## Tribology Focus Topic
## Room: 19 - Session TR-TuA

### Molecular Origins of Friction and Wear
**Moderator:** S.S. Perry, University of Florida

2:00pm **TR-TuA1 Area, Stiffness, Friction and Adhesion of Contacts Between Rough Surfaces**, ***M.O. Robbins***, *L. Pastewka, T. Sharp*, Johns Hopkins University **INVITED**

Many surfaces have roughness on a wide range of length scales that can be described by self-affine fractal scaling. This roughness has profound effects on contact and friction between experimental surfaces. The talk will present results for the load dependence of contact area, contact stiffness and friction for nonadhesive and adhesive surfaces with a self-affine fractal geometry. Simulations retain atomic structure for a few layers of atoms near the surface and use a Greens function method for an elastic continuum to determine the long-range elastic response. Under a broad range of conditions the area of intimate contact $A_c$ between nonadhesive surfaces and the normal stiffness $k_N$ are both proportional to the applied load. These quantities are relatively insensitive to the atomic scale structure of surfaces, and even local plasticity. In contrast, atomic structure changes friction and tangential stiffness by orders of magnitude. For weak adhesion and strong roughness the linear relation between area, stiffness and load is retained, but the ratio of area to load increases. A simple scaling law predicts the change in ratio and why putty or tape sticks to walls but stiffer solids do not.

2:40pm **TR-TuA3 Crystallographic Wear Patterns in Ionic Solids**, ***B.A. Krick***, *K.R. Marchman, S.B. Sinnott, W.G. Sawyer*, University of Florida

Ionic solids have simple and well known crystalline structures while spanning several orders of magnitude in wear rates; this makes them excellent candidates for fundamental studies in wear. Wear experiments on the (001) surface of rock-salts, including NaCl and MgO, revealed that the material wear rates have significant dependency on crystallographic wear direction. The materials experienced maximum wear when sliding in the <100> family of directions and minimum wear when sliding in the <110>. For MgO the wear rate in the <100> direction was approximately three times that in the <110> direction. Wear experiments were performed at angles relative to the [100] direction in six degree increments revealing wear as a sinusoidal function of direction with 90 degree periodicity. These results offer a direct link between material structure and the wear properties of a material.

3:00pm **TR-TuA4 Measurements of Off-axis Friction Forces**, ***K. Kristiansen***, *X. Banquy*, University of California, Santa Barbara, *H. Zeng*, University of Alberta, Canada, *E. Charrault, S. Giasson*, Universite de Montreal, Canada, *J.N. Israelachvili*, University of California, Santa Barbara

Current measurements of frictional forces are usually done parallel to the sliding direction. However, when the distances between the moving surfaces and the dimensions of the lubricant approach the nanometer scale, the molecular structure and surface asperities can induce significant frictional forces that are not parallel to the sliding direction. We have developed a new sensor-actuator for the Surface Forces Apparatus which can measure forces and move two surfaces relative to each other in all 3 orthogonal directions with force resolution in the μN range, and distance control in nm range in the normal direction and μm range in the plane of the surfaces. I will present how "off-axis" (anisotropic) friction forces behave when shearing two atomically smooth crystalline (lattice) surfaces separated by nanometer thick layers of hexadecane. These anisotropic friction forces can induce complex transient and steady-state motions involving displacements perpendicular to the applied force and non-zero velocity at all stages of back-and-forth sliding.

4:00pm **TR-TuA7 Temperature-dependent Atomic-scale Friction and Wear on NaCl(001)**, ***X. Zhao***, *S.S. Perry*, University of Florida

Atomic-scale friction and wear were investigated by scanning a $Si_3N_4$ tip on NaCl(001) with variable temperature atomic force microscopy. In the absence of wear, an exponential increase in friction with decreasing temperature was observed. Atomic scale wear was detected through the formation of surface pits with a single atomic layer deep. From quantitative measurements of atomic displacement, microscopic wear coefficients were found to agree with known macroscopic wear properties of this ionic material. Both friction and wear exhibit a thermally activated behavior with different activation energies corresponding to the different energy dissipation processes. The thermal activation energy for friction and wear is ~ 0.12 eV and 0.82 eV, respectively, with wear obviously requiring more energy than friction.

4:40pm **TR-TuA9 Ultra-Low Wear Nanocomposites: How Low Can We Go?**, ***A.A. Pitenis***, *B.A. Krick, J.J. Ewin, W.G. Sawyer*, University of Florida

Polytetrafluoroethylene (PTFE) is an excellent candidate material for solid lubrication applications due to its low friction coefficient and chemical inertness; however, its use is limited due to its high wear rate. Unfilled PTFE is known to suffer from subsurface crack propagation and subsequent delamination during sliding. To combat this high wear mode, fillers of various sizes have been added to a PTFE matrix to increase the wear resistance by typically one or two orders of magnitude by fracture toughening and load support mechanisms. Nanocomposites are the state of the art in ultra-low wear performance in fluoropolymer systems; polymer blends have been shown to achieve nearly zero wear with wear rates below 1 x 10^-8 mm^3/Nm. These low wear rates are consistently accompanied by visually distinct tribofilms at the interface of the bulk material and counterface. Experiments suggest that a combination of mechanical and tribochemical mechanisms are responsible for the development of these tribofilms and consequent ultra-low wear behavior.

5:00pm **TR-TuA10 Direct Measurement of Friction Forces and Shear Strengths at High-Speed Microscopic Contacts using a Probe and Quartz Resonator**, ***B.P. Borovsky***, St. Olaf College

We present a study of the frictional properties of microscopic contacts (radius ~ 1 μm) in the high-speed regime (> 1 m/s). Energy dissipation and lateral stiffness of the contact are measured with a transverse-shear quartz resonator in contact with a spherical probe. A transition from partial to full slip is observed at a critical amplitude of motion. Elastic and dissipated forces (identified with static and kinetic friction) are quantified and interpreted without the need for complex calibration procedures or detailed models of the interaction. Kinetic friction is observed to be independent of sliding speed. Measurements of the lateral stiffness at very low oscillation amplitudes allow evaluation of the contact area. For an interface subject to boundary lubrication, we find that friction increases sub-linearly with applied load, in direct proportion to contact area. We determine the corresponding interfacial shear strengths. Results from the technique demonstrated here may find application in contexts where high sliding speeds are routinely accessed, such as microelectromechanical systems (MEMS) and simulations of friction using molecular dynamics.

5:20pm **TR-TuA11 Isolating the Adhesive Component of Micro-Scale Rolling Friction via Vapor-Phase Lubrication**, ***S. Misra***, *B. Hanrahan, R. Ghodssi*, University of Maryland, College Park

Microball bearings have been successfully utilized in several micro-machinery applications, providing low friction, low wear contact, long lifetimes, and device robustness. On all size scales, rolling friction arises from a combination of volumetric mechanical properties, surface chemical properties, and bearing geometries. On the micro-scale, surface effects are enhanced relative to volume, and geometries are dictated by microfabrication techniques. Due to these unique factors, there is not a comprehensive understanding of the fundamental source of rolling friction in microscale systems, but adhesion is theorized to dominate. Vapor-phase lubrication has been implemented to change the chemistry of the surface, specifically addressing the adhesive compon ent of micro-scale rolling friction, leading to reduced friction and enhancing the overall understanding of the system. Future microball bearing supported microsystems will benefit from the work presented here due to a greater knowledge of the influence of adhesion on micro-rolling friction.

A custom silicon micro-turbine supported on ball bearings serves as the platform for the study of rolling friction. 440C stainless steel microballs (285 micrometers diameter) are housed in deep reactive ion-etched silicon raceways. The tribological properties of this device have been the focus of numerous previous studies. The micro-turbine is operated such that normal load and turbine speed can be independently controlled for normal load-resolved spin-down friction testing. The spin-down testing methodology reveals the relationship between friction torque and normal load, which is used to understand the fundamental sources of rolling friction. Vapor saturation techniques have been integrated within the turbine actuation scheme by bubbling nitrogen gas through heated liquid and then using it to actuate and provide normal load for the micro-turbine. A condenser is employed before the output to assure no liquid condenses within the raceway.

A water vapor-lubricated micro-turbine has demonstrated a 43% reduction of friction versus dry nitrogen at a normal load of 50mN in spin-down testing as well as a 37% increase in overall turbine performance. Additionally, with the introduction of vapor, the relationship between friction torque and normal load was fundamentally changed, revealing the significant influence of adhesion to the system. Vapor lubrication adsorbed on the surface of the ball and raceway lowers their surface energies, reducing the effect of adhesion. These results show the first conclusive demonstration of the adhesive component to micro-scale rolling friction by using vapor phase lubrication.

5:40pm **TR-TuA12 Electronic Friction at the Atomic Scale: Conduction, Electrostatic and Magnetic Effects**, ***J. Krim***, North Carolina State University, *I. Altfeder*, Wright Patterson Air Force Laboratory

We have performed a magnetic probe microscopy study of levitation and atomic-scale friction for Fe on YBCO (Tc = 92.5K) in the temperature range 65 - 293 K, to explore electronic contributions to friction at the atomic scale. The samples were prepared with oxygen-depleted surfaces, with thin semiconducting surface layers present atop the bulk. Below Tc, the friction coefficient was observed to be constant at 0.19 and exhibited no correlation with the strength of superconducting levitation forces observed below Tc. The friction coefficient exhibited a change in slope within experimental error of Tc that increased progressively above Tc and reached 0.33 by room temperature. The results were analyzed within the context of underlying atomic-scale electronic and phononic mechanisms that give rise to friction, and it is concluded that contact electrification and static electricity play a significant role above Tc. Quartz crystal microbalance studies of sliding friction studies of molecularly thin films in the presence and absence of magnetic fields, were also performed for both paramagnetic oxygen and diamagnetic nitrogen films on substrates in various magnetic states.

[1] I. Altfeder and J. Krim, J. Appl. Phys. (2012), in press

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