

A NOVEL TESTING APPARATUS FOR TRIBOLOGICAL STUDIES AT THE SMALL SCALE

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Abstract— A novel flexure-based biaxial compression/shear apparatus has been designed, built, and utilized to conduct tribological studies of interfaces relevant to MEMS. Aspects of our new apparatus are detailed and its capabilities are demonstrated by an investigation of two interfaces for MEMS applications. Tribological tests may be performed with normal and tangential forces in the μN to N range and relative sliding displacements in the nm to mm range. In this testing range, the new experimental apparatus represents an improvement over existing techniques for tribological studies at the small scale.

Keywords— MEMS, Friction, Mechanical testing.

I. INTRODUCTION

THE useful life of a variety of MEMS is to a large part determined by friction and wear between contacting parts in relative motion. A better understanding of contact mechanics at the small scale will allow for the development of improved friction models for the optimum design of MEMS. Further, a more accurate account of the physical aspects of friction at the small scale, in particular of the effects of the surface topography on the frictional response, may allow for the design of interfaces with optimal surface micro-topography for minimized friction and wear.

We have developed a novel compression/shear apparatus to study the tribological response of interfaces at the small scale. The “small scale” in this context is normal and tangential forces in the μN to N range, and relative sliding displacements in the nm to mm range. We begin by detailing the physical aspects of our new apparatus, and then demonstrate its capabilities by studying the frictional response of silicon on silicon, as well as the effects of diamond-like carbon coatings on friction.

II. BIAXIAL COMPRESSION/SHEAR APPARATUS

The biaxial testing apparatus is shown in Fig. 1. Two flat bodies whose interfacial response is to be investigated are brought together in the space denoted as “specimen.” One body is attached at the base of the “flexure for normal force,” and the opposing body is secured to the “shear displacement flexure.” Normal forces on the interface are applied using a voice-coil actuator (BEI Sensors and Systems Co., CA, Model LA13-12-000A) acting through the “flexure for normal force.” Tangential displacements at

the interface are achieved by actuating the “shear displacement flexure” with a piezo-electric inchworm actuator (Burleigh Instruments, NY, Model IW700). The tangential force arising from the interfacial interaction is measured by the resulting displacement of the “flexure for shear force.” All displacements are measured using non-contacting eddy current sensors (Kaman Instrumentation, CO, Model SMU9000-5U) with a resolution of 20 nm over a range of 1.25 mm.

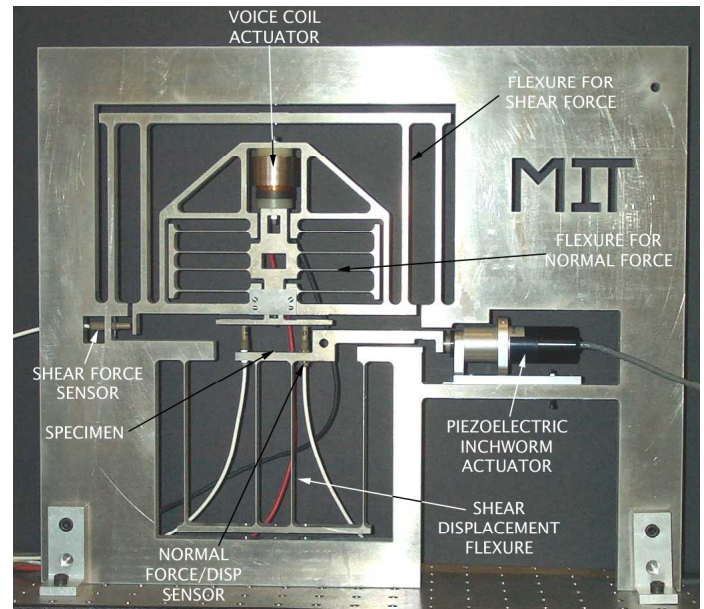


Fig. 1. BIAXIAL COMPRESSION/SHEAR APPARATUS.

The design incorporates compound spring flexures within a monolithic frame and possesses only a limited number of assembled parts. Thus, device assembly errors and backlash are minimized. The use of the double compound springs for actuation in the normal direction minimizes the potential for rotations or parasitic deflections due to either machining imperfections or to variations in the properties of the frame material. The frame is a monolithic, light weight design made of 12.7 mm thick Al7075-T6 plate and is 440 mm x 460 mm in size. Hard-stops ensure that the maximum bending stress in the spring webs does not exceed 5 MPa, which provides essentially infinite fatigue life. The normal axis is nested within the shear load cell and has been designed using FEA to minimize cross-talk between normal

force application and shear force measurement. The design also allows for the measurement of relative separation or approach of the surfaces in the normal direction as a test is conducted.

The normal force is controlled with a resolution of 80 μN over a range of 5 N, the shear force is measured with a resolution of 225 μN up to 15 N, tangential displacement is imposed in 4 nm steps up to 6.35 mm, and the relative motion of the surfaces in the normal direction is measured with a resolution of 20 nm over a range of 1.25 mm.¹ Imposed displacement rates range from 0.5 $\mu\text{m/s}$ to 600 $\mu\text{m/s}$. The entire system rests upon a vibration-isolated table to minimize environmental disturbances.

Calibration of the flexure stiffness for each axis is achieved by measuring the displacement of the axis under precision weights. In the present embodiment of the design, the normal axis has a stiffness of 9.53 N/mm, and the stiffness of the tangential axis is 43.2 N/mm. The electronics driving the normal axis are calibrated by measuring the normal displacement due to known computer output voltage ramps. The electronic system (consisting of a 16-bit data acquisition board, a precision amplifier powered by a low-noise source, and the voice coil) has a transfer function of 1.33 N/V. All system responses are highly linear over their operating ranges. The transfer functions of the mechanical and electrical systems are utilized to apply a precise normal load on an interface under compression. The simple, compact physical design of the apparatus may be scaled to allow for testing over a wide range of normal and shear forces, as well as a large range of imposed tangential displacements.² Design and manufacturing issues concerning the compression/shear apparatus as well as several other novel small scale testing devices recently developed at MIT may be found in Gudlavalleti et al. [1].

An example of experimental data obtained with the biaxial apparatus is shown by the tangential force-sliding distance response in Fig. 2. The interface is an Al6111-T4 2 mm x 2 mm coupon (with an as-received surface texture) against polished tool steel. A normal force of 1 N was imposed on the interface, and the tangential sliding velocity was 6 $\mu\text{m/s}$, with regions where the tangential displacement was reversed and then imposed again in the initial sliding direction. The negative sign on the tangential force axis indicates motion in the opposite direction to that initially imposed on the interface. The ability to precisely measure the tangential stiffness of an interface (represented by the slope of the linear “unloading-reloading” regions) is a novel capability of our apparatus. These “unloading-reloading” portions are reminiscent of the classical results (at a more macroscopic scale) of Courtney-Pratt and Eisner [2], and serve as experimental motivation for adhering-slipping models of interface friction (e.g. Anand [3]; Gearing et al. [4]). The slope of the “unloading-reloading” curve is termed the tangential stiffness in adherence in Anand [3], and previously was experimentally difficult to measure.

¹Displacement sensors with improved sensitivity may be used for better force and displacement resolution.

²Various aspects of the design are patent pending.

The coefficient of friction μ (defined as the ratio of the tangential force to the applied normal force) as a function of sliding distance is shown in Fig. 3, where we note that the measured values of μ are consistent with previous standard pin-on-disk friction tests.

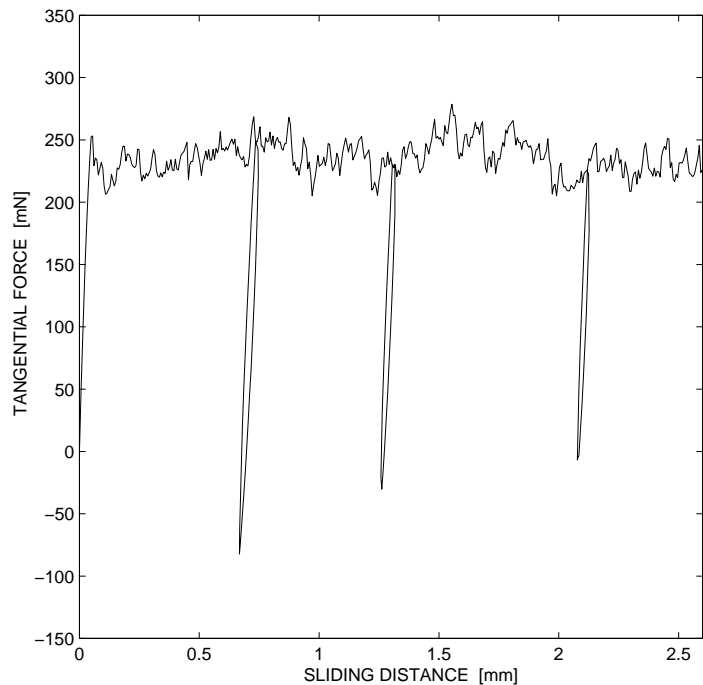


Fig. 2. FRICTIONAL RESPONSE OF AN AL6111/TOOL STEEL INTERFACE AT A NORMAL FORCE OF 1 N.

A second diagnostic test was conducted to demonstrate the range of tangential displacement rates attainable with the apparatus. A 1 mm thick 2 mm x 2 mm coupon of polycarbonate (PC) was loaded against the polished tool steel surface with a normal force of 750 mN. A sliding velocity of 100 $\mu\text{m/s}$ was applied and the PC specimen was displaced cyclically relative to the tool steel until the tangential force reached a steady-state value of 171 mN, which occurred at a total displacement of about 11 mm. At this state, the sliding velocity was reduced to 10 $\mu\text{m/s}$ for an additional 2 mm of sliding. The velocity was then increased to 500 $\mu\text{m/s}$ at the final stage of sliding. Figure 4 shows the tangential force as a function of sliding distance as the sliding rate decrement and increment are imposed. The solid lines are the average value of the tangential force at the corresponding sliding velocity. We note that this interface exhibits *positive rate sensitivity*. This result demonstrates the range of displacement rates that may be obtained with the apparatus.

III. TRIBOLOGICAL STUDIES AT THE SMALL SCALE

This section further demonstrates our new testing capabilities by investigating the frictional response of two interfaces of relevance to MEMS. The first interface is single crystal silicon (Si) contacting Si, and the second interface

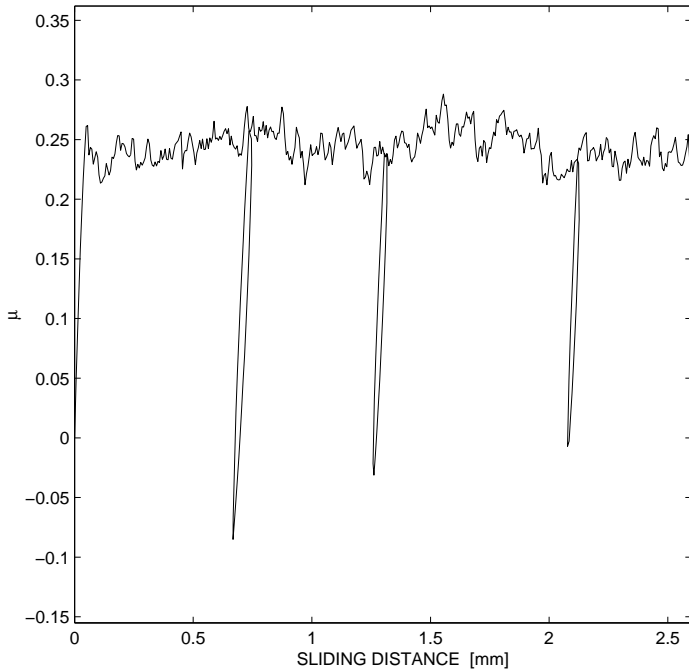


Fig. 3. μ FOR AN AL6111/TOOL STEEL INTERFACE AT A NORMAL FORCE OF 1 N.

is a $1\ \mu\text{m}$ thick diamond-like carbon (DLC) thin film on Si contacting DLC on Si. Both tests were conducted on *as-fabricated* $0.8\ \text{mm}$ thick $2.2\ \text{mm} \times 2.2\ \text{mm}$ diced square coupons against $0.8\ \text{mm}$ thick $12.7\ \text{mm} \times 12.7\ \text{mm}$ pieces.

The normal load was held constant at $2\ \text{N}$ as the interfaces were displaced relative to each other at a velocity of $10\ \mu\text{m/s}$. Fig. 5 shows the measured tangential force-sliding distance response, and Fig. 6 shows the friction coefficient μ as a function of the imposed tangential sliding distance. At a sliding distance of $400\ \mu\text{m}$, μ is 0.32 for the Si/Si interface, which compares to the much lower value of 0.11 for the DLC/DLC interface. These results serve as confirmation of the current trend to use DLC as low friction bearing surfaces for MEMS. The evolution of the tangential force with sliding distance at imposed normal forces may be utilized to develop improved friction models for the design of low friction and low wear interfaces for MEMS.

The relative displacement η of the interface in the normal direction is shown in Fig. 7, where it is noted that both interfaces showed a small amount of *relative approach* as the tangential displacement was imposed. At a sliding distance of $400\ \mu\text{m}$, η is about $621\ \text{nm}$ for the Si/Si interface as compared to $200\ \text{nm}$ for the DLC/DLC interface.

IV. CONCLUSION

Our novel biaxial compression/shear apparatus is shown to provide precise, low-noise experimental data over a large range of forces and displacements of interest for studying the tribological responses of interfaces of interest in MEMS applications. Further, certain features of the frictional response (e.g. the tangential stiffness in adherence and the relative approach/separation of surfaces during slid-

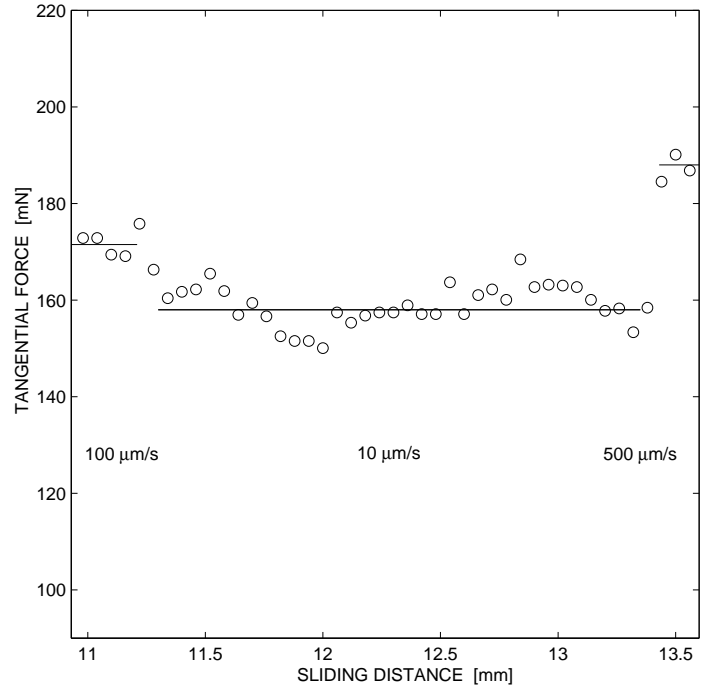


Fig. 4. RATE SENSITIVITY OF A PC/TOOL STEEL INTERFACE AT A NORMAL FORCE OF 750 mN.

ing) that were previously difficult to measure experimentally, are now readily obtained. We note that the design of the biaxial apparatus may be scaled to allow for testing over various ranges of forces and displacements. This new experimental capability should provide the tribological data necessary to design the next generation of low friction interfaces for the optimal performance of MEMS.

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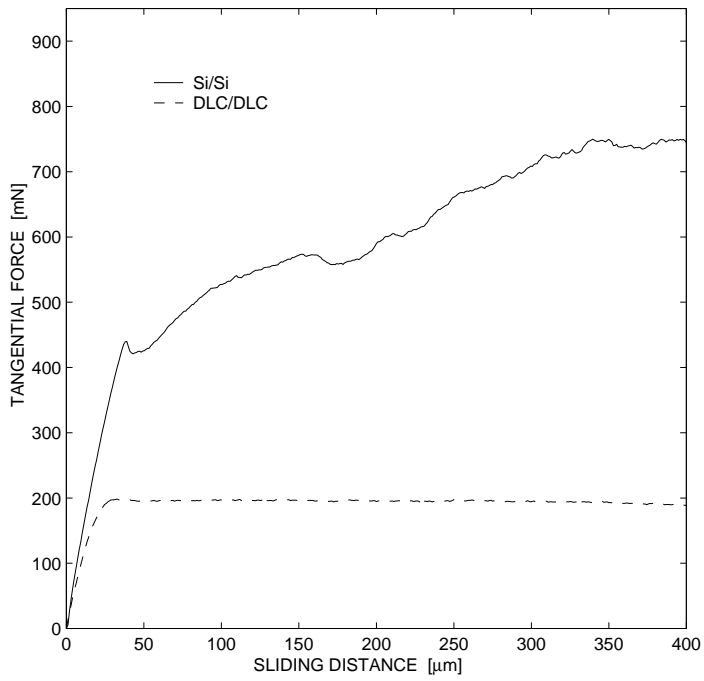


Fig. 5. FRICTIONAL RESPONSE OF MEMS INTERFACES AT A NORMAL FORCE OF 2 N.

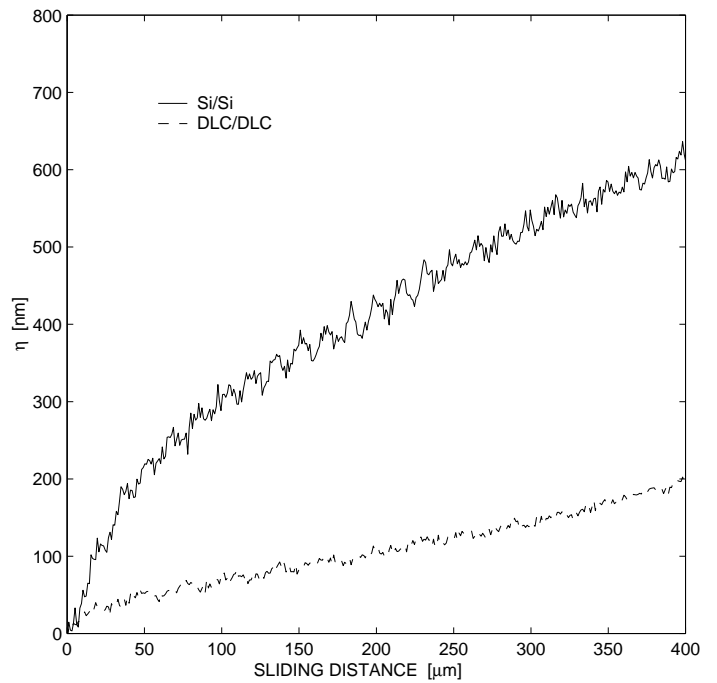


Fig. 7. η FOR MEMS INTERFACES AT A NORMAL FORCE OF 2 N.

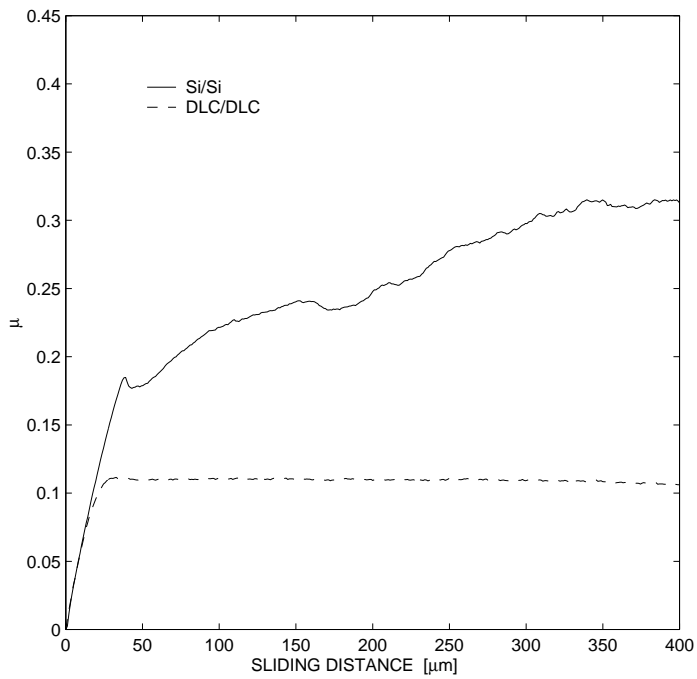


Fig. 6. μ FOR MEMS INTERFACES AT A NORMAL FORCE OF 2 N.