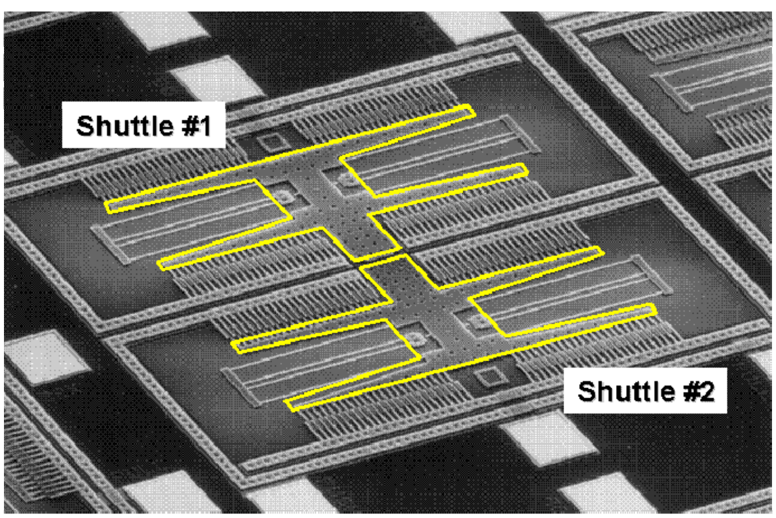
PhD Dissertation Seminar

Topics

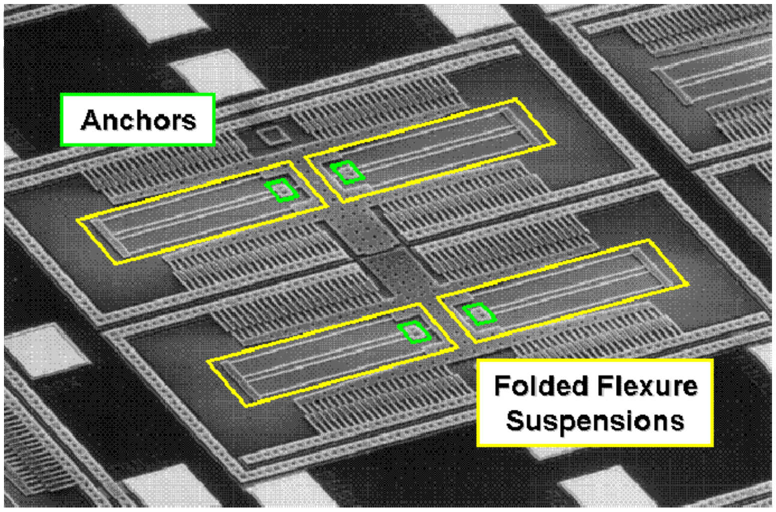
- Introduction and Motivation
- **Device Descriptions**
- Static Adhesion Measurements
- Static Friction Measurements
- Dynamic Sliding Measurements
  - Changes in Tribological Properties
  - Examination of Wear
- Conclusions and Acknowledgements

Device #1 – Adhesion Testing Structure

The device consists of two symmetric surface micromachined shuttles suspended approximately 2 μm off the substrate



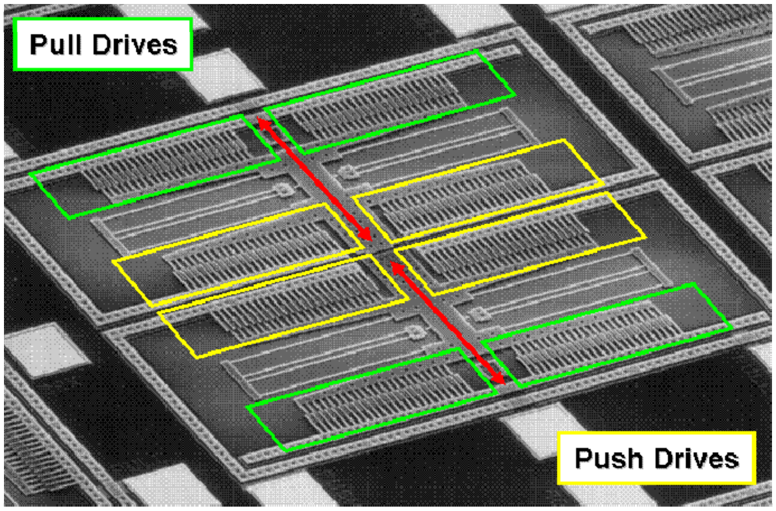
Device #1 – Adhesion Testing Structure



The shuttles are suspended off the substrate by folded flexure systems with inner anchors

University of California at Berkeley — *Shannon James Timpe*

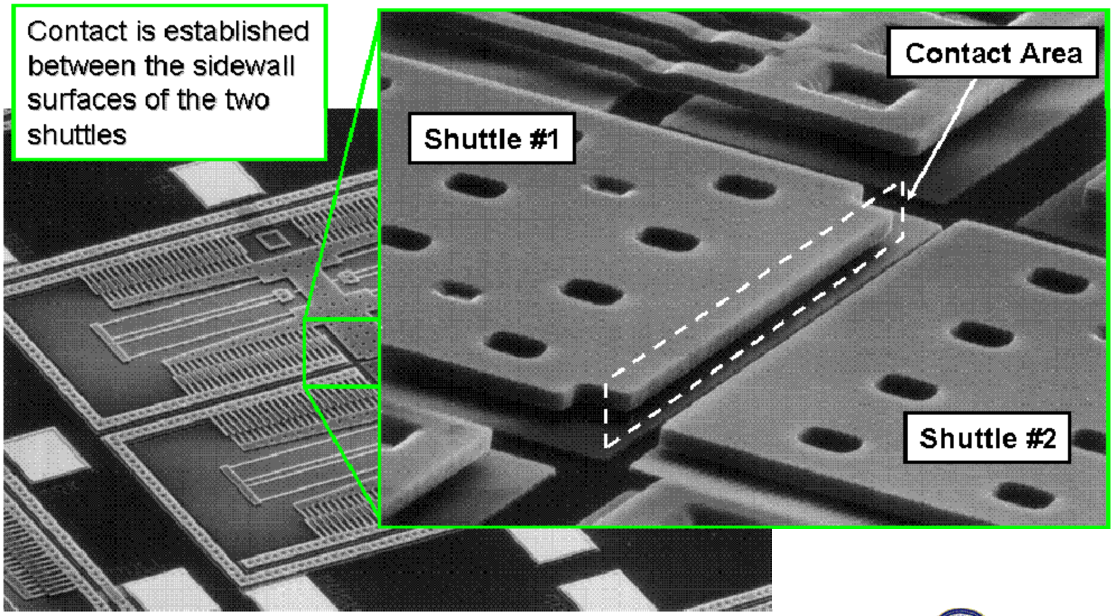
Device #1 – Adhesion Testing Structure



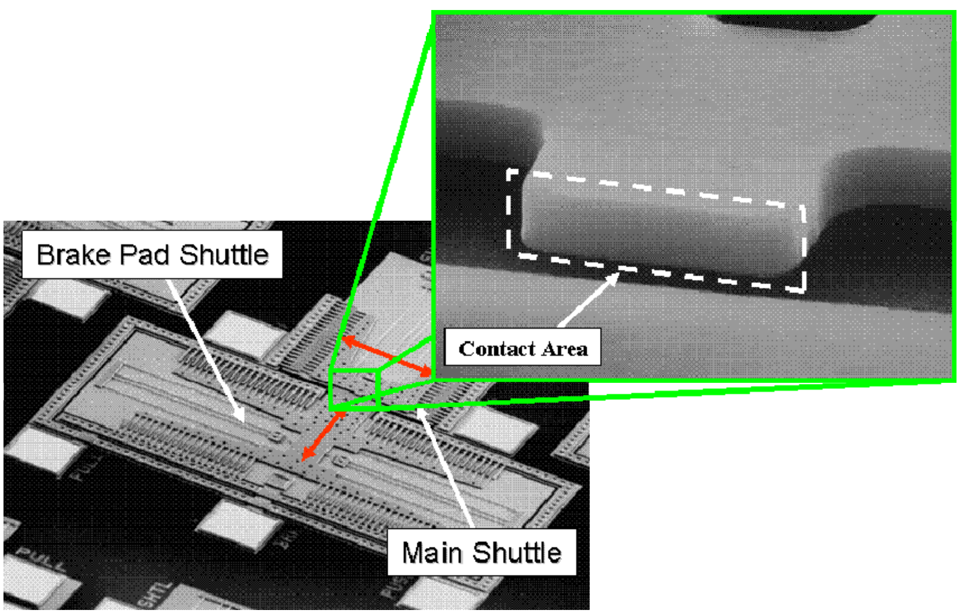
In-plane displacements are generated by comb drive actuators

PhD Dissertation Seminar

Device #1 – Adhesion Testing Structure

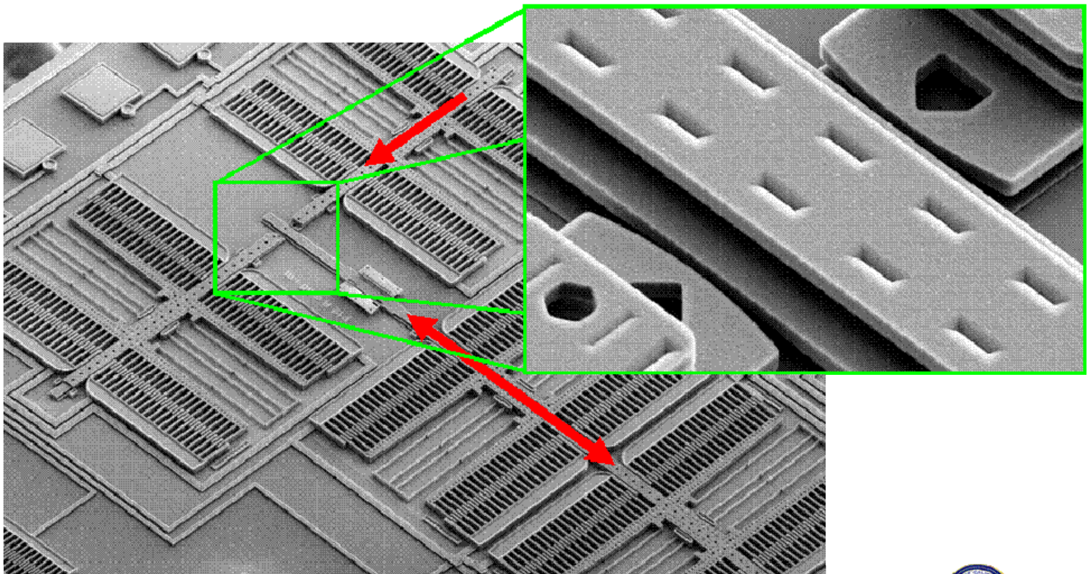


Device #2 – Friction Testing Structure



Device #3 – Sandia National Laboratories Device

Designed by M.T. Dugger



Topics

- Introduction and Motivation
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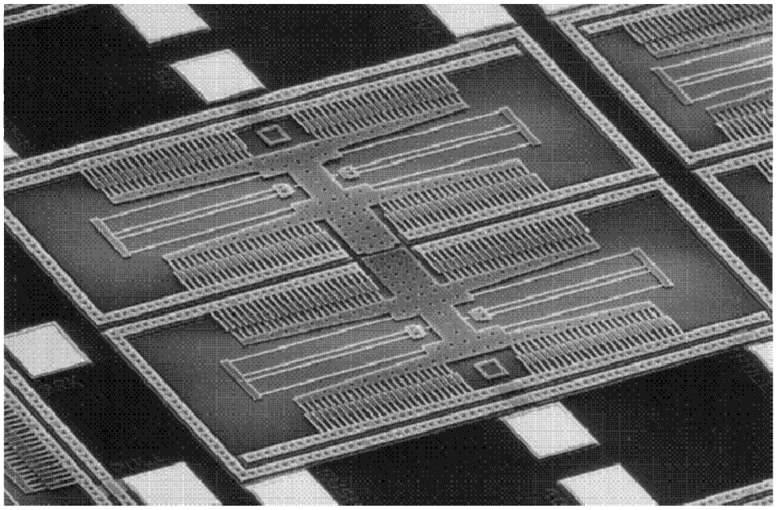
- Static Friction Measurements
- Dynamic Sliding Measurements
  - Changes in Tribological Properties
  - Examination of Wear
- Conclusions and Acknowledgements

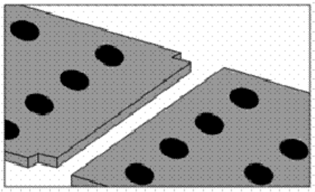
Static Adhesion Experiments

Experimental Procedure



Step #1:

Shuttles begin in the rest position and are separated by approximately 4 μm



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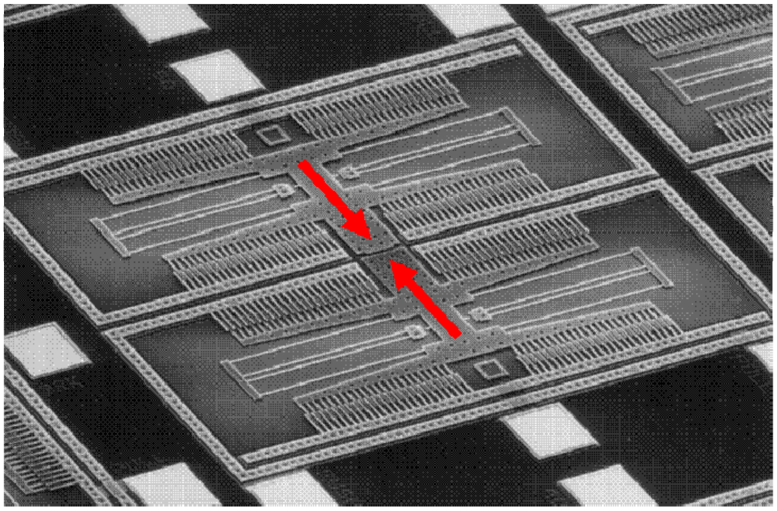
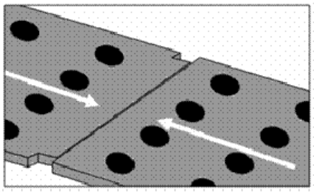
Static Adhesion Experiments

Experimental Procedure



Step #2:

The shuttles are brought into contact along their sidewalls and a pre-determined contact load is applied at the interface



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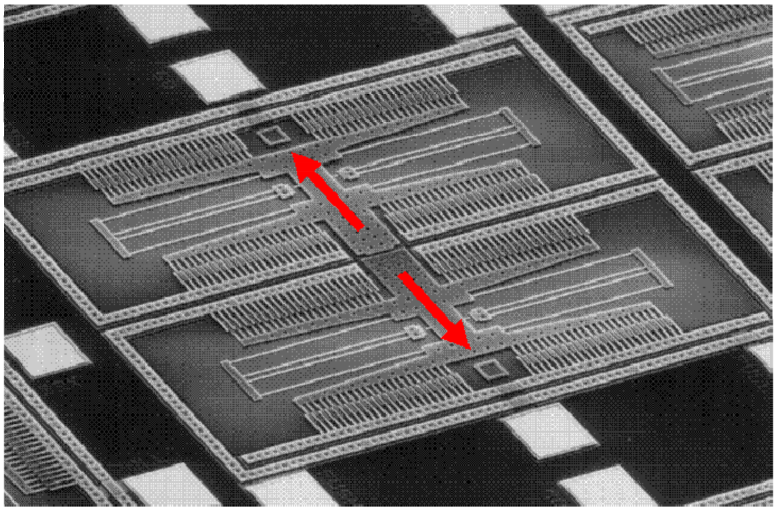
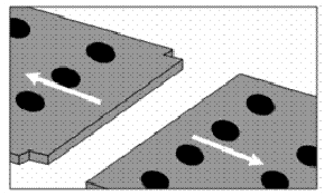
Static Adhesion Experiments

Experimental Procedure



Step #3:

The pull comb drives are activated in order to separate the shuttles



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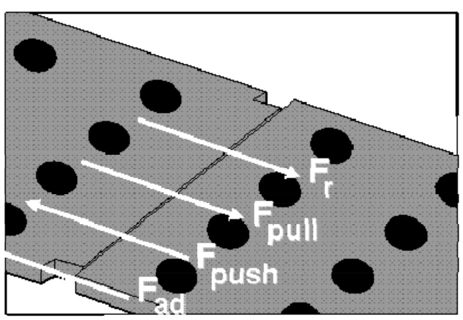
Static Adhesion Experiments

Experimental Procedure



Calculation:

At the instant of surface separation, a force balance can be drawn in order to calculate the adhesion force

$$F_{ad} = F_r + F_{pull} - F_{push}$$

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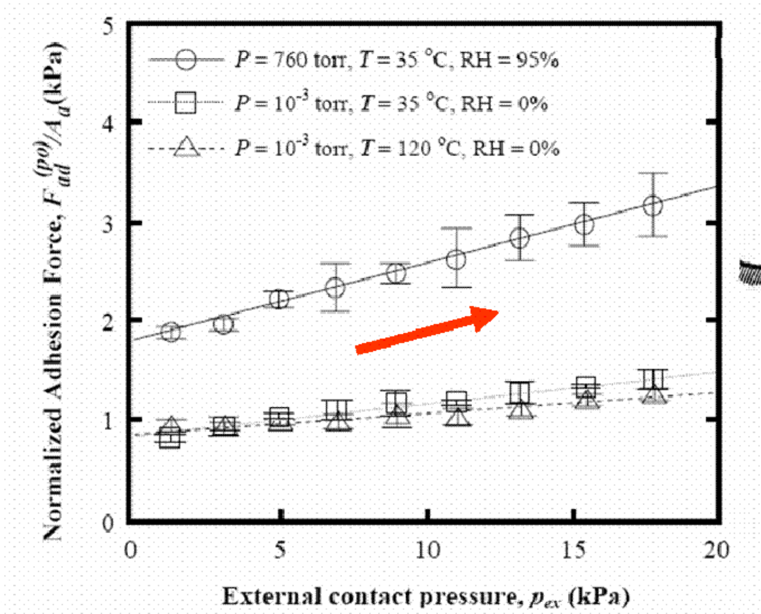
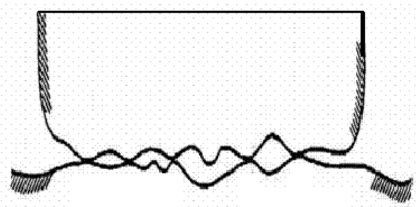
Static Adhesion Experiments

Characteristic Data



Permanent Deformation



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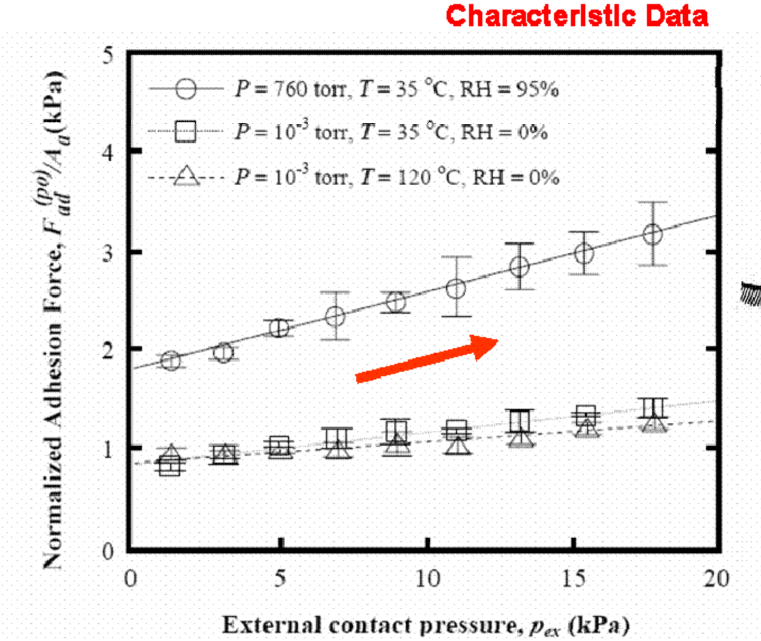
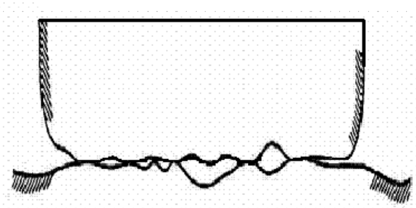
Static Adhesion Experiments

Characteristic Data



Permanent Deformation



- Real Area Increase
- Relative Separation Decreases

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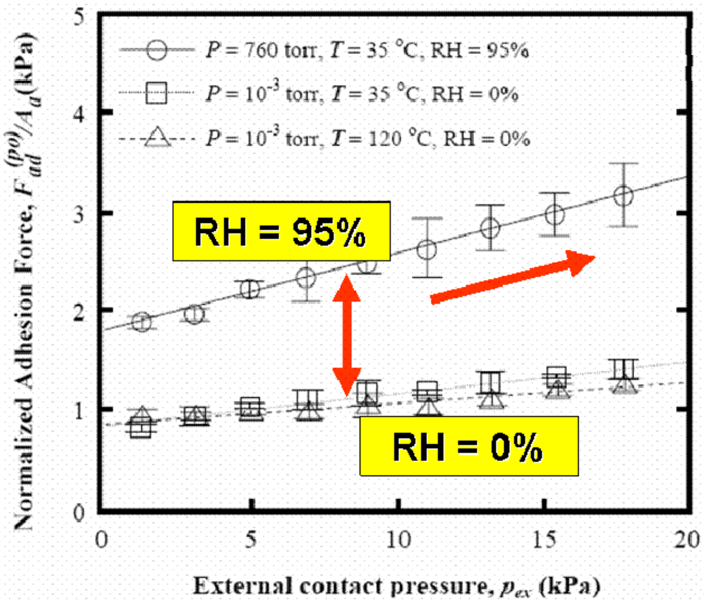
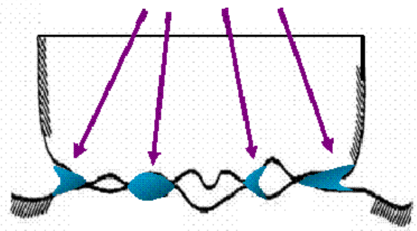
Static Adhesion Experiments

Characteristic Data



Capillary Condensation



Increasing load increases meniscus formation

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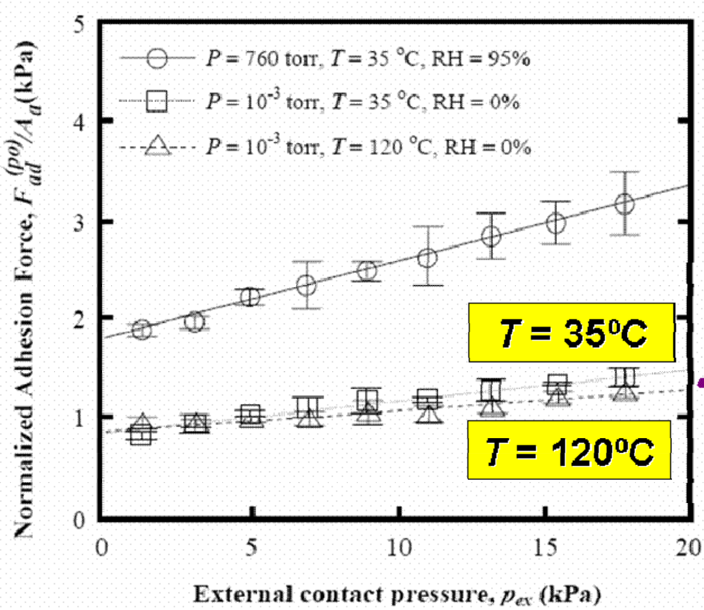
Static Adhesion Experiments

Characteristic Data



- No change in elastic properties
- Vacuum testing achieves baseline liquid content

PhD Dissertation Seminar

Topics

- Introduction and Motivation
- Device Descriptions
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- Dynamic Sliding Measurements
  - Changes in Tribological Properties
  - Examination of Wear
- Conclusions and Acknowledgements

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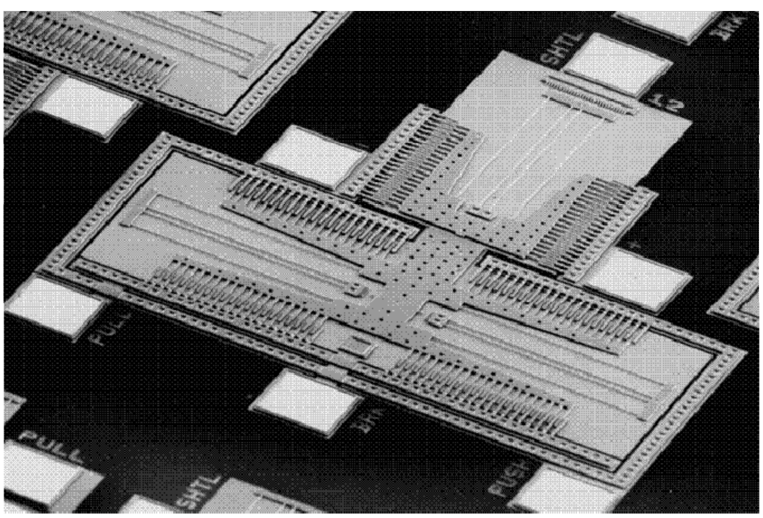
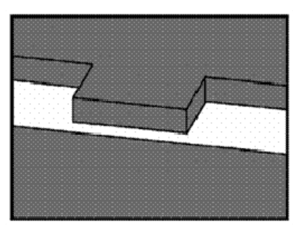
Static Friction Experiments

Experimental Procedure



Step #1:

Shuttles begin in the rest position and are separated by approximately 4 µm



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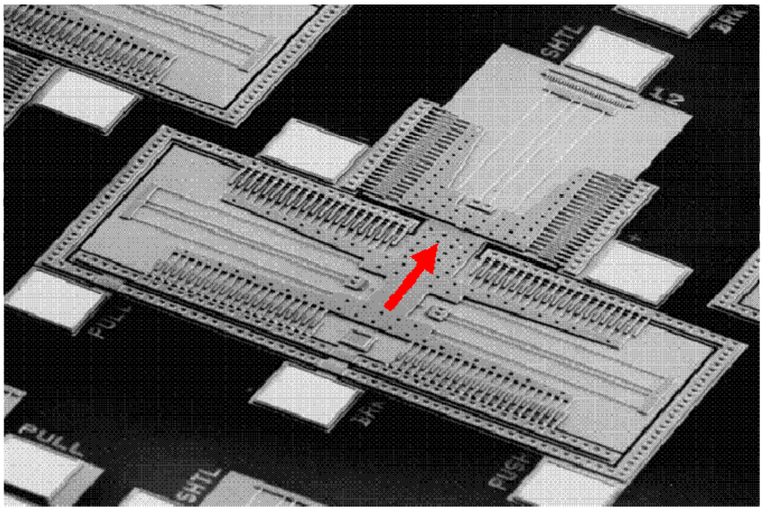
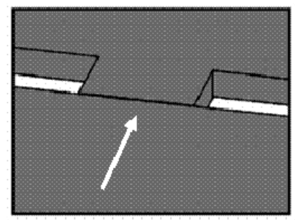
Static Friction Experiments

Experimental Procedure



Step #2:

The shuttles are brought into contact along their sidewalls and a pre-determined contact load is applied at the interface



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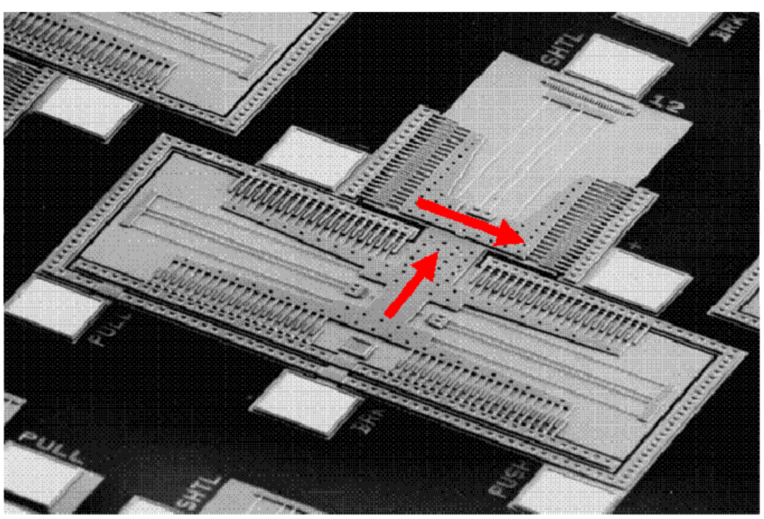
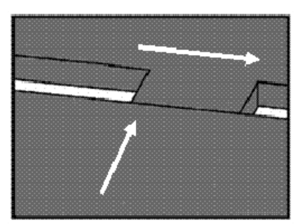
Static Friction Experiments

Experimental Procedure



Step #3:

The shear drives are activated in order to provide a shear load to the contact interface



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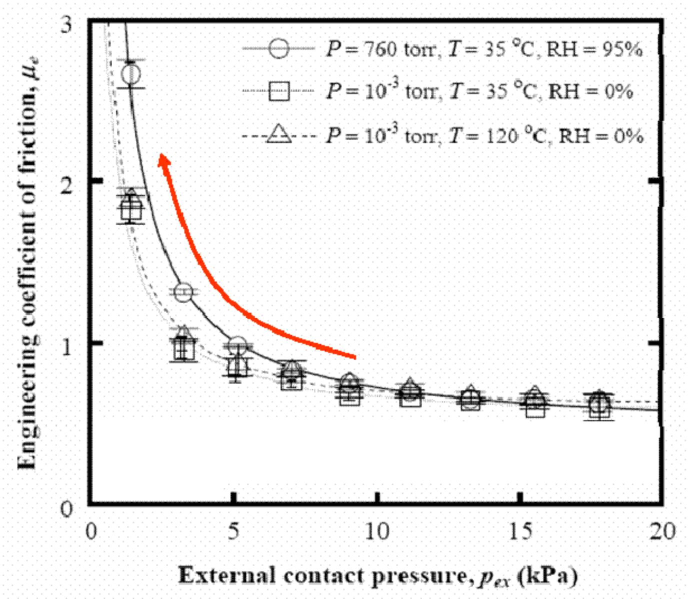
Static Friction Experiments

Characteristic Data



Adhesion Effect

$F_{ad} \sim F_{ex}$

$F_{tot} \not\approx F_{ex}$

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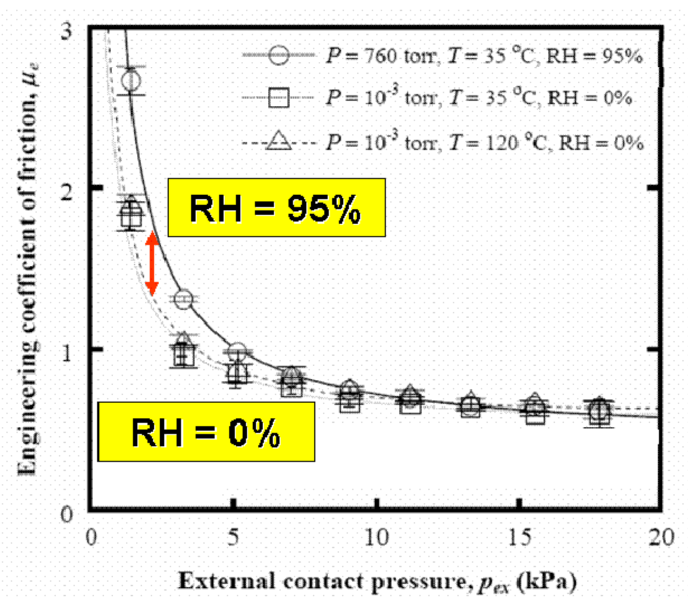
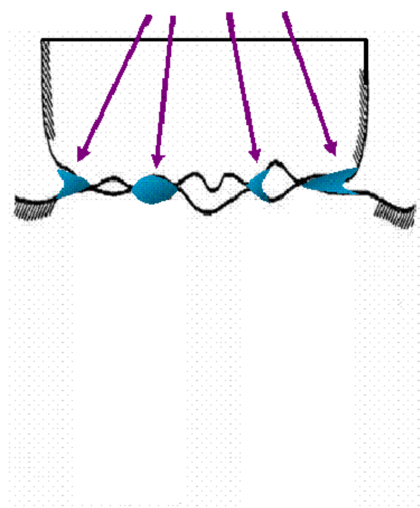
Static Friction Experiments

Characteristic Data



Capillary Condensation



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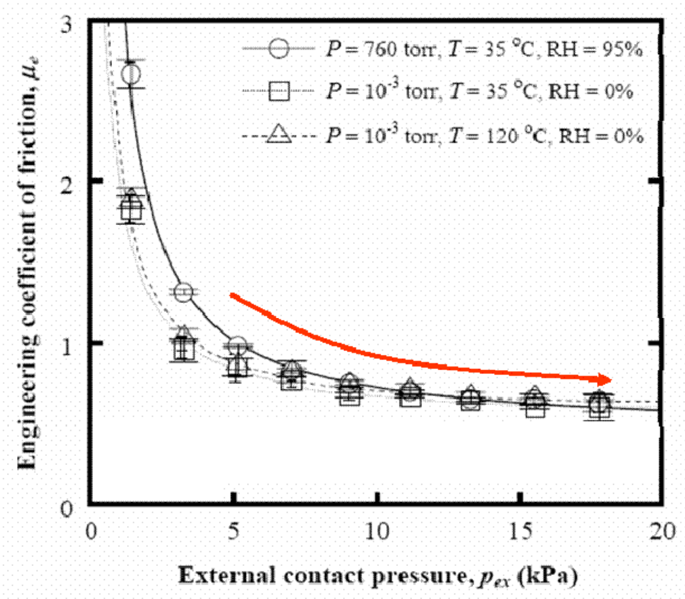
Static Friction Experiments

Characteristic Data



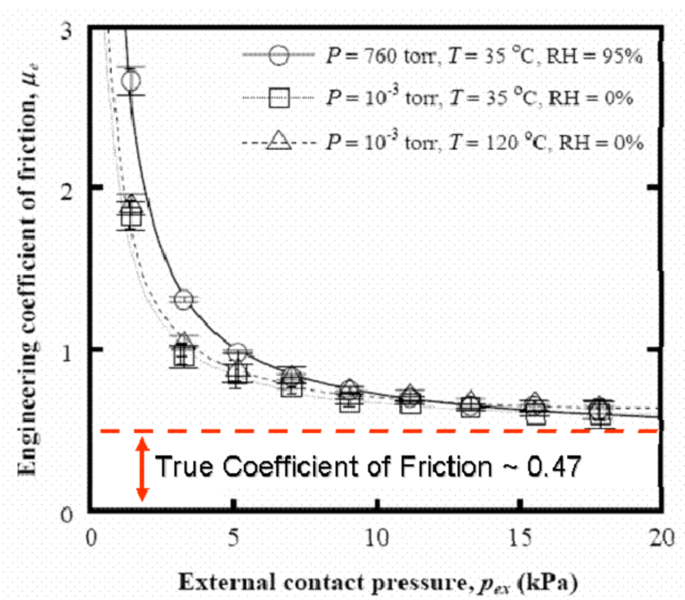
Adhesion Effect

$$F_{ad} \ll F_{ex}$$

$$F_{tot} \approx F_{ex}$$

Static Friction Experiments

Characteristic Data



Fitted True Coefficient of Friction

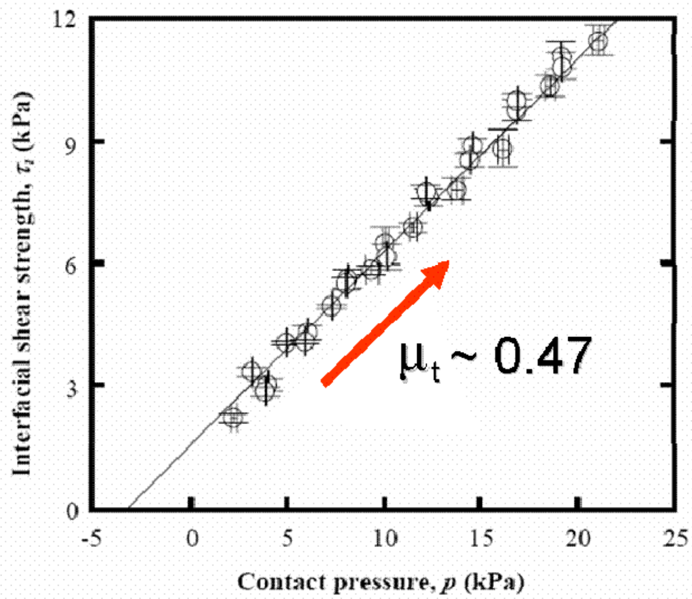
$$\mu_t = \frac{F_f}{F_{ex} + F_{ad}}$$

$$\approx \frac{F_f}{F_{ex}}$$

(at high loads)

Static Friction Experiments

The Effect of Adhesion on the Static Friction Behavior



True Coefficient of Friction

$$\mu_t = \frac{F_f}{F_{ex} + F_{ad}}$$

Independent of Environment

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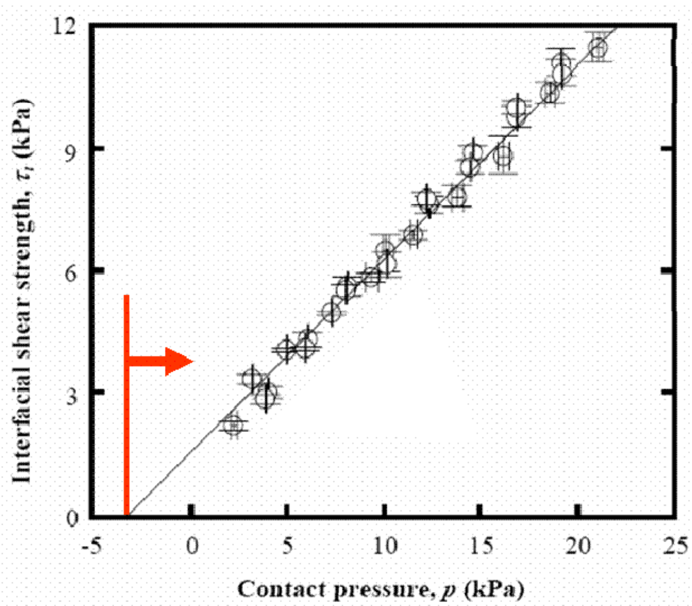
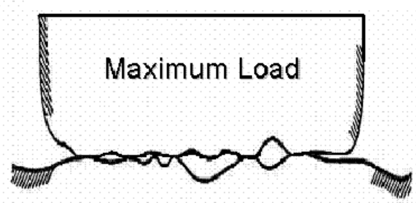
Static Friction Experiments

The Effect of Adhesion on the Static Friction Behavior



Elastic Recovery of Asperities



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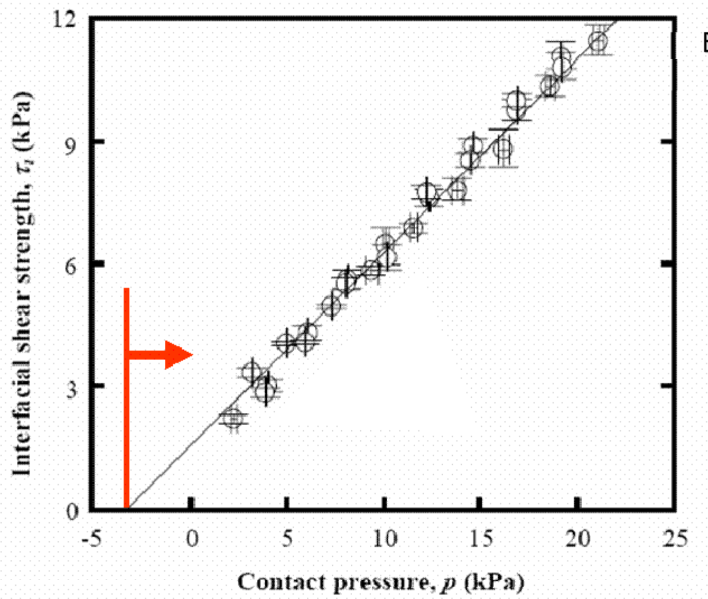
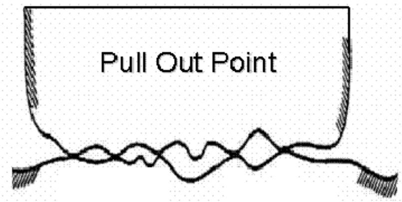
Static Friction Experiments

The Effect of Adhesion on the Static Friction Behavior



Elastic Recovery of Asperities



Adhesion is Underestimated

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Topics

- Introduction and Motivation
- Device Descriptions
- Static Adhesion Measurements
- Static Friction Measurements
- Dynamic Sliding Measurements
    - Changes in Tribological Properties
    - Examination of Wear
- Conclusions and Acknowledgements

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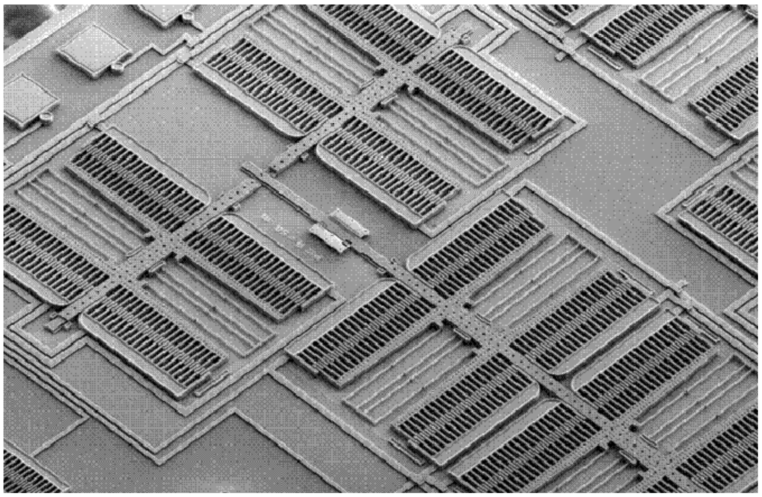
Dynamic Sliding Experiments

Experimental Procedure

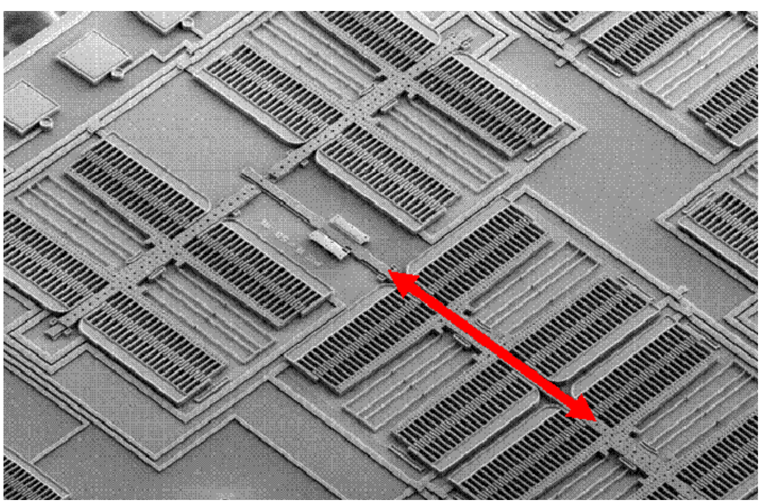


Step #1:

Shuttles begin in the rest position and are separated by approximately 1.2 μm

Dynamic Sliding Experiments

Experimental Procedure



Step #2:

An AC signal is applied to the main shuttle to provide oscillatory motion

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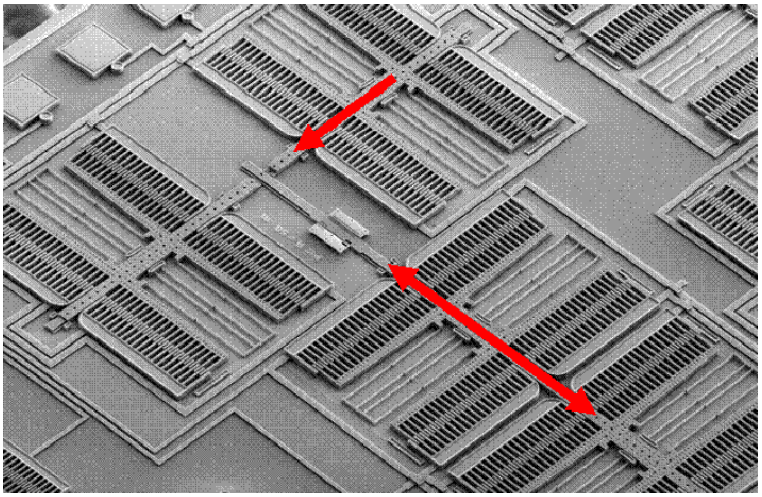
Dynamic Sliding Experiments

Experimental Procedure



Step #3:

Use the loading shuttles to apply a known contact load to the interface

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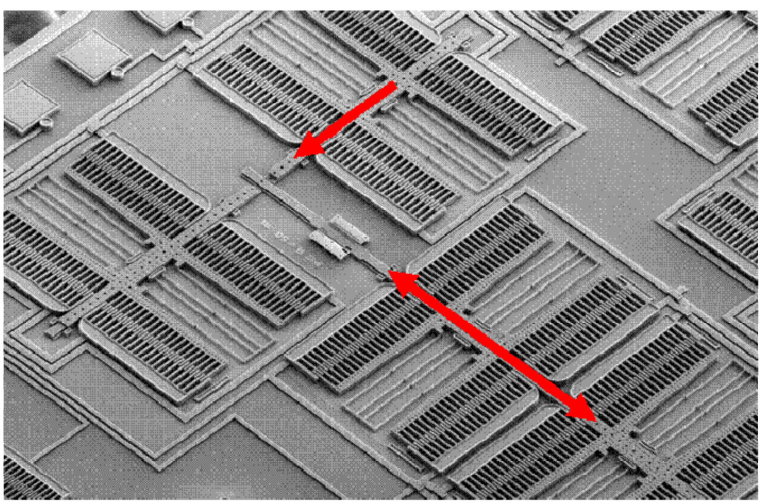
Dynamic Sliding Experiments

Experimental Procedure



In Situ Measurements:

- Dynamic Friction Force
- Static Friction Force

Ex Situ Measurements:

- Static Adhesion Force
- Wear Debris Generation (SEM)

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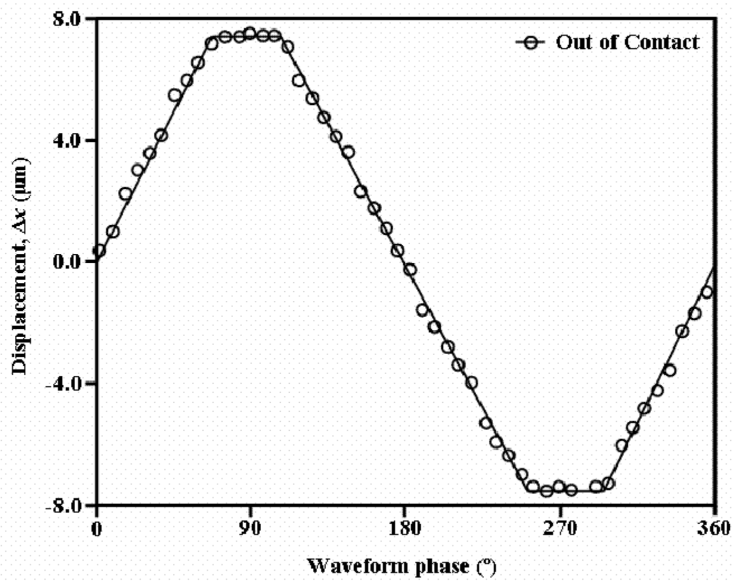
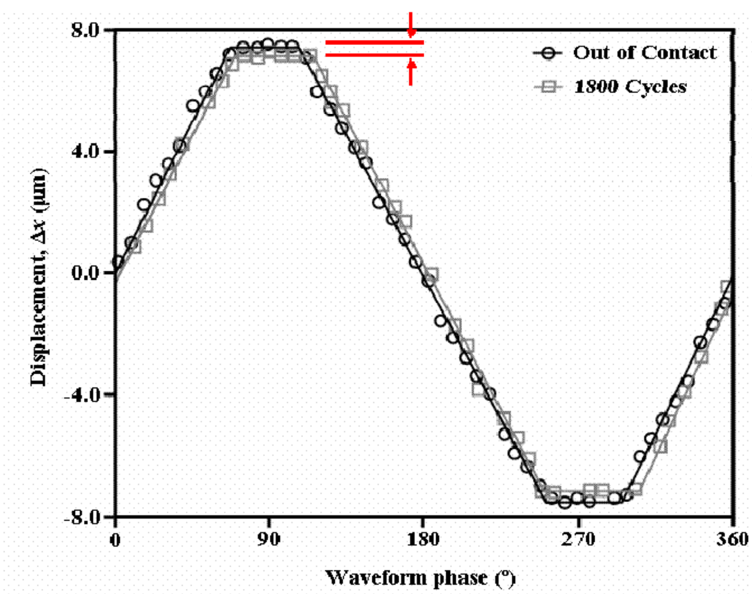
Dynamic Sliding Experiments

Characteristic Low-Cycle Data



Dynamic Sliding Experiments

Characteristic Low-Cycle Data



Dynamic Friction Force:

The dynamic force is manifested in a reduction in the range of motion

$$F_f^d = k(\Delta x_{oc} - \Delta x_{ic})$$

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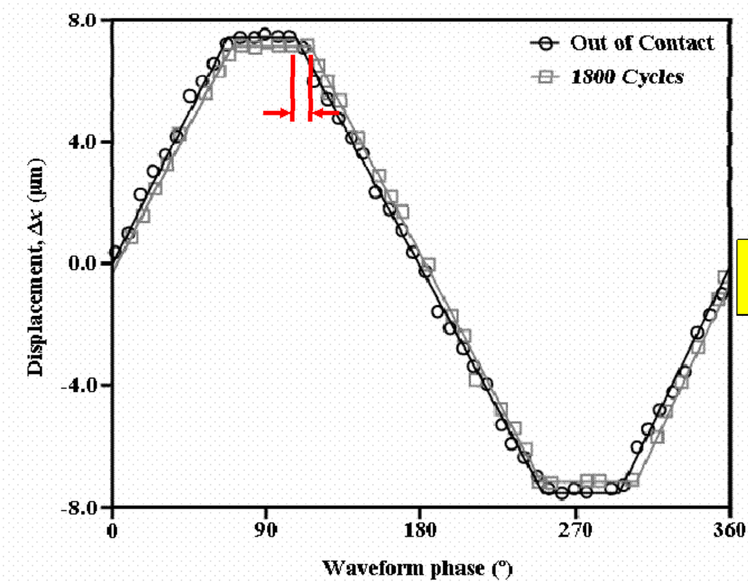
Dynamic Sliding Experiments

Characteristic Low-Cycle Data



Static Friction Force:

The static force is manifested in an increased dwell time at the endpoints of motion

$$F_f^S = F_r + F_{pull} - F_{push}$$

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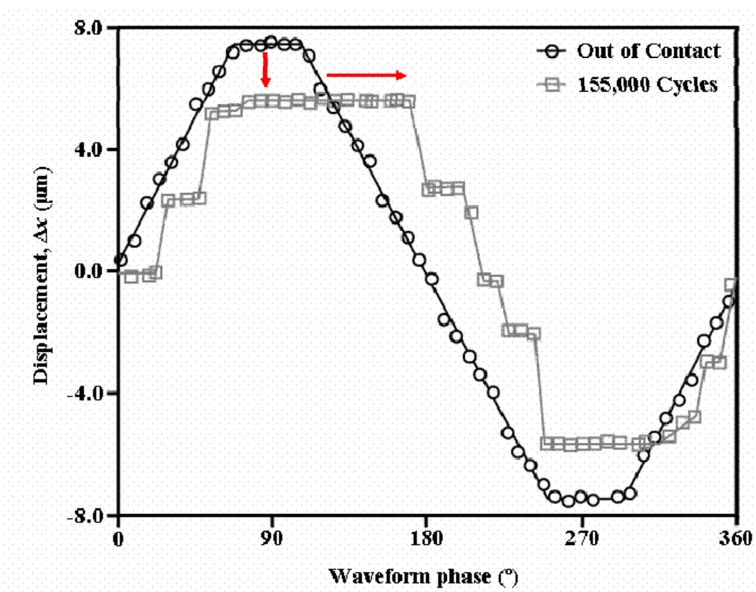
Dynamic Sliding Experiments

Characteristic High-Cycle Data



Both dynamic friction and static friction increase with increasing cycles

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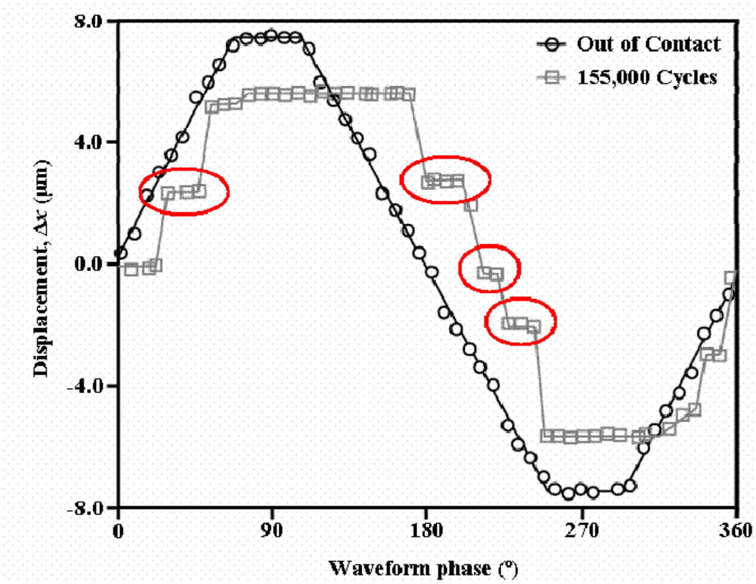
Dynamic Sliding Experiments

Characteristic High-Cycle Data



High cycle sliding contact displays an emerging stick-slip behavior in which stop points occur periodically during the movement between the endpoints

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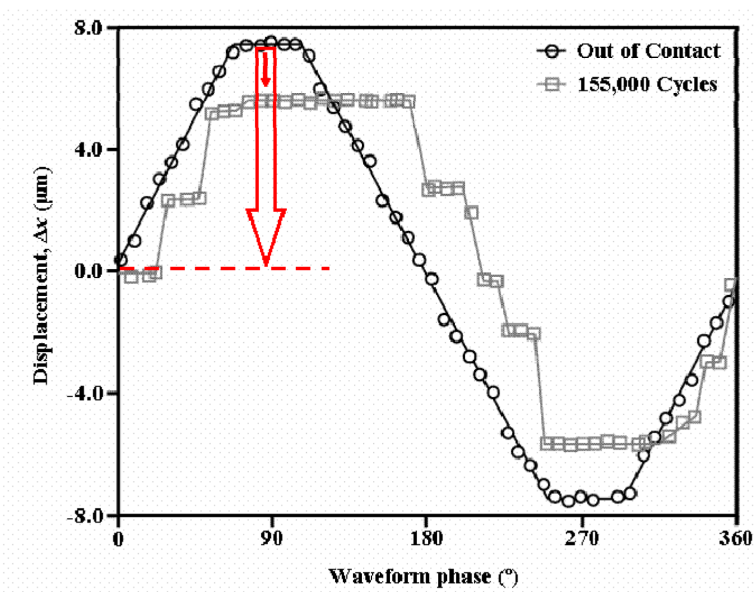
Dynamic Sliding Experiments

Characteristic High-Cycle Data



Dynamic friction failure is predicted when the motion range is reduced to zero

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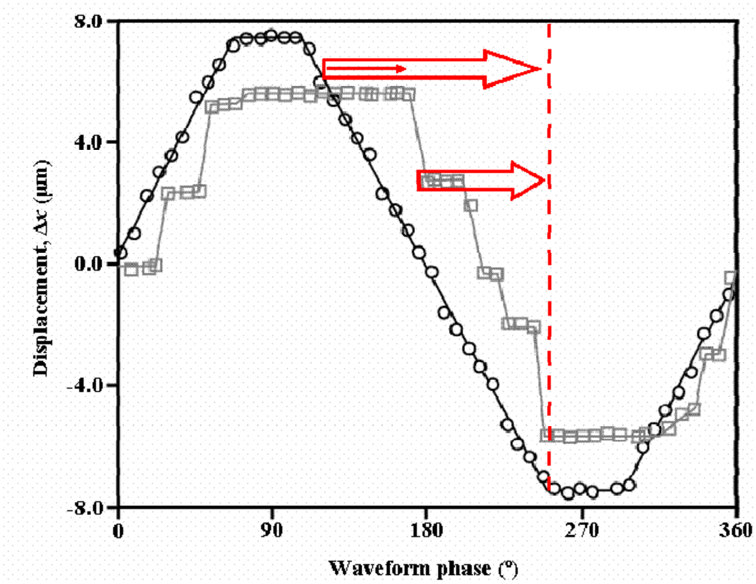
Dynamic Sliding Experiments

Characteristic High-Cycle Data



Static friction failure is predicted when the mechanical restoring force and the maximum electrostatic force are insufficient to overcome the static friction force

At the inception of stick-slip instances, the failure limit is reduced due to the smaller mechanical restoring force available

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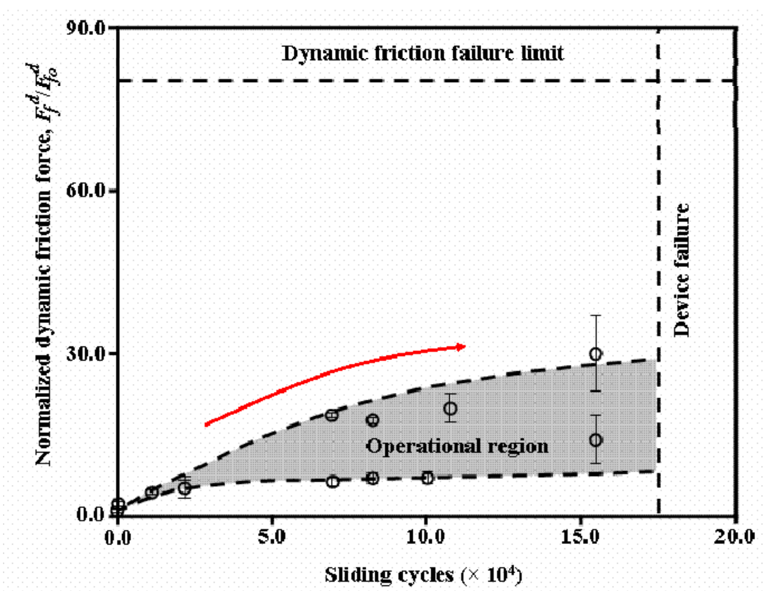
Dynamic Sliding Experiments

In Situ Dynamic Friction Data



Dynamic friction force increases with the number of sliding cycles

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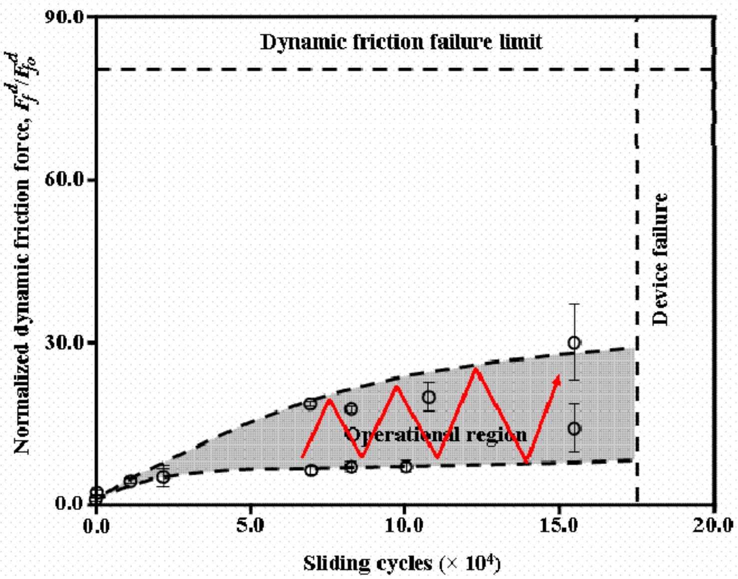
Dynamic Sliding Experiments

In Situ Dynamic Friction Data



Stick-slip phenomena and the generation of wear debris leads to fluctuation between two distinct limits

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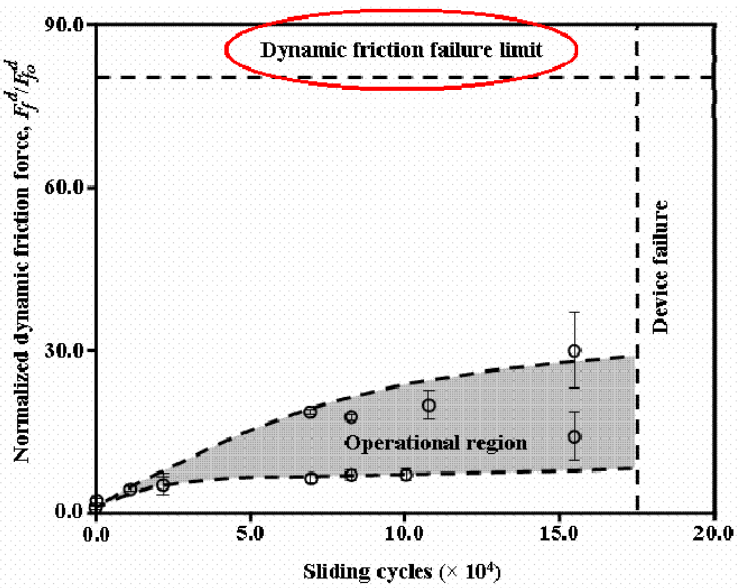
Dynamic Sliding Experiments

In Situ Dynamic Friction Data



Failure is predicted when the motion range is reduced to zero

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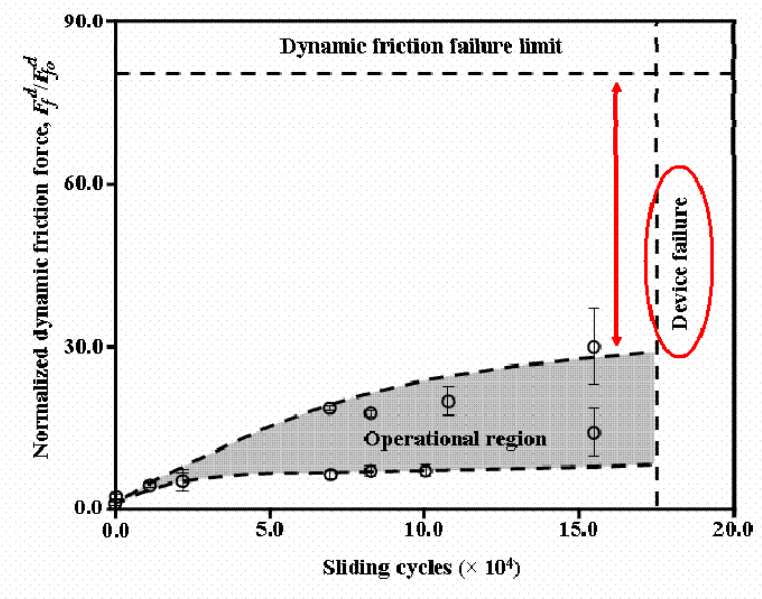
Dynamic Sliding Experiments

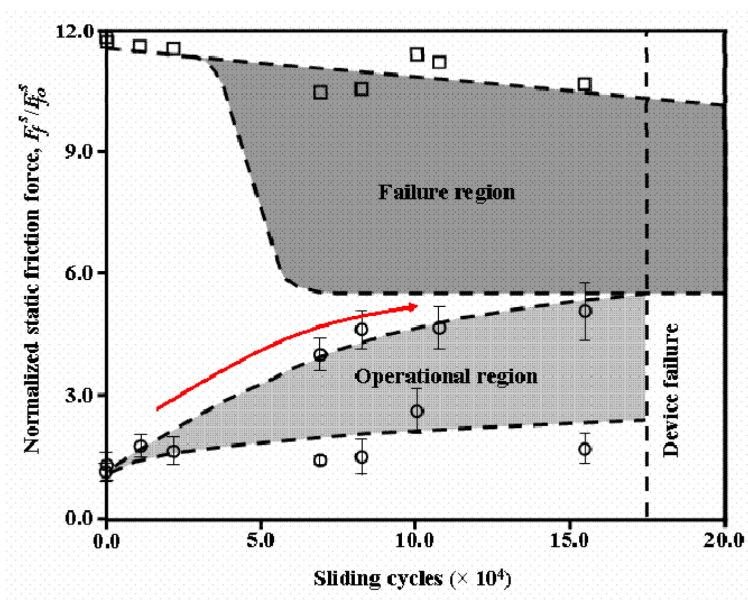
In Situ Dynamic Friction Data



Observed device failure occurred well within the operational limits for dynamic friction

Dynamic Sliding Experiments

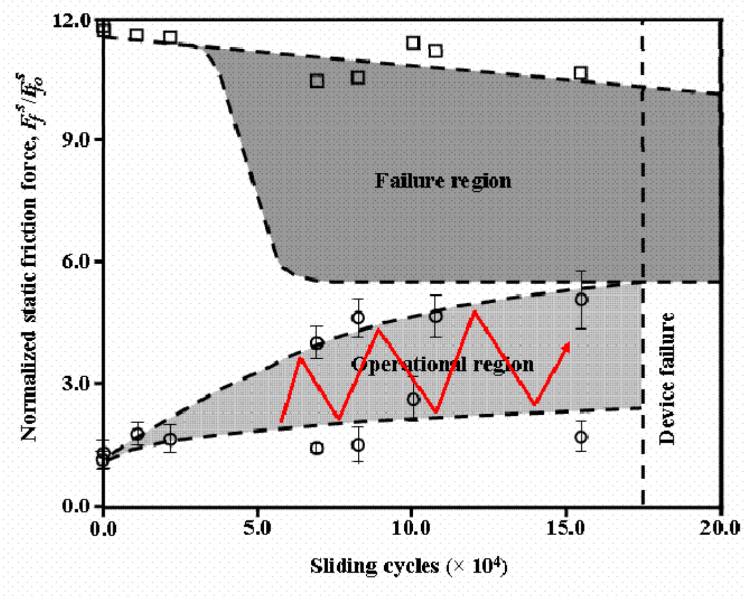
In Situ Static Friction Data



Static friction force increases with the number of sliding cycles

Dynamic Sliding Experiments

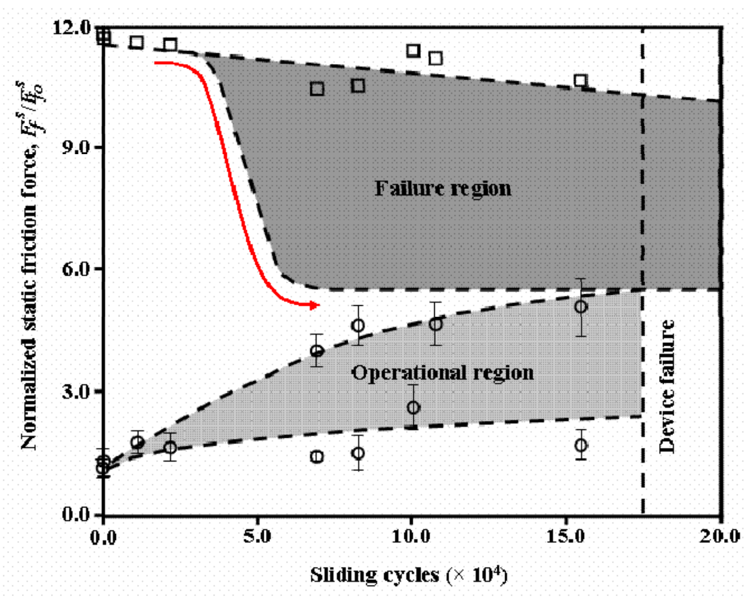
In Situ Static Friction Data



Stick-slip phenomena and the generation of wear debris leads to a fluctuation between two distinct limits

Dynamic Sliding Experiments

In Situ Static Friction Data

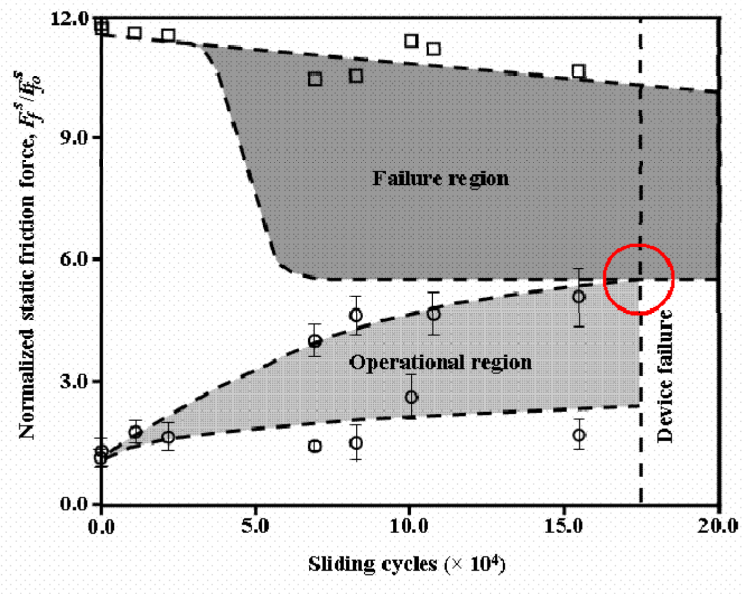


Failure is predicted when the electrostatic and mechanical restoring forces are insufficient to overcome static friction

The stick-slip phenomena leads to an expansion of the predicted failure region

Dynamic Sliding Experiments

In Situ Static Friction Data



Failure is predicted when the lower bound of the failure region meets the upper bound of the operational region

Prediction Matches Experiments

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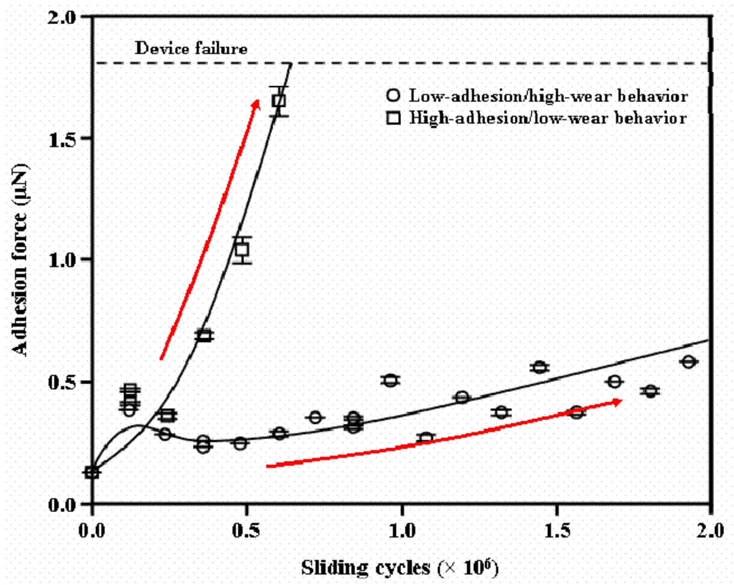
Dynamic Sliding Experiments

Ex Situ Static Adhesion Data



The static adhesion force increases with the number of sliding cycles

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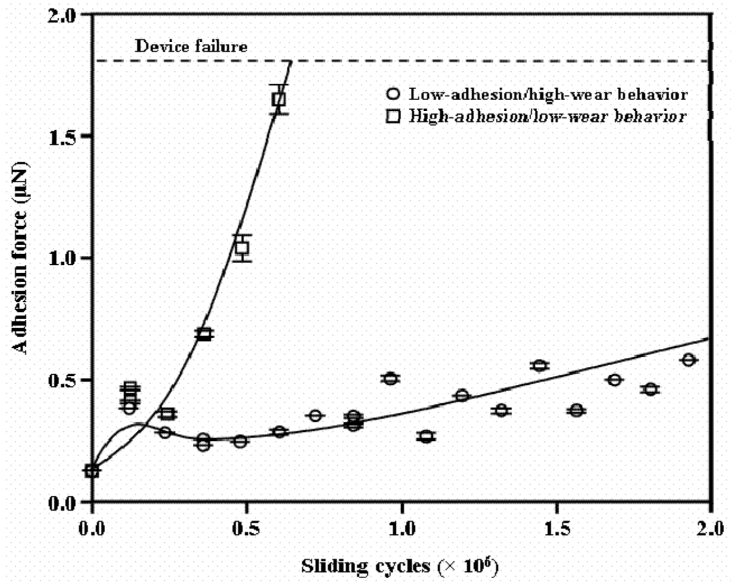
Dynamic Sliding Experiments

Ex Situ Static Adhesion Data



Two unique tribological behaviors are observed with correspondingly unique wear surfaces

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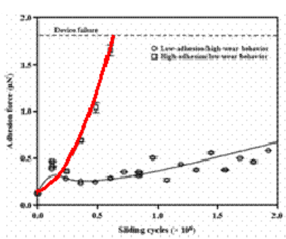
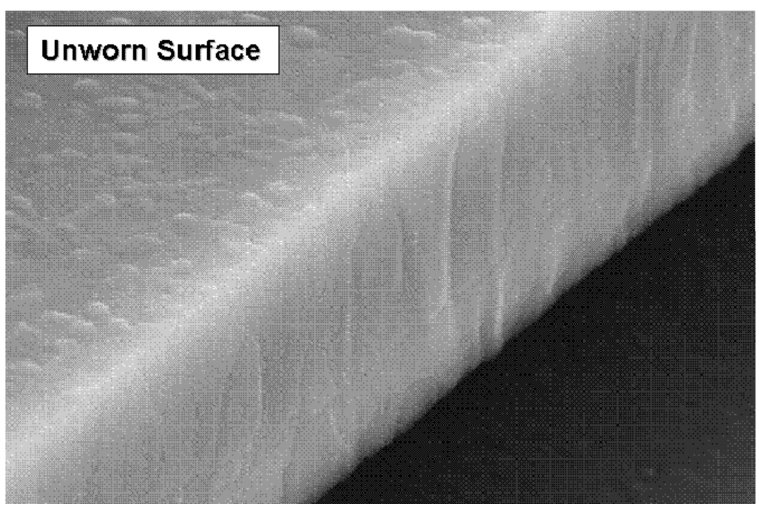
Dynamic Sliding Experiments

Ex Situ Examination of Wear Debris

High-Adhesion/Low-Wear Behavior





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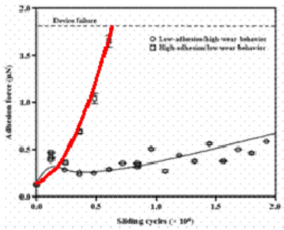
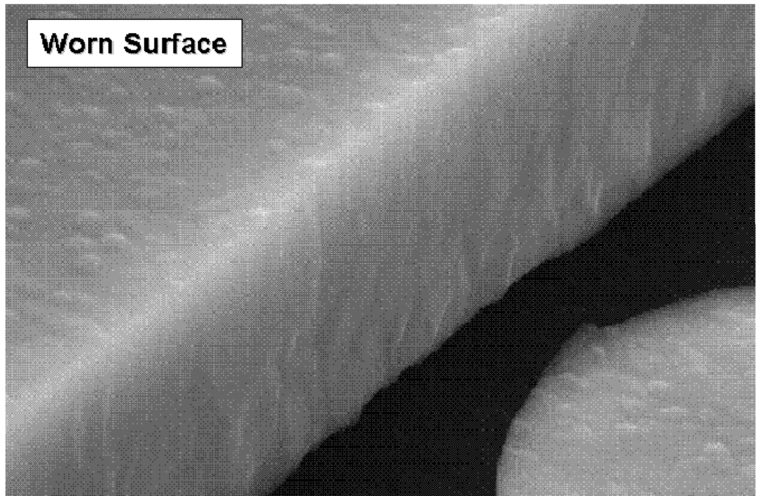
Dynamic Sliding Experiments

Ex Situ Examination of Wear Debris

High-Adhesion/Low-Wear Behavior





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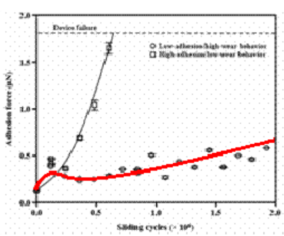
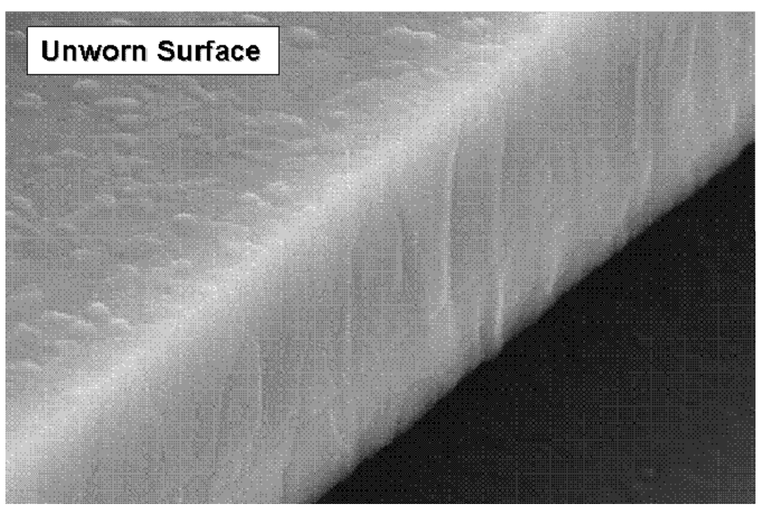
Dynamic Sliding Experiments

Ex Situ Examination of Wear Debris

Low-Adhesion/High-Wear Behavior

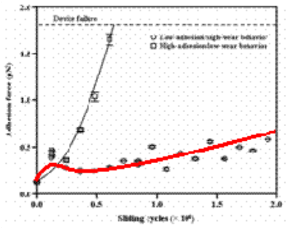


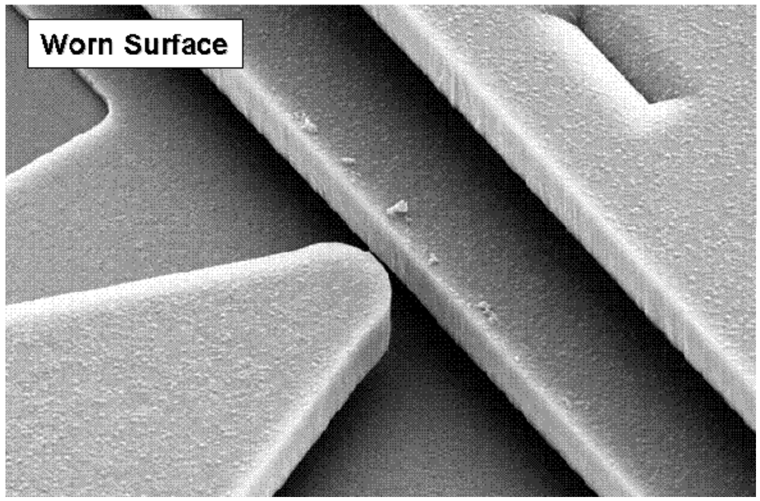


Dynamic Sliding Experiments

Ex Situ Examination of Wear Debris

Low-Adhesion/High-Wear Behavior





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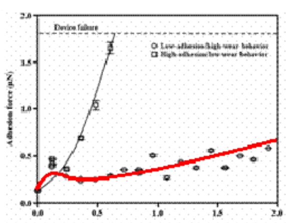
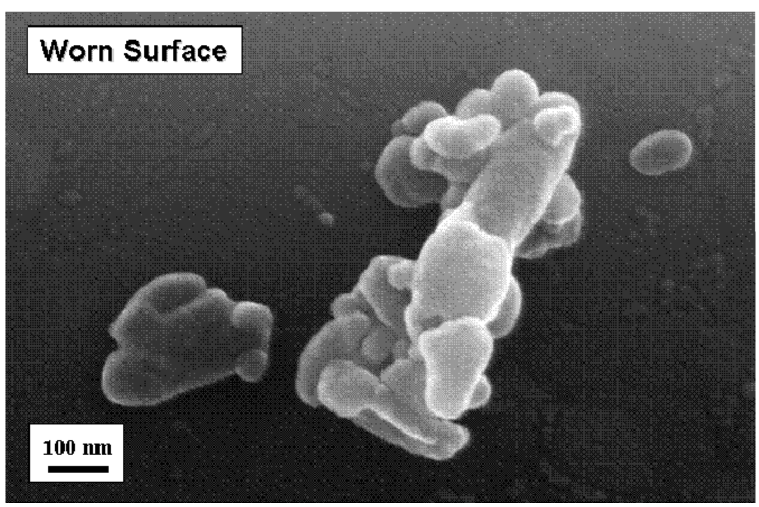
Dynamic Sliding Experiments

Ex Situ Examination of Wear Debris

Low-Adhesion/High-Wear Behavior

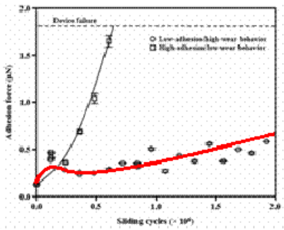


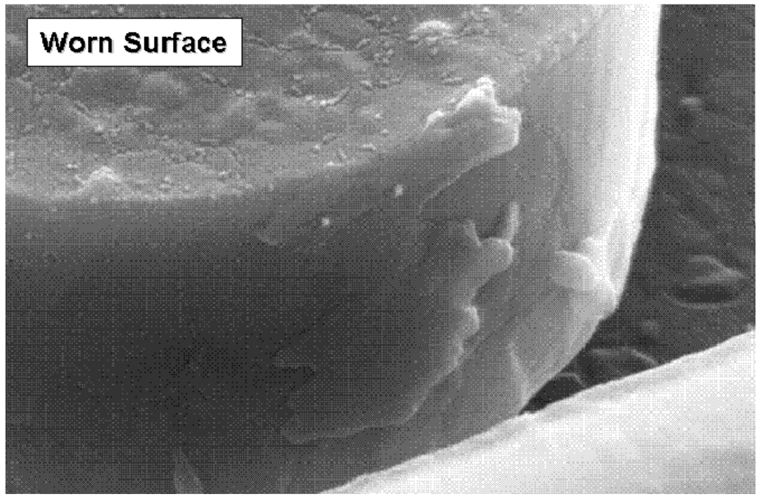


Dynamic Sliding Experiments

Ex Situ Examination of Wear Debris

Low-Adhesion/High-Wear Behavior





Conclusions

- The pull-out force shows a linear dependence on applied load unique to each environmental condition
- The engineering coefficient of friction shows a power law dependence on applied load unique to each environmental condition
- The interfacial shear strength shows a linear dependence on the total normal load that is independent of environmental conditions
- Under dynamic sliding contact, the adhesion force, static friction force and dynamic friction force increase with the number of cycles
- Microdevices fail in static friction at operation stop points or during the commencement of stick-slip
- A binary wear behavior is observed characterized by high-adhesion/low-wear and low-adhesion/high-wear result

Acknowledgements

- Sandia National Laboratories
- Professor Kyriakos Komvopoulos
- Dr. Michael Dugger, Sandia National Laboratories
- Members of the Surface Mechanics and Tribology Laboratory
- Dissertation Committee:
    - Professor Liwei Lin
    - Professor Kris Pister

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