Thursday Afternoon, October 18, 2007

Tribology

Room: 617 - Session TR3+NS-ThA

Nanotribology and Nanomechanics

Moderator: P.R. Norton, University of Western Ontario, Canada

2:00pm **TR3+NS-ThA1 Quantitative Direct-Observation Nanomechanical Testing in the Transmission Electron Microscope**, ***O.L. Warren***, *Z. Shan, S.A.S. Asif,* Hysitron, Inc., *E.A. Stach,* Purdue University, *A.M. Minor,* Lawrence Berkeley National Laboratory **INVITED**

The increasingly strong interest in measuring and understanding the sometimes extraordinary mechanical properties of nanomaterials and individual nanostructures has encouraged us to develop the first depth-sensing indenter compatible with quantitative nanomechanical testing in the transmission electron microscope (TEM). This ambitious undertaking has encountered a number of significant technological hurdles to overcome; nevertheless, we have achieved a versatile in-situ TEM instrument that compares favorably to leading conventional nanoindenters in terms of control modes and performance specifications. Scientifically, we have exploited the unique capabilities of this novel instrument to perform direct-observation nanoindentation into thin films and monolithic materials using sharp indenters, direct-observation nanocompression onto hollow and solid nanospheres as well as onto crystalline and amorphous nanopillars using miniature flat punches fashioned with a focused ion beam (FIB), and direct-observation bending of nanowires using the aforementioned flat punches. This presentation will share the powerful nature of time correlating the often discrete features of force-displacement curves to the accompanying morphological and microstructural changes that are directly observed in the corresponding TEM movies. Our research results range from some validating current mechanistic thinking to others that are counterintuitive and therefore a challenge to conventional wisdom.

2:40pm **TR3+NS-ThA3 Tribology in Full View**, ***L.D. Marks***, *A. Merkle,* Northwestern University **INVITED**

Experiments in tribology have long suffered from the inability to directly observe what takes place at a sliding contact - the classic buried interface problem. As a consequence, although many friction phenomena at the nanoscale have identified, there can be interpretation issues resulting from indirect or ex-situ characterization of the contact surfaces or because the experimental measurements are volume averaged, rather than giving direct insight into what is taking place at a single asperity-asperity contact. We have been recently exploiting a unique instrument that allows us to simultaneously slide a tip across a surface and look at the sample using transmission electron microscopy. Using this technique, we can directly image the nanoscale processes taking place at scales from 0.2 nm to microns, as well as obtain local chemical information from techniques such as electron energy loss spectroscopy. Using this instrument we have recently observed "liquid-like" deformation where the material is solid, but behaves as if it was a liquid due to very rapid surface diffusion, similar to the classic case of liquid-like growth of gold and silver particles; the formation of a graphitic transfer layer during sliding of tungsten on graphite as well as in-situ observation of graphitization of diamond-like carbon during sliding observed by electron energy loss spectroscopy. Further results include observation of wear debris during sliding of tungsten on graphite whose size is consistent with a dislocation standoff model and a recently published dislocation model for friction at the nanoscale. These and additional results will be described.

3:40pm **TR3+NS-ThA6 Atomic-scale Friction on Ultra Thin Films**, ***T. Filleter***, *W. Paul, R. Bennewitz*, McGill University, Canada

Friction force microscopy (FFM) provides a powerful method to study the microscopic origins of friction. FFM has previously demonstrated that a single sharp asperity scanned over an atomically flat crystalline surface can exhibit a periodic stick-slip movement following the periodicity of the underlying lattice.[1] This has been observed for a range of different crystalline surfaces, including alkali halides and metal single crystals.[2,3] In this work we have extended the FFM technique to study atomic-scale friction on a model solid lubricant system. The system was chosen to satisfy two criteria; be composed of materials with well known bulk atomic frictional properties, and to be topographically well defined with atomic resolution. The model system, which satisfies both criteria, are ultra thin films of KBr grown on a single crystal Cu(100) substrate. Ultra thin films have been grown under ultra high vacuum conditions with a thickness of up to five monolayers of KBr on an atomically flat Cu(100) substrate. The films have first been characterized using high resolution noncontact atomic force microscopy (NC-AFM). The first and second monolayers are found to grow in a carpet-like mode overtop of the existing Cu monatomic steps. Subsequent layers grow as rectangular islands with a minimum of corner and kink sites. Atomically resolved NC-AFM topography images of the films reveal a regular superstructure in the growth which is consistent with the KBr/Cu lattice mismatch. FFM measurements show that, as expected, the KBr films do act as a solid lubricant exhibiting lower friction than the bare Cu(100) surface. It is also observed that layers with a thickness of two and greater monolayers supports stable atomic stick-slip friction. The atomic frictional properties on films as thin as two monolayers (0.66 nm) are found to be consistent with that of bulk KBr. Lateral force maps of films exhibiting a topographic superstructure do not reveal a superstructure in the lateral force. The bare Cu(100) substrate has also been found to support stable stick-slip friction which has previously not been achieved.

[1] Bennewitz, R., Materials Today, May 2005, p.42

[2] Socoliuc, A., et. al, Phys. Rev. Lett. 92, 13 (2004) 134301/1-4

[3] Bennewitz, R., et. al, Phys. Rev. B 60, 16 (1999) R11301-4.

4:00pm **TR3+NS-ThA7 A Scanning Tunneling Microscope and Quartz Crystal Microbalance Study of Heating and Wear at a Sliding Interface**, ***B.D. Dawson***, *S.M. Lee, J. Krim*, North Carolina State University

In order to probe the rise in temperature of a sliding interface, a Scanning Tunneling Microscope and Quartz Crystal Microbalance has been combined to produce a rubbing action of a tungsten tip on a copper and indium electrode, respectively. The amplitude of oscillation[1] and wear of the electrodes is observed directly with the STM. Negative frequency shifts, which are indicative of a liquid-solid interface,[2] were observed for tungsten on indium rubbing. The chamber was heated and negative frequencies were observed at reduced sliding speeds, implying surface melting at the indium interface. This work was funded by The National Science Foundation and the AFOSR Extreme Friction MURI.

[1] B. Borovsky, B. L. Mason, and J. Krim, J. Appl. Phys. 88, 4017 (2000).

[2] C. M. Flanigan, M Desai, and K. R. Shull, Langmuir. 16, 9825 (2000).

4:20pm **TR3+NS-ThA8 Radial Breathing Mode Frequencies of Single-Walled Carbon Nanotubes Determined by Nanoindentation with an AFM**, ***J. Fraxedas***, ICMAB-CIN2-CSIC, Spain, *G. Rius, F. Pérez-Murano,* IMB-CNM-CSIC, Spain, *A. Verdaguer*, ICN-CIN2, Spain

We have experimentally determined the radial breathing mode frequency of individual single-walled carbon nanotubes with a diameter of 1.3 nm by nanoindentation measurements using an Atomic Force Microscope with commercial microfabricated silicon cantilevers with ultrasharp tips, evidencing the sensitivity of such instruments to frequencies in the THz range, well above the resonance frequencies of the cantilevers (ca. 130 kHz).[1]

[1] Europhys. Lett. 78 (2007) 16001.

4:40pm **TR3+NS-ThA9 The Importance of Nanoscale Meniscus Formation During High-Speed Sliding Contacts**, ***C.M. Mate***, *R.N. Payne, Q. Dai*, Hitachi San Jose Research Center, *K. Ono*, Hitachi Central Research Laboratory, Japan

To help determine the nanoscale origins of friction at high-speed sliding contacts, we have developed a High Shear Rate Apparatus using technology from the disk drive industry. This technique enables us to study friction, adhesion, and wear at ultra-high sliding speeds (1 to 100 m/s) for a small pad contacting a rotating disk with an atomically smooth surface and covered with a nanometer thick lubricant film.[1] We find that the sliding characteristics are dominated by the non-equilibrium meniscus of lubricant that forms between the pad and disk surfaces and by the vibrational dynamics of the sliding interfaces. In particular, the high sliding speed results in the friction, adhesion, and bounce dynamics being asymmetric with respect to sliding direction for a pad tilted at a slight angle with respect to the rotating disk surface. These differences are attributed to the mechanical action of the lubricant layer against the converging and diverging wedges of the pad, leading to an asymmetric meniscus to form around the contact pad at high speeds. Under suitable conditions, we also find a self-excited vibration of the slider pad, a few nanometers in amplitude, which is induced by friction hysteresis coupled with adhesion hysteresis.

[1] C. M. Mate, R.N. Payne, Q. Dai, and K. Ono, "Nanoscale Origins of Dynamic Friction in an Asymmetric Contact Geometry", Phys. Rev. Lett. 97 (2006) 216104.

5:00pm **TR3+NS-ThA10 Effects of Interfacial Structure on Atomic-Scale Friction Examined using MD**, ***J.A. Harrison***, *M.T. Knippenberg, J.D. Schall, G. Gao, P.T. Mikulski*, United States Naval Academy

The development of micron-sized devices, such as microelectromechanical devices, for terrestrial and space applications has prompted the need for protection of the surfaces of these devices. Self-assembled monolayers (SAMs), both alkanethiols and alkylsilanes, are possible candidate for the passivation and lubrication of these devices. The fundamental problem associated with controlling friction is a lack of understanding of the underlying atomic-scale processes that govern both friction and wear. We have conducted extensive molecular dynamics (MD) simulations using our AIREBO potential aimed at understanding the atomic-scale mechanisms of friction in SAMs. We have examined the way in which the contact forces present at the interface influence friction and made direction connections between interfacial structure and friction. We have examined the effects of changing the interface structure in several ways. Some of these include changing the structure of the SAM (e.g., end-group, chemical identity, hybridization, connectivity of chains) and altering the roughness of the interface. In this talk, we will discuss our most recent findings that have examined the way in which the structure of both the SAM and the tip influence friction. ** Work supported by The Office of Naval Research and The Air Force Office of Scientific Research as part of the Extreme Friction MURI.

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