

# Monday Morning, October 28, 2013

## Tribology Focus Topic

Room: 203 C - Session TR+AS-MoM

## Bridging Scales and Characterization

**Moderator:** R.W. Carpick, University of Pennsylvania, L. Marks, Northwestern University

9:00am **TR+AS-MoM3 Friction in Full View**, *L. Marks*, Northwestern University **INVITED**

Friction is a pervasive problem, by some estimates consuming about 5% of the GDP of the economies of the developed world, and a recent analysis has indicated that about one third of the fuel energy in automobiles goes to overcoming frictional losses. While the importance of minimizing friction can be traced back at least as far as the tomb of Tehuti-Hetep, circa 1880 B.C, where a man can be seen pouring a lubricant to assist moving a statue, there are still many unknowns in the field of tribology which encompasses friction as well as other critical processes such as wear and lubrication. For many of the phenomena in tribology there are still numerous unknowns, due in large part to what has been called the buried interface problem. The triboactive layer, is almost always hidden by the materials on both sides of it so the exact details of what is occurring are often hidden, only accessible by post-facto analyses and sometimes a matter for debate. While there have been several attempts to image the triboactive layer directly at the atomic scale dating from the original work by Gane and Bowden, progress has been slow. Over the last few years we have been developing both models from a materials science viewpoint via dislocations as well as in-situ techniques for imaging the buried interface. Related to this (perhaps not obviously) we have recently become involved in understanding the nanoscale tribology of hip replacements, including the perhaps surprising observation of a graphitic layer *in-vivo* that appears to play a major role in reducing implant failures. This talk will focus upon some of the recent results, ranging from more basic observation such as connecting wear fragment size and a new layer-by-layer wear mechanism to the standoff distance of interfacial dislocations through the formation of graphitic materials *in-vivo* as well as some direct observations of wear and sliding at the atomic scale.

9:40am **TR+AS-MoM5 Combining In Situ Nanotribology and Atomistic Simulations to Reveal the Strong Effect of Atomic-Scale Roughness on Nanoscale Adhesion**, *T.D.B. Jacobs*, University of Pennsylvania, *K.E. Ryan, P.L. Keating*, United States Naval Academy, *D.S. Grierson*, systeMECH, LLC, *J.A. Lefever, K.T. Turner*, University of Pennsylvania, *J.A. Harrison*, United States Naval Academy, *R.W. Carpick*, University of Pennsylvania

As components in devices and microscopy applications shrink to nanometer length scales, adhesion forces play an increasingly dominant role in the physics of contact. In particular, tip-based approaches for data storage, nanomanufacturing, and nanoelectromechanical systems rely on accurate knowledge and control of adhesion between a sharp asperity and a surface. It is well known that surface roughness affects adhesion at macro- and microscopic scales. However, the atomic-scale roughness of nanoscale tips is rarely measured or accounted for. Here, we characterized the atomic-scale roughness of carbon-based probes, and measured the corresponding effect on adhesion using simulations and experimental techniques.

We have conducted contact and sliding experiments inside of a transmission electron microscope (TEM), using a modified *in situ* nanoindentation apparatus. Similar experiments were used recently to study wear of nanoscale silicon probes<sup>1</sup>. In the present work, nanoscale asperities composed of either diamond-like carbon (DLC) or ultrananocrystalline diamond (UNCD) were brought into contact and separated from a flat diamond substrate. The *in situ* nature of the testing allowed characterization of surface roughness with sub-nanometer resolution immediately before and after contact. Additionally, complementary adhesion simulations were conducted using molecular dynamics (MD) with conditions matched as closely as possible with the experiments (e.g., materials, asperity shape, environment). The RMS roughness for the experimental tips spanned 0.18 - 1.6 nm; for the simulated tips, the range was 0.03 nm (atomic corrugation) to 0.12 nm. Over the tested range of roughness, the measured work of adhesion was found to decrease by more than an order of magnitude as roughness increased, with a consistent trend observed between experimental and simulation results<sup>2</sup>. The dependence of adhesion upon roughness was accurately described by a simple analytical model.

This combination of simulation and novel *in situ* experimental methodologies allowed for an exploration of an unprecedented range of tip sizes and length scales for roughness, while also intrinsically verifying consistent behavior between the two approaches. These results demonstrate

a high sensitivity of adhesion to interfacial roughness down to the atomic limit. Furthermore, they indicate that present approaches for extracting work of adhesion values from experimental measurements of adhesion forces contain significant uncertainty due to an unmeasured variable – atomic-scale roughness.

<sup>1</sup> T. D. B. Jacobs, R. W. Carpick, *Nature Nanotech.*, **8**, 108-112 (2013)

<sup>2</sup> T. D. B. Jacobs, *et al.*, *Tribol. Lett.*, **50**, 81-93 (2013)

10:00am **TR+AS-MoM6 Nanotribological Properties of Positively and Negatively Charged Nanodiamonds as Additives to Solutions**, *Z. Liu, S.D. Corely*, North Carolina State University, *O.A. Shenderova*, International Technology Center, *D. Brenner, J. Krim*, North Carolina State University

Nano-diamond (ND) particles are known to be beneficial for wear and friction reduction when used as additives in liquids,<sup>[1]</sup> but the fundamental origins of the improvement in tribological properties has not been established. In order to explore this issue, we have investigated the nanotribological properties of ND coated with self-assembled monolayers (SAM) as additives to solutions, employing gold/chrome coated quartz crystal microbalances (QCM). Measurements were performed with the QCM initially immersed in deionized water. ND particles with positively and negatively charged SAM end groups were then added to the water, while the frequency and amplitude of the QCM were monitored. Negative shifts in both the QCM frequency and amplitude were observed when ND with positively charged SAM end groups were added, while positive shifts in both the QCM frequency and amplitude were observed when ND with negatively charged ND end groups were added. The results are consistent with a lubricating effect for the negatively charged ND, but were only observed for sufficiently small negative ND particle size. Experiments on QCM surfaces with differing textures and roughness are in progress, to determine the separate contributing effects of surface roughness charge-water interactions.

Funding provided by NSF DMR.

1. Vadym N. Mochalin, Olga Shenderova, Dean Ho & Yury Gogotsi, *Nature Nanotechnology* 7, 11–23 (2012) doi:10.1038/nano.2011.209

10:40am **TR+AS-MoM8 Atomic-scale Processes in Single Asperity Friction and Wear**, *R.W. Carpick*, University of Pennsylvania **INVITED**

I will discuss recent atomic force microscopy studies of nanoscale single asperity contacts that reveal surprising new behavior and insights. First, the behavior of nanoscale contacts with truly 2-dimensional materials will be discussed. For nanoscale contacts to graphene, we find that the friction force exhibits a significant dependence on the number of 2-D layers<sup>1</sup>. Surprisingly, adhesion (the pull-off force) does not. However, studies as a function of scanning history reveal further complexities that arise from the combined effects of high flexibility and variable substrate interactions that occur at the limit of atomically-thin sheets. An even stronger effect occurs when graphene is fluorinated, where experiments and simulations both show that friction between nanoscale tips and fluorinated graphene (FGr) monolayers exceeds that for pristine graphene by an order of magnitude. The results can be interpreted in the context of the Prandtl-Tomlinson model of stick-slip friction.

I will then discuss new insights into the physics of nanoscale wear. A better understanding of wear would allow the development of rational strategies for controlling it at all length scales, and would help enable applications for which wear is a primary limitation such as micro-/nano-electromechanical systems (MEMS/NEMS). We have demonstrated the ability to characterize single-asperity wear with a high degree of precision by performing *in-situ* wear tests inside of a transmission electron microscope. For silicon probes slid against a flat diamond substrate, the shape evolution and volume loss due to wear are well described by kinetic model based on stress-assisted bond breaking mechanisms<sup>2</sup>. This allows new insights to be gained about the kinetics of atomic-scale wear<sup>3</sup>.

[1] Lee, C., Li, Q., Kalb, W., Liu, X.-Z., Berger, H., Carpick, R.W. and Hone, J. "Frictional Characteristics of Atomically-Thin Sheets," *Science*, 328, 2010, 76-80.

[2] Jacobs, T.D. and Carpick, R.W. "Nanoscale Wear as a Stress-Assisted Chemical Reaction," *Nature Nanotech.*, 8, 2013, 108-112.

[3] Jacobs, T.D., Gotsmann, B., Lantz, M.A. and Carpick, R.W. "On the Application of Transition State Theory to Atomic-Scale Wear," *Tribol. Lett.*, 39, 2010, 257-271.

11:20am **TR+AS-MoM10 Examination of Adhesion and Friction of Hydrocarbon-based Materials: Elucidating Atomic-scale Wear Processes via Molecular Dynamics**, *J.A. Harrison, K.E. Ryan, P.L. Keating*, United States Naval Academy, *J.D. Schall*, Oakland University, *K.T. Turner*, University of Pennsylvania, *D.S. Grierson*, systeMECH, LLC, *R.W. Carpick, V. Vahdat, T.D.B. Jacobs*, University of Pennsylvania

Molecular dynamics (MD) simulations are unique in their ability to elucidate atomic-scale phenomena because the positions, velocities, and forces of all atoms in the system are known as a function of time. We have performed complementary atomic force microscope (AFM) experiments and MD simulations aimed at examining adhesion, friction, and wear in diamond, ultrananocrystalline diamond (UNCD), and amorphous carbon (a-C:H) materials. Atomic-scale wear in nanoscale contacts is of particular importance for tip-based nanomanufacturing applications. In this paper, we examine the normal contact of a-C:H and UNCD axisymmetric tips with diamond, UNCD and a-C:H substrates. Adhesion and wear as a function of material, surface termination, impact point, and roughness were all examined. Results from the MD simulations were compared, and lend insight into, complementary AFM experiments. In addition, separate sets of MD simulations were performed using two different potential energy functions. The AIREBO potential is a bond-order potential that contains intermolecular interactions that was developed to model bond-breaking and bond-making processes. Results obtained using the AIREBO potential will be compared results obtained using the recently developed REBO+S potential. The REBO+S potential differs from the AIREBO potential in that alterations were made to the REBO potential cutoff distances, which alters the forces required to make and break bonds. Differences in adhesion and wear events obtained using the two different potentials with identical material pairs will be quantified. Supported by the National Science Foundation

11:40am **TR+AS-MoM11 Speed-Dependence of Atomic-Scale Friction**, *A. Martini, Z. Ye*, University of California Merced, *Y. Dong*, Purdue University, *P. Egberts, XZ. Liu, R.W. Carpick*, University of Pennsylvania

Atomistic simulations and experimental atomic force microscopy measurements on a variety of different materials have shown that atomic-scale single asperity friction can be significantly affected by sliding speed. However, physical insights into how and why sliding speed affects friction are limited because the speeds accessible to most simulations are several orders of magnitude faster than those in the corresponding experiments. Typical simulations must be run at fast sliding speeds due to their necessarily short time scale, and accurate experimental nanoscale asperity friction measurements are limited to slow speeds because of difficulties in measuring high-speed forces with picoNewton resolution. Here we present friction results from molecular dynamics simulations where the sliding speeds are greatly reduced by using parallel replica dynamics. Parallel replica dynamics is an accelerated simulation technique that distributes simulation time across multiple processors and therefore adequately samples the various possible state-to-state pathways accessible to the system, as would a standard, single-processor simulation run for a very long time. This technique, accompanied by experiments where data is obtained using a novel high-speed data acquisition method, enables measurements and simulations to be quantitatively compared within the same physical regime; specifically, at the same sliding speed. Furthermore, the materials, load, contact size and orientation, system compliance, and temperature are identical within experimental uncertainty so as to minimize differences between experiments and simulations, allowing robust comparisons and interpretations. These coordinated studies enable us to understand the dependence of atomic-scale friction on sliding speed, and to determine the limits of validity of the Tomlinson-Prandtl model, a reduced-order model widely-used to describe atomic-scale sliding.

# Monday Afternoon, October 28, 2013

## Tribology Focus Topic

Room: 203 C - Session TR+AS+NS+SS-MoA

## Molecular Origins of Friction

**Moderator:** I. Szlufarska, University of Wisconsin-Madison, M. Müser, Saarland University, Germany

2:00pm **TR+AS+NS+SS-MoA1 Unraveling and Eliminating Dissipation Mechanisms in Polymer Brush Interfaces, M.H. Müser, FZ Jülich, Germany** **INVITED**

Surfaces covered with end-anchored polymers under good solvent conditions have excellent tribological properties. Friction between such surfaces is commonly attributed to the interdigitation of opposing polymer brushes. However, this conclusion tends to be based on idealized geometries neglecting capillaries or surface roughness. Using molecular dynamics simulations, we find that, depending on the direction of motion, dissipation due to capillary and shape hysteresis can contribute in a similar fashion as interdigitation. The two alternative mechanisms are even likely to become dominant at small sliding velocity. We also analyze how friction can be tuned through the solvent quality, thereby providing guidelines for the optimization of the investigated systems.

2:40pm **TR+AS+NS+SS-MoA3 Molecular Dynamics Simulations of Adhesion & Friction between Carbon-based Materials, Silicon, and Silicon Carbide, K.E. Ryan, United States Naval Academy, K. Vummaneni, J.D. Schall, Oakland University, J.A. Harrison, United States Naval Academy**

The nanoscale properties of two bodies in contact cannot be fully analyzed on an atomistic level using experimental methods or understood solely using continuum mechanics. Molecular dynamics (MD) simulations allow nanoscale behavior to be modeled by resolving the positions, velocities, and forces of discrete atoms in the system. Diamond has been of interest as both an object of scientific study and as an ideal material for applications such as, cutting tool coatings, waste water purifiers, chemical sensors, electronic devices, and micro- and nanoelectromechanical systems (M/NEMS) because of its unique electrical, mechanical, and tribological properties. Due to its high fracture strength and chemical robustness, it can withstand exposure to harsh environments and resist mechanical wear. It can be grown in nanocrystalline form with nearly equivalent mechanical performance to the crystalline form. Silicon, due to the ability to create atomically sharp tips, is frequently used in scanning probe microscopy. Recently, carbon implantation of preformed Si-tips has been used to improve wear properties. In this work, MD was used to simulate the nanoscale adhesion and tribological behavior between diamond, diamond-like carbon (DLC) surfaces and silicon, and silicon carbide tips. Work of adhesion values from the MD simulations with axisymmetric tips are compared to, and discussed within the context of, complementary AFM experiments where available, finite element simulations, and continuum mechanics-based analytical models. MD simulations show that the work of adhesion is sensitive to the identity of the contacting materials because they have inherent roughness differences. In addition, work of adhesion values obtained from continuum mechanics-based analytical models are consistently higher than values obtained using the atomic-force microscope, which are higher than the simulated values. A recently developed bond-order potential for C-, H-, and Si-containing systems was used to carry out these simulations. The novel aspects of this model will be discussed.

3:00pm **TR+AS+NS+SS-MoA4 Electronic Friction at the Atomic Scale: Conduction, Electrostatic and Magnetic Effects, Z. Fredricks, K.M. Stevens, J. Krim, North Carolina State University**

In the study of friction at the nanoscale, phononic, electrostatic, conduction electron and magnetic effects all contribute to the dissipation mechanisms [1,2]. Magnetic contributions are increasingly alluded to in current studies, but remain poorly characterized. We report here our observations magnetic friction for sliding adsorbed films on various magnetic films substrates in the presence and absence of an external field. Using a quartz crystal microbalance (QCM), we record the sliding friction of liquid monolayers of nitrogen, a diamagnetic material, as well as liquid oxygen, a paramagnetic material, on nickel alloy and graphene/nickel surfaces. In the prior literature, these systems have been reported to exhibit sensitivity to external fields. The work presented here compares and contrasts fundamental dissipation mechanisms in sliding adsorbed films [3] to studies performed by means of magnetic tip microscopy [1]. [1] I. Altfeder and J. Krim, *J. Appl. Phys.* (2012), [2] Highland et al., *PRL* (2006) [3] J. Krim, *Advances in Physics*, Vol. 61, Iss. 3, 155-323 (2012); Work supported by NSF DMR

3:40pm **TR+AS+NS+SS-MoA6 Chemical Origins of Interfacial Friction: Insights from Atomistic Simulations, I. Szlufarska, K. Huang, University of Wisconsin-Madison, Y. Liu, Massachusetts Institute of Technology** **INVITED**

While interfacial chemistry plays a critical role in frictional response of materials, understanding chemical changes that occur in sliding mechanical contacts has been challenging. Experimentally, the difficulty lies in the limited ability to characterize contacts *in situ* and typically chemical characterization of interfaces is carried out before or after sliding. Modeling and simulations can provide powerful insights into the chemistry of frictional contacts, however models that possess a high level of chemical fidelity are often limited to small system sizes and short simulation time scales. Here, we overcome this limitation by bringing together complementary simulation methods that range from *ab initio* calculations based on the density functional theory (DFT), large scale molecular dynamics (MD) simulations with reactive empirical potentials, and the kinetic Monte Carlo (kMC) technique. In this talk we will discuss examples of how these methodologies have been used to identify chemical origins of friction. One example is the discovery of mechanisms that underlie aging of silica in aqueous environments, which is of interest for multiple phenomena ranging from wafer bonding to shallow tectonic earthquakes. We have demonstrated that in the absence of deformation creep, aging of silica takes place by formation of interfacial siloxane bridges. We have discovered a new mechanism for interaction between these bridges and have shown that this interaction is critical to explain experimentally observed logarithmic dependence of aging on time. In addition, we will discuss our newly developed theory that enables efficient and accurate calculations of friction at solid/liquid interfaces directly from MD simulations and that overcomes the typical time scale limitations of standard MD simulations. This theory has been validated for multiple types of surfaces and liquids and it can be used for design of chemical interfaces for applications in aqueous environments, such as nano- and micro-fluidics.

4:20pm **TR+AS+NS+SS-MoA8 The Relationship Between Molecular Contact Thermodynamics and Surface Contact Mechanics, N. Nikogeorgos, C.A. Hunter, G.J. Leggett, University of Sheffield, UK**

The atomic force microscope (AFM) has been used widely to study nanoscale tribological phenomena, but a unified model for the mechanics of the tip-sample interaction is lacking. Experimental data show that nanoscale friction depends strongly on interfacial chemistry, but these correlations are not explained adequately by existing models. Here we report measurements of interactions between hydrogen bond-forming molecules adsorbed onto solid surfaces and AFM tips. By making measurements in liquid mixtures, we demonstrate a quantitative correlation between the surface shear strength in a nanoscale contact and the free energy of solution-phase hydrogen bonding interactions, uniting classical contact mechanics with equilibrium thermodynamics. We demonstrate that the thermodynamics of intermolecular interactions may be determined quantitatively from nanoscale friction measurements. It has been found that the contact mechanics are best modeled by treating the friction force as the sum of a load-dependent term (attributed to "molecular plowing") and an area-dependent term attributed to shearing (adhesion). The relative contributions of plowing and shearing are determined by the coefficient of friction,  $\mu$ , and the surface shear strength  $\tau$ . The transition from adhesion- to load-determined friction is controlled by the solvation state of the surface: solvated surfaces represent a limiting case in which the shear term approaches zero, and the friction-load relationship is linear, while in other circumstances, the friction-load relationship is non-linear and consistent with Derjaguin-Muller-Toporov (DMT) mechanics. A striking correlation has been observed between the concentration-dependence of the association constant ( $K_a$ ) for the formation of 1:1 hydrogen-bonded complexes and the pull-off force  $F_a$  and surface shear strength  $\tau$  for the same molecules when one partner is immobilized by attachment to an AFM probe and the other is adsorbed to a surface. Analysis of the concentration-dependence of  $F_a$  and  $\tau$  enables the prediction of  $K_a$  with remarkably high precision, indicating that for these hydrogen bonding systems, the tip-sample adhesion is dominated by the H-bond thermodynamics. For hydrocarbon surfaces, we have found that friction-load relationships are also fitted by DMT mechanics, and experimentally determined works of adhesion correlate closely with predictions from Lifshitz theory. For polymer brushes, a broader range of behavior is observed, but this may also be understood if the contact mechanics are modeled by treating the friction force as the sum of a load-dependent term and an area-dependent term attributed to shearing.

4:40pm **TR+AS+NS+SS-MoA9 Friction of a Thermally Activated Ensemble of Nanocontacts**, *P.V. Antonov, J.W.M. Frenken*, Leiden University, Netherlands

We report the first stages of an experiment to lower dry, unlubricated friction by use of a tailor-made nanostructure. In previous studies, we have demonstrated that random thermal fluctuations change the familiar, atomic stick-slip motion of the tip of a friction force microscope (FFM) into a thermal drifting motion, when these fluctuations are strong enough with respect to the barriers in the energy landscape. Based on a two-mass-two-spring model of an FFM [1], we know that these excitations are concentrated in the last nanometers of the tip, because of its extremely small mass and its flexibility. To achieve similar behavior in a macroscopic contact with an area well beyond that of the very specific tip-surface geometry of an FFM, we have shaped one of the two, macroscopic contacting surfaces in the form of a micro-fabricated array of Si nanopillars, each with a well-defined spring coefficient, equal to that of a standard FFM tip. This pattern can be regarded as a large multitude of FFM-like tips, each one exhibiting the thermal fluctuation motion that we identified as a lubricating effect in an FFM. Since the density of these asperities is high, the forces on each individual asperity are always low enough to keep its deformations completely elastic. We expect that each of the tip-like pillars will fluctuate independently under the load of a ball-shaped AFM tip and as a result of this, it should be possible to translate the entire, multi-asperity contact by an extremely low lateral force. This approach should lead not only to low friction, but also to a characteristic, strong dependence of the sliding motion and the friction force on temperature and on sliding velocity. We will also explore how the thermal fluctuation behavior changes as a function of the dynamic properties of the individual nanopillars and how it evolves when we scale up the total number of asperities that are simultaneously in contact.

[1] S.Yu. Krylov, J.W.M. Frenken, *Phys. Rev. B* **80**, 235435 (2009).

5:00pm **TR+AS+NS+SS-MoA10 Nanoprobng of Friction and Charge Transport Properties of Vanadium Dioxide under the Metal-Insulator Transition**, *J.H. Kim*, KAIST, Republic of Korea, *D. Fu, K. Wang, J. Wu*, University of California, Berkeley, *J.Y. Park*, KAIST, Republic of Korea

The nanomechanical and electrical properties of vanadium dioxide ( $\text{VO}_2$ ) thin films across thermal-driven phase transitions were investigated using ultra-high vacuum atomic force microscopy.  $\text{VO}_2$  thin films were deposited on an n-type, heavily-doped silicon wafer by pulsed laser deposition. X-ray diffraction revealed textured polycrystalline structures in the monoclinic phase with preferential orientations in the (100) and (120) planes. Friction and conductance mapping were obtained as a function of temperature across the metal-insulator transition. When below the transition temperature, the friction decreased, whereas the friction increased markedly when above the transition temperature. This peculiar result can be attributed to the combined effects of thermally-activated tip sliding, associated with phonon at the insulating phase, and electronic contributions in the metallic phase.

5:20pm **TR+AS+NS+SS-MoA11 Non-Uniform Friction-Area Dependency for Antimony Oxide Surfaces Sliding on Graphite**, *M.Z. Baykara*, Bilkent University, Turkey, *C. Ritter*, Humboldt Universität zu Berlin, Germany, *B. Stegemann*, HTW Berlin – University of Applied Sciences, Germany, *M. Heyde*, Fritz-Haber-Institut der Max-Planck-Gesellschaft, Germany, *K. Rademann*, Humboldt Universität zu Berlin, Germany, *J. Schroers, U.D. Schwarz*, Yale University

We present frictional measurements involving controlled lateral manipulation of antimony nanoparticles on graphite featuring atomically smooth particle-substrate interfaces via tapping- and contact-mode atomic force microscopy. As expected from earlier studies, the power required for lateral manipulation as well as the frictional forces recorded during the manipulation events exhibit a linear dependence on contact area over a wide size range from 2000 nm<sup>2</sup> to 120,000 nm<sup>2</sup>. However, we observe a significant and abrupt increase in frictional force and dissipated power per contact area at a value of about 20,000 nm<sup>2</sup>, coinciding with a phase transition from amorphous to crystalline within the antimony particles. Our results suggest that variations in the structural arrangement and stoichiometry of antimony oxide at the interface between the particles and the substrate may be responsible for the observed effect.

## Tribology Focus Topic

Room: 203 C - Session TR+SE-TuM

### Low Friction Materials

**Moderator:** R. Bennewitz, INM - Leibniz-Institute for New Materials, D. Irving, North Carolina State University

8:20am **TR+SE-TuM2 Ultra Low Friction Surface Designed by Biomimetic Approach**, A. Takahara, Y. Higaki, M. Minn, M. Kobayashi, JST ERATO Takahara Soft Interfaces Project, Japan

The environmentally friendly biomimetic lubrication system was designed by tethering polyelectrolytes on the substrates with sufficiently high grafting density, so-called 'polymer brushes'. The hydrated brushes in aqueous media formed water lubrication layer to reduce friction coefficient, which is useful not only for artificial joints and bio-devices but also for various mechanical devices. Macroscopic tribological properties of polyelectrolyte brushes bearing ammonium salt, sulfonic acid, or phosphorylcholine unit were characterized by ball-on-plate type tribotester in the air, water, and salt solution through sliding a glass ball on the surface under a normal pressure of ca. 130MPa. The low friction coefficient below 0.02 was observed in polyelectrolyte brushes in water.

8:40am **TR+SE-TuM3 Thin Organic Monolayers on Inorganic Substrate: Ultra-Low Adhesion Friction and Wear Resistance Properties**, S.P. Pujari, H. Zuilhof, Wageningen University, Netherlands

Micro and Nano Electro Mechanical Systems (MEMS/NEMS) are considered to be an important technology for the development of several products in daily life such as electronics, medical devices, and packaging. Despite the tremendous progress in micro-fabrication, the development of highly robust surfaces, having ultra-low adhesion as well as friction and resistance against wear, is still a challenging subject of accomplishment. To this aim, new fluorine-containing terminal alkynes and alkenes were synthesized and self-assembled onto inorganic substrates (Si(111), SiC, and CrN) to obtain fluorine containing organic monolayers. The resultant covalently bound organic monolayers have similar surface properties as polytetrafluoroethylene (PTFE), but they are more stable than traditionally coated PTFE.

A combination of spectroscopic (XPS, IR), nanoscopic (AFM), and contact angle measurements shows that these monolayers were ordered and highly hydrophobic. Increasing the amount of fluorine on the alkyne precursor resulted in monolayers with a greatly reduced adhesion to silica probes, as well as an almost 5-fold decrease in the coefficient of friction on the surface. Overall, this yields a friction coefficient that is – to the best of our knowledge – lower than reported for any other thin organic monolayer. In addition, these monolayer-coated Si(111), SiC, and CrN surfaces perform superiorly over uncoated.<sup>1,2,3</sup> For instance, at a normal force of ~7  $\mu$ N, the monolayer-coated samples are still nearly undamaged, while an uncoated Si surface displays already wear marks of 8 nm deep. The remarkable tribological properties make these fluorinated monolayers promising candidates for the development of robust, high-performance MEMS/NEMS systems.

1. Ultralow Adhesion and Friction of Fluoro-Hydro Alkyne-Derived Self-Assembled Monolayers on H-Terminated Si(111) Sidharam P. Pujari, Evan Spruijt, Martien A. Cohen Stuart, Cees J. M. van Rijn, Jos M. J. Paulusse, and Han Zuilhof Langmuir 2012 28 (51), 17690-17700.

2. Covalently Attached Organic Monolayers onto Silicon Carbide from 1-Alkynes: Molecular Structure and Tribological Properties Sidharam P. Pujari, Luc Scheres, Tobias Weidner, Joe E. Baio, Martien A. Cohen Stuart, Cees J. M. van Rijn, and Han Zuilhof Langmuir 2013 29 (12), 4019-4031.

3. Tribology and Stability of Organic Monolayers on CrN: A Comparison between Silane, Phosphonate, Alkene, and Alkyne Chemistries Sidharam P. Pujari, Li Yan, Regeling Remco, and Han Zuilhof Langmuir 2013 Submitted.

9:00am **TR+SE-TuM4 Mechanical and Tribological Behavior of Carbon-Based Coatings Sliding against PEEK Polymer Counterfaces**, E. Broitman, Linköping University, Sweden, S. Laino, University of Mar del Plata, Argentina, S. Schmidt, Linköping University, Sweden, P.M. Frontini, University of Mar del Plata, Argentina, L. Hultman, Linköping University, Sweden

Carbon-based coatings are known for their good mechanical and tribological properties. By tuning the C sp<sup>3</sup>-to-sp<sup>2</sup> bonding ratio and by alloying the carbon with other elements, it is possible to tailor hardness, elasticity, friction and wear resistance. Also, polyether-ether-ketone (PEEK)

polymers are increasingly used by the industry because of their corrosion resistance, mechanical stability, and self-lubricating ability. Huge amount of data regarding their individual interaction with steel counterfaces is available; however, very little information is found regarding the interaction of both materials.

In this work, we studied mechanical and tribological properties of carbon nitride (CN<sub>x</sub>) and carbon fluoride (CF<sub>x</sub>) coatings sliding against PEEK. The coatings were deposited on SKF3-steel balls by high power impulse magnetron sputtering (HiPIMS) using an industrial deposition system CemeCon CC800/9ML. CN<sub>x</sub> was prepared at room temperature (RT) and 180 °C (HT) by reactive sputtering from C target in a N<sub>2</sub>/Ar discharge at 400 mPa. CF<sub>x</sub> was prepared at RT by reactive sputtering from a C target in a CF<sub>4</sub>/Ar mixture at 400 mPa. PEEK 6 mm-thick unfilled plates were produced via injection molding (GATONE™ 5600). The friction and wear properties were measured by a pin-on-disk device using 6.35 mm-dia coated and uncoated balls against PEEK in dry slide at pressure contacts from 860 to 1240 GPa. Optical and scanning electron microscopy, and EDX spectroscopy were used to observe the wear tracks and analyze the presence and composition of transfer films. A triboindenter TI-950 (Hysitron) was used to measure hardness, elastic modulus, and roughness of the materials.

For uncoated steel counterfaces, the running-in friction ( $\mu$ ) takes place during the first 300 s, and shows peak values in the range 0.40-0.47. In the steady state,  $\mu$  decreases to 0.30-0.35. The contact area shows big and deep scratches, oxidation, and no film transfer.

RT-CF<sub>x</sub> and HT-CN<sub>x</sub> coatings have similar behavior. Both have running-in periods of 1000 s,  $\mu$  in the range 0.25-0.45, which increases in the steady state to 0.45-0.50. The microscopy reveals that the coatings have failed; big wear scars and the presence of film transfer are easily observed.

RT-CN<sub>x</sub> coatings show the best performance. At the end of 1000 s running-in period  $\mu$  is in the range 0.25-0.33, and increases slightly to 0.35-0.38 after 6000 s. The coatings show a very small wear scar and the presence of film transfer.

Our results demonstrate that a RT-CN<sub>x</sub> coating on a steel counterface sliding against a PEEK polymer improves the tribological behavior of the sliding couple, and also is advantageous due to the coating chemical inertness.

9:20am **TR+SE-TuM5 Microstructure, Mechanical and Friction Behavior of Magnetron-sputtered V-C Coatings**, M. Stüber, P. Stoyanov, Karlsruhe Institute of Technology, Germany, E. Nold, Fraunhofer-Institute for Mechanics of Materials IWM, Germany, J. Schneider, H.J. Seifert, S. Ulrich, Karlsruhe Institute of Technology, Germany

Transition metal carbides exhibit superior mechanical and tribological properties at a wide range of environmental conditions and contact pressures. More recently, vanadium carbide coatings have been considered for a number of industrial applications (e.g. automotive components, cutting tools, ball bearings) due to their high corrosion resistance and mechanical stability at elevated temperatures. While some studies have provided significant new insights on deposition methods of vanadium carbides, the friction and wear mechanisms of these coatings have received little attention. The goal of this study is to link micro- to macroscale tribology in order to provide an excessive understanding of the sliding mechanisms of various vanadium carbide-based (VC<sub>1+x</sub>) coatings. More generally, we are studying the influence of V:C ratio over a wide range of normal loads and contact areas. The coatings are prepared using non-reactive d.c. magnetron sputtering with a segmented VC/graphite target (i.e. target diameter of 75 mm, 500 W target power, substrate temperature < 150°C, and Ar gas pressure of 0.6 Pa). The resulting V:C ratios vary between 1:1 and 1:3. The microstructures of the as deposited coatings are characterized using X-ray diffraction and cross-sectional focused ion beam imaging, while elemental analysis is performed by means of X-ray photoelectron spectroscopy, electron probe microanalysis, and micro-Raman spectroscopy. Mechanical properties measurements show that the hardness (H) and the reduced modulus (E<sub>r</sub>) of the coatings decrease with increasing the carbon concentration (i.e. H ranges between 15 and 33 GPa and E<sub>r</sub> ranges between 239 and 391 GPa for the low and high vanadium concentration respectively), which correlates well with the adhesion results obtained from scratch tests. However, reciprocating micro- and macroscale tribological tests reveal higher friction values and increased wear with the high vanadium content coatings. This sliding behavior is attributed to differences in the third body formation and velocity accommodation modes, which are analyzed *ex situ* by means of XPS, micro-Raman spectroscopy and atomic force microscopy. The results obtained on the V:C coatings are compared to friction and sliding mechanisms in W:C systems.

9:40am **TR+SE-TuM6 Interaction of Stearic Acid with Iron-based Surfaces Coupling Experimental and Numerical Approaches for a Better Understanding of its Friction Behavior**, C. Minfray, C. Matta, S. Loehle, T. Le Mogne, J.M. Martin, Ecole Centrale de Lyon - LTDS, France, R. Iovine, Total, Solaize Research Center, France, Y. Obara, R. Miura, A. Miyamoto, Tohoku University, Japan

Organic friction modifiers (OFMs) have been used for many years in metallic contacts to reduce friction under mild conditions. The interest for such friction modifiers is still very strong because environmental regulations ask for slightly hazardous lubricant additives. It is proposed here to revisit adsorption and friction behavior of fatty acids by coupling experimental and computational chemistry approaches.

The OFM studied is stearic acid, used as pure additive or blended at 1%w in PAO4 synthetic base oil. The surfaces of interest are iron-based materials (including pure iron and iron oxides) as they can be encountered in a steel/steel contact under mild or severe friction conditions. Adsorption and friction properties of such systems were studied experimentally (friction, XPS and PM-IRRAS surface analyses) and adsorption kinetics was also studied by computational chemistry (UA-QCMD).

Adsorption experiments of stearic acid (gas form) on the different surfaces (gold, pure iron, iron oxides) were carried out in an environmentally controlled chamber for different adsorption time (10 min to 2 hours). This was followed by *in-situ* XPS analyses of the surfaces. XPS analyses results, especially the position of the C1s peak contribution from the carboxylic group, show differences depending on the nature of surfaces.

Computational chemistry study was also performed to investigate the *in vacuo* interaction of stearic acid molecules with the different model surfaces (pure iron, Fe<sub>2</sub>O<sub>3</sub>, and FeOOH). An ultra-accelerated quantum chemical MD (UA-QCMD) simulator has been used in order to deal with chemical reaction dynamics for large complex systems. Different models have been built starting with one single molecule up to self-assembled monolayer (SAM) on iron based surfaces at 50 °C. We found differences in adsorption energy (physisorption or chemisorption) depending on the kind of surface and regarding the presence of one single molecule or a SAM.

Eventually, friction experiments were carried out on a cylinder-on-flat reciprocating tribometer using samples in AISI52100 steel. The lubricant was stearic acid blended at 1%w in PAO4 and temperature was set to 50°C, 100°C and 150°C with an applied load of 50 N (corresponding to a maximum contact pressure of 320 MPa). After the tribological tests, PM-IRRAS analyses were conducted on the tribofilms. Results show the presence of stearic acid in the wear track as well as carboxylate forms.

All experimental and simulation results of both adsorption and friction experiments are discussed for a better understanding of complex interactions between stearic acid and iron-based surfaces.

10:40am **TR+SE-TuM9 Low Friction on Metals – Glide Planes and Molecular Lubricants**, R. Bennewitz, INM - Leibniz-Institute for New Materials, Germany **INVITED**

Nanotribological investigations of flat crystalline metal surfaces by means of friction force microscopy often result in extremely low friction coefficients. Experimental results indicate that the actual glide occurs between the low-indexed crystalline surface and a metallic neck, which forms by transfer of metal to the tip of the force microscope [1]. In the case of Au(111) surfaces, the apparently simple gliding process requires surfaces diffusion to operate, as evident from a failure of atomic friction mechanisms at lower temperatures [2]. Friction coefficients measured by friction force microscopy approach values known from macroscopic experiments when the tip plastically deforms the surface by scratching [3].

Electrochemical methods allow for an *in-situ* modification of surfaces by electrochemical oxidation, reduction, ion adsorption, or change in surface reconstruction. All of these influence nanometer-scale friction. For example, variation of the surface reconstruction reveals that friction increases with atomic-scale roughness [4]. Friction experiments in ionic liquids demonstrate that the preferential adsorption of anions or cations opens an opportunity for reversible switching of lubrication [5].

[1] N.N. Gosvami et al., Microscopic Friction Studies on Metal Surfaces, Tribol Lett 39 (2010) 19

[2] N.N. Gosvami et al., Ageing of a Microscopic Sliding Gold Contact at Low Temperatures, Phys. Rev. Lett. 107 (2011) 144303

[3] M. Mishra et al., Friction model for single-asperity elastic-plastic contacts, Phys. Rev. B 86 (2012) 045452

[4] F. Hausen et al., Surface structures and frictional properties of Au(100) in an electrochemical environment, Surf. Sci., 607 (2013) 20

[5] J. Sweeney et al., Control of Nanoscale Friction on Gold in an Ionic Liquid by a Potential-Dependent Ionic Lubricant Layer, Phys. Rev. Lett., 109 (2012) 155502

11:20am **TR+SE-TuM11 Few Layer Graphene as a Potential Solid Lubricant**, D. Berman, A. Erdemir, A.V. Sumant, Argonne National Laboratory

In recent years, reducing friction and wear-related mechanical failures in moving mechanical systems has gained increased attention due to their adverse impacts on efficiency, durability and environmental compatibility of such systems. Accordingly, search continues for novel materials, coatings, and lubricants (both liquid and solid) that can potentially reduce friction and wear. The majority of the existing solid lubricants (MoS<sub>2</sub> graphite, hexagonal boron nitride, etc.) requires full coverage, strong bonding, and relatively thick layers to provide lubricity to sliding interfaces. Moreover, their lifetimes and lubricating properties vary a great deal when operated under different environmental and tribological conditions. In this study, we demonstrate that a few layers of graphene are able to drastically reduce friction and wear of sliding steel surfaces under both inert and humid environments. The reduction in wear is as much as 4 orders of magnitude while friction is cut down by factors of 4 to 5. We believe that the anti-corrosion property of graphene coupled with its self-lubricating nature is mainly responsible for such remarkable friction and wear properties and the surface microscopic and spectroscopic studies confirm our hypothesis by confirming the presence of very thin and continuous graphene layers on both the ball and disk surfaces which were slid against one another under 1 N load in both humid air and dry nitrogen environments. In addition, we show that graphene application as well as re-application does not require any additional processing steps other than just applying a small amount of ethanol solution containing graphene on the surface of interest making this process simple, cost effective, and environmental friendly. Most of all, we found that unlike conventional solid lubricants which are all sensitive to environmental conditions, graphene provides low friction and wear regardless of the operating environment.

[1] D. Berman, A. Erdemir, A.V. Sumant: "Few layer graphene to reduce wear and friction on sliding steel surfaces". Carbon, 54, 454-459 (2013)

[2] D. Berman, A. Erdemir, A.V. Sumant: "Reduced Wear and Friction Enabled by Graphene Layers on Sliding Steel Surfaces in Dry Nitrogen", Carbon, in press. <http://dx.doi.org/10.1016/j.carbon.2013.03.006>

#### ACKNOWLEDGMENTS

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11:40am **TR+SE-TuM12 Scaling of Structural Lubricity**, D. Dietzel, M. Feldmann, University of Giessen, Germany, U.D. Schwarz, Yale University, H. Fuchs, University of Muenster, Germany, A. Schirmeisen, University of Giessen, Germany

In an effort to reduce the friction between sliding components scientists and engineers have developed a multitude of lubrication schemes. One of the most intriguing concepts is referred to as 'structural lubricity', where at surfaces are thought to slide past each other virtually frictionless if their atomic structures are incommensurate, i.e. they do not match. Corresponding theories are based on sub-linear power laws for the area-dependence of friction in the structural lubricity regime, but this unusual scaling has never been observed so far. Here, we present experiments that quantify nanoparticle sliding resistance of amorphous antimony particles on crystalline graphite [1,2]. Our results confirm the predicted sub-linear scaling behavior for incommensurate, disordered interfaces, and allow a direct link between mesoscopic friction and atomic principles. Additionally, the case of crystalline incommensurate interfaces is investigated for gold crystals on graphite, pointing towards a more complex scaling behavior that accounts for particle shape and orientation. Our findings point towards a new route to engineer surfaces with unprecedented low friction on the basis of well-defined nanocontacts.

[1] A. Schirmeisen and U. D. Schwarz, ChemPhysChem 10 (2009) 2358

[2] D. Dietzel et al., Physical Review Letters 101 (2008) 125505

# Tuesday Afternoon Poster Sessions

## Tribology Focus Topic

Room: Hall B - Session TR-TuP

## Tribology Poster Session

**TR-TuP1 Study of Charge Separation and Relaxation during Friction between Metal and Plastics in a Vacuum and in Air.** *T. Miura*, National Institute of Occupational Safety and Health, Japan

Electric charges generated by friction, i.e., triboelectricity, between industrial materials induce incendiary electrostatic discharges, such as a spark. In fact, many industrial accidents involving explosions and fires occur due to the electrostatic discharges. In this study, we focus on the elemental processes, e.g., charge separation and relaxation, during friction between metal and plastics. Measurement of the charge separation in a vacuum makes it clear that the real amount of triboelectrification between solid materials because of suppression of charge relaxation through gas discharge in a micro-gap interface of them. In air, we can obtain the relaxation efficiency for the initial charge separation.

The experimental equipment was constructed on the basis of pin-on-disk technique in a vacuum chamber. The pin was made of metal and the disk was made of plastic material. Amount of the separated electric charges between them during sliding friction was measured with an electrometer by connecting to the metal sample.

Experiment with a stainless steel pin and a poly-ethylene terephthalate (PET) disk was performed. The charge density on the rubbed surface of PET was calculated to be about  $-5 \times 10^{-4}$  C/m<sup>2</sup> from the generated charges and the width of the friction track. In air, the charge accumulation was, however, one order of magnitude less than the value measured in a vacuum. This should be caused by the charge relaxation as a result of the micro-gap discharge [1].

[1] T. Miura and I. Arakawa, IEEE Transactions on Dielectric and Electrical Insulation, **14**, 560-565 (2007).

**TR-TuP2 Development of Solid Lubricant Films for Smooth Motion at High Temperatures.** *A. Kasahara, M. Sasaki, M. Goto, H. Honda, H. Suzuki, M. Tosa*, National Institute for Materials Science, Japan

Research on low friction materials has attracted considerable attention from the viewpoint of effective energy use for realizing a low carbon society, as these materials can substantially reduce energy loss in bearings, gears, and other mechanical drive parts. However a problem is an increase in friction due to the oxidation reaction in high-temperature environments.

We therefore tried to develop advanced high-temperature motion materials with excellent tribological properties (i.e.: little wear, low friction, good lubrication) in order to guarantee a smooth sliding motion over long periods. Our final purpose is to design coatings suitable for smooth sliding motion up to 1073K.

As a first step, In order to measure friction at high-temperatures exceeding 673K, we designed and manufactured a prototype of a high temperature tribological evaluation device. For this purpose high-temperature friction measurement system based on Bowden-Leben type system has been successfully developed that can evaluate sliding friction force under changing load from 9.8N to 0.098N and under changing heat temperature from 1073K to room-temperature.

We have investigated solid lubricant coatings in order to develop high performance motion mechanism at high-temperature. In previous work, we developed high temperature lubricating coatings by precise control of coating processes using ceramics such as copper oxide, zinc oxide, boron nitride, etc. This time, we focused Cr<sub>2</sub>O<sub>3</sub>, since this material has been reported to be suitable at high-temperature, but not well been investigated for industrial application to sliding parts.

We have carried out basic study of SUS304, SUS440C and SUJ2 to find out suitable friction parameter at high-temperature from 973K to room-temperature. Their tribological characteristics at high-temperature was evaluated by high-temperature friction measurement system, abrasion measurements by Stylus Surface Profiler and Micro Slurry-jet Erosion.

**TR-TuP3 Wear and Oxidation Behaviors of Ti(C, N, O) Coatings.** *J.H. Hsieh, Y.R. Cho*, Ming Chi University of Technology, Taiwan, Republic of China

It has been known that the life time of Ti-based hard coatings is dependent on the oxidation rate of Ti. Here, Ti(C,N,O) coatings prepared by an unbalance magnetron sputtering were studied and compared using a static oxidation approach as well as a pin-on-disc tribometer. Ti(C,N,O) thin film

prepared with different N<sub>2</sub>/O<sub>2</sub> flow rates were deposited on M2 steel substrates. The films properties were analyzed by Raman spectroscopy, SEM and X-ray Diffraction. These samples then went through static oxidation and tribological testing. The surface morphology and the thickness of oxidation layer were obtained by using scanning electron microscopy (SEM).

In static oxidation, the formed titanium oxide (TiO<sub>2</sub>) was found to have mainly anatase structure at temperatures between 500°C to 600°C and transform to rutile structure at temperature higher than 600°C. Through this study, oxidation rate and activation energy of oxidation for each sample were evaluated. It is found the samples exhibited higher activation energy could have higher oxidation resistance. These results are consistent with those obtained from wear testing.

**TR-TuP4 Multi-Scale Simulation of Ohmic Contact Deformation in RF-MEMS.** *C.R. Freeze, X. Ji, B.E. Gaddy, D.L. Irving*, North Carolina State University

“Ohmic” RF-MEMS are radio frequency Microelectromechanical Systems (RF-MEMS) switches relying on metal-metal contact. They are of great interest to the telecommunications and defense industries due to their potential for use in switching networks, low-noise/power circuits, portable wireless systems, phased arrays, filters, and antennas. Issues with reliability, however, have prevented widespread commercial use of these devices. In an effort to better understand important degradation mechanisms in the vicinity of the contact, we simulated the complicated environment at the electrical contact through implementation a multi-scale method. This method incorporates an overlay of a finite difference mesh on top of a traditional molecular dynamics simulation. Thermal and electric transport equations are solved via finite difference part of the method and the results are coupled to an underlying atomistic simulation. In this work, contact deformation of ohmic RF-MEMS was approximated as the indentation of a single-asperity on a variety of substrates. These substrates included polycrystalline gold, polycrystalline gold with a void and polycrystalline gold with a trapped pocket of contamination. Indentation was performed for a variety of pressures and applied voltages. The different structures of the substrate result in drastically different steady state thermal profiles when voltage was applied. This significantly affected the indentation depth as compared to room temperature no voltage cases. Flow stress calculations as a function of bulk temperature were used to provide insight into trends in indentation depths as a function of load and underlying structure of the substrate.

**TR-TuP5 Effects TiN and TaN Barrier Layers on the Emergence of Ag and Cu Particles and the Subsequent Mechanical and Antibacterial Properties of TaN-(Ag,Cu) Nanocomposite Films.** *J.H. Hsieh, Y.R. Cho, Y.H. Lie*, Ming Chi University of Technology, Taiwan, Republic of China

TaN-(Cu,Ag) nanocomposite films were deposited by reactive co-sputtering on Si(001) and M2 tool steels. Prior to annealing, the films were deposited with a barrier layer of TiN or TaN (with various thickness) in order to control the amount of emerged Ag and Cu particles. As a result, the tribological and anti-bacterial behaviors can be controlled. The films were then annealed using RTA (Rapid Thermal Annealing) at 200 °C–400 °C to induce the nucleation and growth of metal particles. These films' structures, surface morphologies, and mechanical properties were analyzed. The samples were tested for their anti-wear and anti-bacterial behaviors against Gram-negative Escherichia coli, as function of barrier layer thickness. It is found that, through the application of diffusion barrier, the antibacterial efficiency against E. coli as well as the tribological properties can be changed and controlled, depending on the layer thickness of TiN and TaN. In general, the films with TiN layer tended to allow more Ag and Cu particles to form on the surface.

**TR-TuP6 Study of the Wear Mode in Tribocorrosion Tests of CoCrMo Alloys Coated with TiAlN/TiAl Multilayers.** *M. Flores, O. Jimenez, E. Rodriguez*, Universidad de Guadalajara, México, *C.E. Canto, E. Andrade*, Universidad Nacional Autónoma de México

The tribocorrosion phenomenon is present in biomedical alloys that are used in artificial implants to replace natural joints. This damage limit the service life of such implants, the hard coatings can improve the resistance of wear and corrosion. The multilayers of TiAlN/TiAl were deposited on CoCrMo alloys by magnetron sputtering. The structure of coatings was studied by means of XRD and the composition by RBS and EDS techniques. The tribocorrosion behavior of CoCrMo alloys alone and coated with TiAlN/TiAl multilayers was studied in simulated body fluid. The tribocorrosion was performed using a ball on plate reciprocating tribometer, the test was conducted in a simulated body fluid at 37 °C of temperature. The loads used were between 0.25 N to 2N, the oscillating frequencies was

1Hz. The corrosion and tribocorrosion were studied using open circuit potential (OCP), potentiodynamic polarization, cyclic polarization and potentiostatic polarization measurements. The potentiodynamic polarization was used to estimate the change in the corrosion rate due to wear and the potentiostatic polarization in the passive region to measure the change in the wear rate due to corrosion. In order to study the wear mechanisms, the topography and composition of worn surfaces were analyzed by means of profilometry, SEM and EDS. For the CoCrMo alloy the corrosion augmentation factor was greater than the wear augmentation factor. The coatings improve the corrosion and tribocorrosion resistance of CoCrMo alloys.

**TR-TuP8 Shape-dependent Adhesion and Friction on Au Nanoparticles Studied using Probing Atomic Force Microscopy, Y.J. Yuk, J.W. Hong, S.W. Han, J.Y. Park, KAIST, Republic of Korea**

Shape control of metal nanocrystals has broad applications, including catalysis, plasmonics, and sensing. It was found that controlling the atomic arrangement on metal nanocrystal surfaces affects many properties, including the electronic dipole or work function. Tuning the surface structure of exposed facets of metal nanocrystals was enabled by shape control. We investigated the effect of shape on nanomechanical properties, including friction and adhesion forces. Two nanoparticles systems, high-index {321} and low-index {100}, were used as model nanoparticle surfaces. Scanning force microscopy was used to probe nanoscale friction and adhesion. Because of the abundant presence of high-density atomic steps and kinks, high-index faceted nanoparticles have a higher surface energy than low-index faceted cubic nanoparticles. Due to this high surface energy, high-index faceted particles have shown stronger adhesion and higher friction than low-index nanoparticles. We discuss the results in light of the differences in surface energy as well as the effect of capping layers in the measurement.

**TR-TuP9 Effect of Plasma Nitriding Treatment Time on the Tribology of Tool Steels, P. Abraha, Meijo University, Japan, J. Miyamoto, Toba National College of Maritime Technology, Japan**

The effect of the plasma treatment time on the formation of the hard but brittle compound layer and the subsequent change on the tribological properties of the tool steel surface were investigated. The nitriding of tool steel was performed in electron beam excited plasma using neutral and charged nitrogen species. The tribological experiments were carried out at room temperature using a pin on disc tribometer. The results show that the tool steel nitrided by neutral nitrogen species for six hours produced a nitrided layer up to 40  $\mu\text{m}$ , without altering the pretreatment surface finish,  $R_a=14\text{nm}$ . The specific wear rate was less than one hundredth,  $4.3 \times 10^{-7} \text{mm}^3/\text{Nm}$  that of the untreated sample. On the other hand, the samples produced by the charged nitrogen species, ions, produced rough and brittle compound layer on the surface. Consequently, the friction coefficient of the former showed slightly lower friction coefficient compared to that of the latter. The results demonstrate that neutral species based nitriding is effective for high performance precision mechanical components that require better friction and wear performance while keeping the as finished pre-treatment dimensional accuracy, surface roughness and appearance of the sample.



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