# STUDENT AND EARLY CAREER POSTERS

*The posters are located in the Omni Nashville Hotel Broadway Ballroom Foyer.*

## Student Posters

### Effect of Chemical Structure on Triboflim Formation

**Kun Qian, Mark Devlin, Afton Chemical Corp., Richmond, VA, Timothy Cameron, Mark Sidebottom, Zhijiang (Justin) Ye, Miami University, Oxford, OH**

Under shear stress, chemical compound in lubricants may form solid tribofilm on surface which contributes to lower friction and wear. Previous studies show that the formation of this tribofilm is closely related to load, temperature, speed, types of additive, and types of base-oils. Here we investigate the frictional performance and tribofilm formation at bearing steel contacts in different base oil groups (group I-V). The pre- and post-experimental surface was characterized using scanning electron microscope and energy-dispersive X-ray spectroscopy. Our results show that the friction behavior and tribofilm formation was correlated to structure of major chemical components (paraffin, cycloalkanes, etc.) in base oils.

### Effects of Surface Defects on Rolling Contact Fatigue

**Zamzam Golmohammadi, Purdue University, West Lafayette, IN**

Surface defects such as dents have a significant influence on the RC life of REBs. In this study, a coupled multibody elastic-plastic FE model was developed to study the effects of surface defects on rolling contact fatigue. This model was used to determine the contact pressure acting over the surface defect, internal stresses, damage, etc. In order to determine the shape of a dent and material pile up during the over rolling process, a rigid indenter was pressed against a semi-infinite domain. Continuum damage mechanics was used to account for material degradation during RCF. A parametric study using the model was performed to examine the effects of dent sharpness, pile up ratio and applied load on the spall formation and fatigue life. The spall patterns were found to be consistent with experimental results. Moreover, the results indicate that the sharper the edges of the dent and higher the pile up cause larger pressure spikes and consequently reduced the fatigue life.

### Effects of Diffraction Gratings on Frictional Properties and Wettability of Beetle Elytra

**Lihua Wei, Kristen Reiter, Thomas McElrath, Marianne Alleyne, Alison Dunn, University of Illinois at Urbana-Champaign, Urbana, IL**

Under broad-spectrum light, many beetles show iridescence on wing covers (elytra). Some forms of it originate in micro-features that act as diffraction gratings, but beetles are unlikely to see it due to behavioral and physical limitations. This leads to the hypothesis that these features serve physical functions that mediate beetle interaction with environment. We studied frictional properties and wettability of elytra of four pairs of contrasting species. Each pair of species belong to the same genus but are with or without diffraction gratings. We tested them in sliding and indentation against dry and wet filter-paper, which we chose as a standardized surface to mimic leaf litter that beetles encounter in habitats. Based on friction coefficients, drag and meniscus forces results, we developed a model for the tribological behaviors of elytra. Contact angle and curvature were measured to demonstrate the viability of the model. This work affirms the multifunctionality of insect cuticle.

### The Evolution of Dark Etching Regions and White Etching Bands in Bearing Steel Due to Rolling Contact Fatigue

**Mostafa El Laithy, Ling Wang, Terry Harvey, University of Southampton, Southampton, Hampshire, United Kingdom, Bernd Vierneusel, Martin Correns, Toni Blass, Schaeffler Technologies GmbH & Co. KG, Schweinfurt, Germany**

Subsurface microstructural alterations such as Dark Etching Regions (DERs) and White Etching Bands (WEBs) can form in bearing components due to Rolling Contact Fatigue (RCF) under medium to high over-rolling cycles. These alterations are found to initiate as DERs followed by WEBs firstly at a low angle of 30° then at a high angle of 80° over hundreds of million cycles. Such transformations have been widely reported in literature however their formation mechanisms and the influence of bearing operating conditions are not well understood. This paper presents a study of DERs and WEBs formed in the bearing inner ring at two grades of AISI 52100 steel cleanliness under two different contact pressures over a range of load cycles. The results show while DERs and WEBs appear to be uniformly distributed when fully developed, the 30 & 80° WEBs are found to form in conglomerates at their early stages.

### Influencing Friction on $MoS_2$ through Speed, Temperature, and Preparation Method

**Kathryn Hasz, Robert Carpick, University of Pennsylvania, Philadelphia, PA, Mohammad Rasool Vazirisereshk, Ashlie Martini, University of California, Merced, Merced, CA**

While bulk $MoS_2$ has been used as a solid lubricant for decades, its monolayer form has recently become of interest for its electronic, optical, mechanical, and tribological properties. Through ultrahigh vacuum atomic force microscopy experiments, we investigate the speed and temperature dependence of a series of tip materials sliding on mono- and few layer $MoS_2$, observing that both factors can significantly affect friction. We also investigate the often-seen enhancement of friction for mono- and few layer 2D materials and see a dependence on $MoS_2$ preparation method, namely by mechanical exfoliation and chemical vapor deposition (CVD). In particular, we observe that mechanical exfoliation shows the expected enhancement while CVD does not. By combining these experimental results with complementary molecular dynamics simulations, we gain insight into the atomic-scale mechanisms governing $MoS_2$ friction behavior.

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## Friction and Wear Characteristics of Polymer Overlay Under Elevated Temperature Conditions

**Yokota Keisuke, Tomomi Honda, University of Fukui, Fukui, Japan, Kenji Nimura, Shigeru Inami, Daido Metal Co., Ltd., Aichi, Japan**

Overlays with solid lubricant improve the running-in process for sliding bearings. The polymer overlay technique has been developed and the overlay improves the wear and seizure resistance of sliding bearing. However, the friction and wear characteristics of polymer overlay have not ever been investigated under high temperature conditions. Thus, lubrication properties such as friction and wear should be clarified for the wide temperature range. In the present study, the friction and wear characteristics of the three materials were investigated such as the polymer overlays with only solid lubricant, that with only hard particles, and that with both solid lubricant and hard particles, respectively. The specimens with polymer overlay were tested at several temperatures ranging from room temperature until 200 °C. The case of polymer overlay with both solid lubricant and hard particles has shown the superior tribological characteristics at the higher temperature condition in our research.

## The Friction Coefficient and Wear Mechanisms of PEEK and PEEK Composite in Water Lubricated Sliding Contacts

**Ali Alsaegh, Cardiff University, Cardiff, United Kingdom**

The friction coefficient and wears mechanisms of PEEK and PEEK composite running against bearing steel in reciprocating sliding contacts has been investigated in dry lubricated and water lubricated conditions. Experiments explored how the lubrication state, load and rotational speed influenced the tribological performance of the polymers. Tribological tests were conducted on a TE77 high frequency tribometer, running in a ball-on-plate configuration and cylinder-on-plate configuration, scanning microscopy was used to investigate the wear mechanisms.

## Methods to Study the Life of an Asperity Subjected to Tribological Contact

**Arnab Bhattacharjee, Nikolay Garabedian, David Burris, University of Delaware, Newark, DE**

Friction and wear are consequences of complex phenomena that occur within a buried tribological interface. Directly interrogating these phenomena often requires methods to penetrate the contact interface in real time or methods to separate the contact without disturbing the processes. Engines, and many other applications involve self-mated metals, which virtually precludes the former. We have challenged ourselves to develop interrupted methods to study the life of an asperity in self-mated metallic contacts. The goal here was to break and recreate tribological contact with repositioning errors of 150 nm or less. Validation testing demonstrated that, with methods that are relatively easy to duplicate, contact locations can be replaced with a repositioning error of ±100 nm. Additionally, validation experiments with self-mated steel and a neat PAO lubricant demonstrate that the tribological contacts can be broken and replaced without any statistically significant effect on the wear rate.

## Friction Characterization of Ex Vivo Horse Hooves on Solid Surfaces

**Matthew Ergle, Kelsey Elliot, Chase Matthews, Carter Pegues, Morgan Price, Robert Jackson, Michael Zabala, Auburn University, Auburn, AL**

The traction of a horse's hooves is crucial in racing, orthopedic applications, and even walking because of the tendency of lower leg injuries such as lameness and hoof axis misalignment. In order to design better horseshoes and orthotics, an attempt was made to characterize the coefficient of friction of horse hooves using a tribometer, samples of hoof, and various surfaces that horses contact. Because of the fibrous and anisotropic form of horse hooves, the experiment isolated various locations of the hoof wall (exterior portion of the hoof that is typically contacting the ground). Concrete, rubber used for barn flooring, and tile were used as surface samples for the testing. The data was compiled and averaged across a five-minute time frame to gain a better understanding of the friction between each surface. By proceeding in this method, the coefficients of friction between the hoof wall samples and each surface were found to be between 0.9 and 1.3 for various locations on the hoof.

## The Effects of 3D Micro-Texture Shape on the Tribological Properties of the Textured Surfaces

**Mahyar Afshar Mohajer, Min Zou, University of Arkansas, Fayetteville, AR**

Texturing decreases the friction by reducing the real area of contact and hence adhesion between two surfaces. However, it undermines the durability of surfaces by increasing the contact pressure. Techniques used to fabricate textured surfaces have so far been limited to create 2.5D or randomly distributed structures. Utilizing a micro/nano-scale additive manufacturing method based on two-photon polymerization, we have fabricated textures with precise control over the texture shape, dimension, and arrangement. This allowed us to systematically investigate the effects of structure three-dimensionality by comparing textures with 3D features (cones) to 2.5D features (cylinders). Cones not only have lower friction due to their reduced area of contact provided by the sub-micron diameter tip, but also have better durability as the cone's base supports the load. This paves the way for low friction durable surfaces in micro/nano-device applications where adhesive friction is dominant.

## Rail Steel Wear Behavior Under Alternate-Phase Conditions

**Hao Fu, University of Illinois at Urbana-Champaign, Champaign, IL**

Heavy weight train wheels usually operate under complex conditions which may include combinations of pure rolling and sliding at the same time. Multiple research focus on the effect of wear on rolling contact fatigue but not the opposite. Here we studied how pure rolling will influence wear behavior of steel. In total, four experiments with fixed length (cycle) and initial contact pressure were conducted. In each experiment, a free rolling phase (one disk is disconnected from motor and driven by friction) was followed by a sliding phase (two disks rotate at different speeds). As a result, the highest fraction of a free rolling phase presents the widest track and highest wear rate. Further hardness measurements beneath track and SEM scanning results are also presented and analyzed.

## Wear Behavior in Polydimethylsiloxane (PDMS) Elastomers Under Milli-Newton Loads

**Christopher Johnson, Alison Dunn, University of Illinois at Urbana-Champaign, Urbana, IL**

Polydimethylsiloxane (PDMS), also known as silicone, is commonly used for numerous applications such as sealants, contact lenses, lithography, and medical devices. However, the wear characteristics of PDMS are still relatively unknown. We conducted long-duration wear experiments with a reciprocating microtribometer on numerous PDMS base-to-binder compositions. Optical profilometry was used to determine surface parameters and wear volume loss. We found non-monotonic material loss with respect to normal load for the standard composition, with minimum loss occurring at the transition point between the abrasive-dominant (higher pressure) and fatigue-dominant (lower pressure) regimes. Differences in wear track appearance were also observed between PDMS compositions, with stiffer compositions trending towards abrasive wear and softer compositions showing more localized wear deeper in the sample. These results will help design PDMS and other elastomers for longevity in low-pressure contact.

## Wear Behavior of Polyacrylamide Hydrogels

**Shabnam Bonyadi, Jiho Kim, Alison Dunn, University of Illinois at Urbana-Champaign, Urbana, IL**

Because of the structural and mechanical similarities between articular cartilage and hydrogels, an investigation of the wear behavior of hydrogels would provide valuable insight to the progression of osteo-arthritis. In this work, we explored the wear resistance of polyacrylamide hydrogels and the material properties that elicit its distinct behavior. Hydrogels were abrasively worn under different sliding conditions (normal load and speed). By measuring the subsequent wear volumes and analyzing the topography of the wear scars (3D Laser Scanning Confocal Microscope), we found that the wear volumes increased with normal load. Wear rates were calculated using Archard's wear law (ranging from 0.0444 mm3/Nm to 0.4144 mm3/Nm), which showed a sliding speed dependence. Currently, there are no laws that describe the wear behavior of solid-fluid composite materials, and this work is the beginning of developing more accurate predictions of the intricate wear behavior of hydrogels.

## Characterization of White Etching Areas in Annealed AISI 52100 Processed by High Pressure Torsion Tests

**Luis Wilches Peña, Ling Wang, Brian Mellor, University of Southampton, Southampton, United Kingdom, Joachim Mayer, Alexander Schwedt, RWTH, Aachen, North Rhine-Westphalia, Germany, Walter Holweger, Schaeffler Technologies AG & Co. KG, Herzogenaurach, Bavaria, Germany**

The study of White Etching Areas (WEAs) has mainly focused on samples those from field bearings disassembled after failure and bearings subjected to rolling contact fatigue tests in laboratories under various accelerators. This study investigated WEAs formed in annealed AISI 52100 after being processed on a High-Pressure Torsion (HPT) test rig where high strain is rapidly applied to create severe plastic deformation in materials (1) (2). Result show that WEA similar to those in bearings are formed in the annealed AISI 52100 bearing steel discs at three different locations under a range of loads and number of turns. Detailed SEM/EBSD/EDS characterization on the WEAs both on the surface and in the subsurface of the HPT processed samples suggests that non-metallic inclusions in the material were found to interrupt the plastic flow in the samples under HTP testing, which has promoted the dissolution of carbides into the refined ferritic matrix.

## A Fundamental Examination of the Oil Separation Behavior of Grease

**Nikhil Prasad, Paul Shiller, Gary Doll, The University of Akron, Akron, OH**

Grease has a myriad of uses and is vitally important in industrial applications. The molecular basis for its structure and oil release properties are poorly understood. Understanding these properties will allow the creation of more efficient and more application specific greases. The structure formation was measured using cone on plate rheometry. Different concentrations of thickeners have been tested using small angle oscillatory shear (SAOS) experiment coupled with cone bleed measurements to model bleed through Darcy's equation. The effects of thickener structure (type) and bleed characteristics may also show up in tribological systems, which were investigated using a lubrication evaluation machine (LEM) to investigate the role bleed or thickener plays in lubrication. Differences in the bearing torque are given as the lubricant bleed characteristics change during initial thickener agglomeration; i.e., grease formation concentration.

## Nanodiamonds for Improving Lubrication of Titanium Surfaces in Simulated Body Fluid

**Asghar Shirani, Diana Berman, The University of North Texas, Denton, TX**

Addition of small amounts (less than 0.2 wt.%) of nanodiamonds (NDs) to simulated body fluid promotes a substantial improvement in friction (3 times reduction) and wear (up to 2 orders of magnitude wear reduction) behavior of the titanium surfaces. Interestingly, the amount of NDs needed for improvement of friction and wear characteristics is critically dependent on the applied loads. With higher contact loads, larger concentrations of NDs are needed for better friction and wear reduction. Analysis of the wear track formed during sliding indicates the formation of a carbon-rich tribolayer which improves tribological properties of the contacting surfaces. Our results suggest that the carbon layer is formed from the nanodiamonds embedding in the top layer of titanium.

## Corrosive Wear Mechanisms of a Duplex Stainless Steel

**Peter Renner, Tony Huang, Hong Liang, Texas A&M University, College Station, TX**

Corrosive wear is one of the most common failures in the oil and gas industry due to its accelerated, uncontrollable and often unpredictable damage. The research investigates the mechanisms of corrosion of a duplex stainless steel under the condition of wear. Experimentally, a flat-on-flat configuration was developed based on a pin-on-disk tribometer. Duplex stainless steel 2205 was studied due to its excellent corrosion resistance and wide applications in harsh environments. The corrosive wear experiments were conducted in a 3.5 wt% NaCl solution under a load range from 1N to 3N at a fixed surface speed of 1.5 cm/s. It was discovered that the passivation current density increased when increasing the load from 1N to 2N but decreased when the load was increased from 2N to 3N. Also, a passivation layer was developed in all experiments, showing the benefits of the flat-on-flat configuration over the pin-on-disk model which generally removed the passivation layer.

## Laser Additive Manufacturing of Ni-Al-Cr-C: A High Temperature Sliding Wear Study

**Tyler Torgerson, Thomas Scharf, The University of North Texas, Denton, TX**

In this study, three novel composites composed of Ni-Al-Cr-C were processed by LENS™. The dry sliding friction and wear behavior of the composites were studied at room temperature (RT) and 500°C to determine the chemical and microstructural evolution during wear. Due to the variation in graphite (C) content in the composites, different microstructures of nickel aluminide ( ′ phase), chrome carbide and C were formed during solidification, directly impacting the corresponding mechanical properties and sliding wear behavior. SEM- EDS and Raman spectroscopy of the worn surface determined that NiO, Cr2O3, and C are the predominate tribochemical phases on the RT wear surfaces with friction coefficients ranging from ~0.55 to 0.15, while at 500°C, NiO, Cr2O3 and NiCr2O4 are the main tribochemical phases on the sliding surfaces, forming a lubricious oxide tribolayer that was advantageous in reducing the friction coefficients and wear rates of the Ni-18Al-11Cr-9C and Ni-14Al-8Cr-29C composites.

## Friction of Fluoropolymer Composites Evaluated Using Ball-on-Flat Configuration

**Sifat Ullah, Mark Sidebottom, Miami University, Oxford, OH**

Fluoropolymers (PTFE, PFA, FEP etc.) have exhibited up to 10,000x improvement in wear performance when composited with nanostructured metal-oxide fillers (such as alumina). This remarkable improvement in wear rate was attributed to tribochemical reactions between the fluoropolymer matrix and the metal oxide fillers. These reactions may be detected using infrared spectroscopy. Flat-on-flat testing has been primarily used to evaluate the wear and friction performance of these composites, which can be time consuming for ultralow wear samples. This study will utilize a ball-on-flat configuration to evaluate friction performance of these composites against ball counterfaces. Infrared spectroscopy of the composites and counterfaces will identify the chemical signature of the tribofilms. This alternate method may allow for faster characterization of these tribofilms. Faster characterization may assist in rapid development of new fluoropolymer composite materials.

## Suspension of Nanoparticles in Base Oils

**Yan Chen, Peter Renner, Hong Liang, Texas A&M University, College Station, TX**

One of most important issues in developing a new nanolubricant is the suspension of nanoparticles. To understand the mechanisms of nanoparticle dispersion, we studied the current approaches and practice in dispersion of nanoparticles in lubricating oil. It was found that the method of surface modification and size of nanoparticle appears to have profound influence on suspension. Further analysis indicated that the thickness of the grafted layer was responsible for suspending small nanoparticles. This poster presentation provides opportunity to discuss about those findings.

## Predicting Intrinsic Friction of 2D Materials Using Machine Learning Techniques

**Behnoosh Sattari Baboukani, Kristofer Reyes, Prathima C. Nalam, University at Buffalo, Buffalo, NY**

The properties such as weak van der Waals interactions and lattice mismatch between adjacent layers in two-dimensional (2D) materials make them promising candidates as lubricant additives. However, over few dozen 2D materials have already been successfully synthesized and other thousand 3D materials have been identified with potential exfoliation properties; and hence identification of 2D materials with high lubricity needs data-intensive machine learning tools. We identified a combination of geometric, electronic and mechanical descriptors to predict maximum potential energy surface (PES) for 13 different 2D materials using Bayesian modeling and transfer learning techniques. Posterior predictions indicated that graphene and WS2 present the lowest PES among the studied 2D materials, which were ~40% and ~25% lower than the average recorded PES, respectively. Further, the PES for transition metal dichalcodenides were found to highly correlate to the size of the chalcogen atom.

## Temperature Dependent Friction and Wear of Solid Lubricant Coatings

**Kandisi Anyabwile, Arindam Paul, Barbara Fowler, Gary Doll, The University of Akron, Akron, OH**

Mechanical systems sometimes are required to operate outside of the environmental conditions where liquid lubricants can function. In these situations, solid lubricant coatings are frequently employed. Successful solid lubricant solutions are generally those that utilize an elastically stiff and hard substrate to support normal loads and keep contact areas small, and a solid lubricant coating to provide shear accommodation and reduce junction strength. An important feature of many solid lubricant coatings is the formation of transfer films, which serves two roles: to prevent direct interaction of asperities in a tribological contact, and to accommodate shear from sliding in the contact. Two material systems known to effectively form transfer films in sliding contact are diachalcogenides (e.g., $MoS_2$) and diamond-like carbons. In this study, we have examined the effect of temperature on transfer film formation for M50 steel paired with several $MoS_2$ and diamond-like carbon coatings.

## Poroelasticity-Induced Thixotropic Mechanics in Inherent Lubrication of Hydrogels

**Jiho Kim, Alison Dunn, University of Illinois at Urbana-Champaign, Urbana, IL**

Hydrogels exhibit unique lubrication behaviors, including frictional hysteresis found in tribo-rheometry measurements. A hydrogel lubrication model that describes the hysteresis was previously developed using a thixotropic fluid model. In this study, the model is modified to incorporate the poroelastic material responses of hydrogel surfaces. Penetration depth of flow field is defined as an effective gap height that determines shear rates. At lower speeds, the time dependent decrease of the penetration depth due to poroelastic diffusion causes the transient increase in shear rate/stress of fluid, and therefore, increases friction. At higher speeds, a water film forms at the interface and rehydrates the gel surface, which increases the penetration depth and decreases friction. Simulations using the new model correlate well with the experimental results, indicating that the poroelasitic behavior of gel surfaces is closely related to the thixotropic mechanics in hydrogel lubrication.

## Subsonic to Intersonic Transition in Sliding Contact of Soft Solids

**Takuya Yashiki, Takehiro Morita, Yoshinori Sawae, Tetsuo Yamaguchi, Kyushu University, Fukuoka, Japan**

In many mechanical systems, the sliding contact occurs between metals. In such a situation, the sliding velocity V is normally much smaller than the elastic wave velocities, Rayleigh wave velocity C_R or the Secondary wave velocity C_S of the metals. On the other hand, if at least one of the frictional pair consists of soft solid such as rubber or gel, it happens that V exceeds C_R or C_S due to its small elasticity; the sliding contact can be intersonic. The situation can be encountered, for example, just when the braking is applied on the F1 car or the aircraft hits the ground on landing. Here we conducted friction experiments in transonic sliding velocities. We used a silicone gel as soft solid and made the experimental apparatus. As a result, we found the subsonic to intersonic transition in the frictional behavior. This result provides the first experimental evidence for the intersonic sliding contact.

## The Friction and Wear Property of Artificial Joint Materials in Synovial Constituent Solutions

**Hironori Shinmori, Mayo Kubota, Takehiro Morita, Tetsuo Yamaguchi, Yoshinori Sawae, Kyushu University, Fukuoka, Japan**

Many previous studies have indicated that biological macro-molecules contained in synovial fluid, such as proteins, lipids and hyaluronic acid, have large influence on the friction and wear of natural synovial joints and implanted artificial joints. However, the physical and chemical properties of prosthetic joint materials are different from that of natural tissues. Therefore, in this study, we explored the effect of synovial constituent on the friction and wear of materials for artificial joints. Pin-on-Plate reciprocating tests and Pin-on-Disk multi direction tests were carried out to investigate friction and wear of artificial joint materials, respectively. Experimental results have clearly indicated that proteins adsorbed on the material surface are the main factor increasing friction and wear of polymeric joint materials. Based on this finding, we prepared surface coatings for UHMWPE to prevent protein adsorption and confirmed their effects experimentally.

Surface Analysis of Brake Pad Specimen from Lab Scale Fine Dust Generation Test Jaesang Yoo, Sungkyunkwan University, Gyeonggi-do, Suwan-si, The Republic of Korea, Eunseok Kim, Juho Park, Youngze Lee, Sungkyunkwan University, Suwon-si, Gyeonggi-do, The Republic of Korea

As a leading study for conducting friction experiments with skin along with fine dust collection and characteristic analysis from brake pads, friction experiments in laboratory units using brake pad specimens were carried out and surface data of specimens were obtained. The friction test was conducted with three types of brake pads, which are shaped like a cube, through one-way face-to-face contact with the rolling gray cast iron disc. The experiment showed that the surface of B's brake pads was worn fairly evenly, whereas fine crack formation was achieved on the surfaces of A and C. In the case of specimen abrasion, grinding wear was the main cause and partial adhesion wear occurred on the surface of C.

## The Effects of Substrate Surface Roughness on the Tribological Performance of Polydopamine/PTFE Solid Lubricant Coatings on NiTiNOL 60

**Charles Miller, Min Zou, University of Arkansas, Fayetteville, AR**

NiTiNOL 60, or 60NiTi, is a nickel-titanium alloy being investigated for bearing and gear applications. It has many desirable properties for these applications; for example, it is hard, electrically conductive, corrosion resistant, superelastic, and non-magnetic. However, its tribological performance is poor in unlubricated conditions. In this study, a PTFE coating with a polydopamine (PDA) adhesive underlayer was deposited on 60NiTi and evaluated for friction and wear reduction. Additionally, the effects of the substrate surface roughness on the tribological performance of the coating were investigated. The results showed that PDA/PTFE coating on 60NiTi reduced the coefficient of friction over 85% and prevented wear of 60NiTi for thousands of cycles of accelerated testing. Furthermore, modifying the 60NiTi substrate roughness increased the durability of the coating over 24 times. Therefore, the coating and substrate surface showed the potential to provide solid lubrication for 60NiTi.

## Incorporation of Silica Nanoparticles into the Underlayer of PDA/PTFE Thin Coatings

**Adedoyin Abe, Dipankar Choudhury, Min Zou, University of Arkansas, Fayetteville, AR**

Polytetrafluoroethylene (PTFE) is a prominent solid lubricant. A polydopamine (PDA) underlayer enhances the durability of a PTFE thin coating. In this study, 75, 100, 200, and 300 μL of aqueous silica nanoparticle (NP) solutions were incorporated to the PDA deposition solution, respectively. Adding NPs to the PDA underlayer creates a rougher surface for PTFE adhesion. The durability and coefficients of friction of PDA/PTFE thin coatings on stainless steel substrates were investigated with and without the silica NPs. The coatings were tested in dry contact conditions using a Universal Mechanical Tester (UMT) with a ball-on-flat configuration in reciprocating motion. Additionally, wear behavior and mechanisms of the coatings were studied. Silica NPs encouraged fragmentation of PTFE, leading to smaller chunks being removed from the wear track. The durability when 75 and 100 μL of silica NP solution were added to the PDA underlayer improved by 77% and 70%, respectively.

## The Effects of PTFE Thickness on the Tribological Behavior of the PDA/PTFE Coatings

**Sujan Ghosh, University of Arkansas, Fayetteville, AR**

Polytetrafluoroethylene (PTFE) is a chemically stable polymer with very low friction and wear resistance. A thin polydopamine (PDA) underlayer can significantly enhance the durability of the PDA/PTFE coating. In this study, the coating thickness on stainless steel (SS) was varied from 3 mm to 42 mm and the effects of the PTFE thickness on the tribological properties of the PDA/PTFE coating was investigated. The coating was characterized by atomic force microscopy, 3D laser scanning microscopy, and a universal mechanical testing machine. The durability of the coating increased sharply when the PTFE thickness was larger than 30 mm. Due to the increasing roughness of the thicker coating, the COF of the coating increases as the thickness of the coating increases. The PDA/PTFE coating shows two to four times better durability than the PTFE only coating in different thickness. The 42 mm thick PDA/PTFE coating shows a 105 times better durability than the 3 mm thick pristine PTFE coating.

## Smart Electromagnetically Responsive Nanoadditized Lubricants

**Robert Elkington, Monica Ratoi, University of Southampton, Southampton, Hampshire, United Kingdom**

Preliminary results using ferromagnetic WS2 nanoadditized oils indicate that it is possible to increase the nanoparticles (NPs) in a tribological contact with an electromagnetic field and instantly generate a tribofilm even in pure rolling conditions. In mixed slide-roll contacts, chemical tribofilms developed thicker (up to 200 nm) and faster (full tribofilms developed in only 10 minutes – 9 times faster) in the presence of an EM field. This opens the possibility to manipulate the lubricant performance i.e. increased wear protection/higher friction or lower friction/reduced wear protection to accomplish an optimum outcome according to specific needs. By engineering the WS2 NPs to make them magnetically responsive, a novel category of lubricant nanoadditives can be developed that combines the properties of both WS2 NPs and ferrofluids. This allows for a reduction of the optimal concentration of NPs, control of NP concentration in a tribological contact, and enables NP recyclability.

## Polymer-Enhanced Fluid Effects on Mechanical Efficiency of Hydraulic Pumps

**Pawan Panwar, Michelle Len, Ashlie Martini, University of California, Merced, Merced, CA, Paul Michael, Milwaukee School of Engineering, Milwaukee, WI**

The mechanical efficiency of hydraulic pumps is affected by the properties of the hydraulic fluids, and particularly by polymeric viscosity modifiers used as additives. However, the mechanisms by which polymers affect efficiency are still poorly understood. Here, a well-characterized isobutylene polymer was blended with (poly) alphaolefin base stocks to produce simple, high-purity hydraulic fluids for analysis using molecular dynamics simulation, rheological testing, and dynamometer evaluations. The simulations were used to understand the polymer's response to shear and the effect on viscosity. The dynamometer incorporated a variable displacement axial piston pump with torque, speed, pressure and flow sensors to measure mechanical and volumetric efficiency under various pressures and speeds. The fluids were also characterized by their permanent and temporary shear thinning. The results provide insight into the relationship between non-Newtonian fluid viscosity and hydraulic efficiency.

## Optimization of CNC Milling Parameters and $TiO_2$ Nanoparticle in Lubricants for Lowering Wear of Cutting Inserts

**Octavio Muñiz-Cepeda, Héctor de la Fuente, Laura Peña-Parás, Universidad de Monterrey, San Pedro Garza García, Nuevo León, Mexico**

Optimization of milling parameters of an AISI 4340 steel performed by Computer Numerical Control was done in this work. Cutting inserts suffer wear during milling operations thus lowering their useful tool life and increase the energy consumption by the process. Nanoparticles of $TiO_2$ were added to a mineral oil cutting fluid with the purpose of reducing the contact between the cutting tools and the workpiece. Preliminary laboratory experiments in a four-ball tribotester showed that a concentration of 0.05 wt.%. $TiO_2$ is able to reduce wear scar diameter and surface roughness of steel balls. Subsequently, a Box Behnken design of experiments was performed to optimize the input milling parameters of cutting speed, depth of cut, feed rate as well as nanoparticle concentration in order to minimize the response parameters of wear of inserts, spindle load, and surface roughness of steel plates.

## Effects of Temperature and Flow Rate on Varnish Removal by Chemical Flushes

**Daniel Sanchez Garrido, Mike Ades, Ashlie Martini, University of California, Merced, Merced, CA, Elizabeth Montalvo, Zhen Zhou, Chevron, Richmond, CA**

Varnish is an oxidative byproduct of lubrication that forms on the surfaces of mechanical components. Varnish buildup reduces clearances on precision parts increasing wear and reducing efficiency during operation. Varnish is often removed using chemical flushes. However, there is no standard method for evaluating the efficacy of various chemicals under different operating conditions. We have developed a custom test rig that enables quantitative characterization of varnish removal rates under controlled conditions. Here, the test rig is used to characterize the effects of fluid temperature and flow rate on varnish removal for an example chemical cleaner. The results show that varnish removal increases with increasing temperature and flow rate, and demonstrate the utility of the newly developed test rig and method for chemical cleaner characterization.

## Grease Lubrication of Self-Mated 60NiTi Bearing Materials

**Aznar Vellore, Nicholas Walters, Ashlie Martini, University of California, Merced, Merced, CA**

60NiTi, an intermetallic alloy of nickel and titanium, exhibits a unique combination of properties, including comparable hardness yet twice the elasticity of steel, high corrosion resistance, and tensile strength comparable to ceramics. These properties are very desirable for bearing materials, especially those used in space applications where components must operate efficiently and reliably in harsh conditions. However, despite the fact that most bearings are grease lubricated, there has not been a systematic study of the tribe-performance of greases for 60NiTi lubrication. To address this, we compare the wear and friction of self-mated 60NiTi lubricated by different greases, including those currently used in space missions and general-purpose grease, in boundary lubricated contact. The results provide valuable information to guide selection of grease for 60NiTi contacts, as well as lay the groundwork for possible development of new greases specifically for 60NiTi tribe-contacts.

## Investigation of Modern Automotive Lubricants

**Wyatt Peterson, Steven Lorenz, Purdue University, West Lafayette, IN, Michael Burhan, Ford Motor Co., Dearborn, MI**

With increasing global awareness of greenhouse emissions, calls for lower fossil fuel consumption have driven the automotive industry to re-analyze parasitic losses in drivetrains which were once considered nominal. To further improve vehicle efficiency, it is suggested that a better understanding is necessary of the frictional power losses associated with rolling element bearings (REBs). Friction coefficients for REBs cover a wide array of values. In practice, however, an imprecise friction coefficient is typically calculated based on generalized curve-fit equations. The purpose of this work is to experimentally observe REB performance in modern automotive lubricants for a set of conditions. These experimental values are then compared against industry standard friction models to assess the validity of their approximations. Based on these observations, conclusions are drawn to determine a more accurate span of friction coefficient values for the REBs and lubricants in question.

## Friction Test of Cylinder Liner-Piston Ring Pair with the Lubricating Oil Diluted by Fuel

**Bo Xu, Biffing Yin, Xin Kiang, Jiangsu University, Zhenjiang, China**

To investigate the wall-wetting effects on ring/liner frictional property, the viscosity test is conducted firstly by mixing diesel into lubrication oil. Then based on several typical wall-wetting ratios, the reciprocating friction tests are carried on to measure the instantaneous friction force of Cylinder Liner-Piston Ring (CL-PR) pair. The experimental results show that the lubrication state of ring/liner is affected by viscosity and loads. Under hydrodynamic lubrication state, the viscosity difference between several wall-wetting ratios has little effects on CL-PR friction, but the reduction of lubricant viscosity may cause the lubrication condition of friction pair to transfer from hydrodynamic lubrication to mixed lubrication, deteriorating the tribological performance of CL-PR. At low or high loads, the fiction force of CL-PR pair raises with more fuel diluting oil, which indicates the viscosity reduction induced by fuel diluting oil will deteriorate the lubrication of CL-PR.

## Non-Invasive Monitoring of Free Surface Thin Film Layer Spread Using an Ultrasonic Continuously Repeated Chirp Longitudinal Wave

**Joseph Kanja, Rob Dwyer-Joyce, Xiangwei Li, University of Sheffield, Sheffield, United Kingdom**

Thin film layers are seen in many applications such as the oil distribution around a gearbox casing and the oil that forms ahead of an approaching piston ring.Measuring thickness of these films provides essential information useful for performance control and monitoring. Performing these measurements can prove to be difficult. However, ultrasound enables measurement indirectly. Piezoelectric transducers on a component back face emit ultrasound waves and receive the waves that bounce off the front face. The magnitude of the reflected wave is dependent on the film thickness at the front face. Pulse-echo ultrasound technique is usually used to perform these measurements. However, as the film becomes thinner, the reflected echoes overlap. In this work, we propose the use of an ultrasonic continuously repeated chirp longitudinal wave to magnify the effect of the film. Multiple reflections occur within the component to form a standing wave whose amplitude spectrum is dependent on the film thickness.

## Probing the Friction Behavior of BCC Metals Using Molecular Dynamics

**Adam Hinkle, John Curry, Nicolas Argibay, Michael Chandross, Sandia National Laboratories, Albuquerque, NM**

We have recently developed a model of friction for FCC metals that accurately predicts the bounds for high and low friction regimes by directly linking interfacial grain structure and its evolution with the macroscopic friction coefficient. Further investigations have revealed similar friction regimes in BCC metals. We present results of atomistic simulations and experiments on BCC metals with the goal of elucidating the structure-property relationships responsible for frictional behavior, allowing for the development of a general framework for the tribological response of both FCC and BCC metals. This work was funded by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

## Stochastic Models for Turbulent Lubrication of Journal Bearing with Rough Surfaces

**Shaoyu Zhu, Jun Sun, Biao Li, Hefei University of Technology, Hefei, China**

The turbulent lubrication model of an isotropic rough surface was generally used in current turbulent lubrication analysis of journal bearing with rough surface. However, the scope of this model is too narrow to use for solving the turbulent lubrication problems of rough surface with directional characteristics. Based on the stochastic laminar lubrication theory of Christensen and the turbulent lubrication theory in the form of zero-equation, the stochastic turbulent lubrication models suitable for the turbulent lubrication analysis of journal bearing with rough surface are derived. The stochastic turbulent lubrication models can be conveniently applied to the turbulent lubrication analysis of rough surfaces with directional characteristics. Moreover, the stochastic turbulent lubrication models are not only suitable for the turbulent lubrication analysis of journal bearing with rough surface, but also for the turbulent lubrication research of other friction pairs with rough surface.

### Investigation on Tribological Behaviors of $MoS_2$/$WS_2$ Quantum Dots as Lubricant Additive in Ionic Liquids Under Severe Conditions

**Xiaobo Wang, Kuiliang Gong, Xinhu Wu, Lanzhou Institute of Chemical Physics, Lanzhou, China**

Despite excellent tribological behaviors of ionic liquids (ILs) as lubricating oils, the friction reducing and wear protection need to be improved when they are used under severe conditions. Here, $MoS_2$ and $WS_2$ quantum dots (QDs) are prepared by a facile and green technique, and both of them can disperse in 1-buty-3-methylimidazolium hexafluorophosphate ([BMIm]$PF_6$) and form homogeneous dispersions that exhibit long term stabilities. Tribological test results indicate that the addition of $MoS_2$/$WS_2$ QDs in ILs can significantly enhance the friction reducing and anti-wear ability of neat ILs under a constant load of 500 N, and a temperature of 150˚C. The exceptional tribological properties of $MoS_2$/$WS_2$ QDs in ILs are attributed to the formation of boundary lubrication film, which can be generated not only by the physical entrapment of $MoS_2$/$WS_2$ QDs at the ball-disk contact surfaces, but also by tribochemical reaction between $MoS_2$/$WS_2$ and the iron atoms/iron oxide species.

### The Effect of Laser Surface Texturing to Prevent Stick-Slip Phenomenon

**Xuan Xie, Xijun Hua, Jiangsu University, Zhenjiang, Jiangsu, China, Bifeng Yin, Xin Kuang, Jiangsu University, Zhenjiang, China**

Stick-slip phenomenon in some mechanical structures especially in machine tools should be eliminated or prevented. In this study, different kinds of surface textures were carried out on the lower samples of the pin-on-disc contact. The starting process of the machine tools was simulated at an Rtec-Multi Function Tribometer. The stick-slip phenomenon was observed in each kind of samples. However, the stick-slip phenomenon of smooth sample is larger than the textured samples. What's more, different texture densities of bulge textured surfaces all show excellent anti-stick-slip effect, the critical stick-slip speed of bulge textured surface is almost 20 times lower than the smooth surface. It can be predicted that the bulge textures can eliminate stick-slip phenomenon when processed in the surface of the machine tool for the bulge textures can effectively improve frictional state and avoid the slip of the contact surfaces.

### Interfacial Assembly Structures and Nanotribological Properties of Lubricating Molecules

**Yuhong Liu, Tsinghua University, Beijing, China**

Saccharides have been recognized as potential bio-lubricants, but their interfacial structures are rarely studied and the molecular details of interaction mechanisms have not been well understood. In this work, the supramolecular assembly structures of two saccharic acids, mediated by hydrogen bonds, were successfully constructed on the HOPG surface by introducing pyridine modulators and were explicitly revealed by STM. Furthermore, friction forces were measured in the saccharic acid/pyridine co-assembled system by AFM, revealing a larger value than a pristine saccharic acid system, which could be attributed to the stronger tip-assembled molecule interactions that lead to the higher potential energy barrier needed to overcome. The effort on saccharide-related supramolecular self-assembly and nanotribological behavior could provide a promising way to explore the interaction mechanisms underlying friction and reveal the structure–property relationship at the molecular level.

### Analysis of Hydrodynamic Pressure Effect of Grinding Bearing Steel with Corundum Grinding Wheel

**Xiaoping Song, Youqiang Wang, Qingdao University of Technology, Qingdao, China**

A steady-state micro-thermal elastohydrodynamic lubrication grinding wheel model was established to study the hydrodynamic pressure effect of ceramic corundum grinding wheel on bearing steel, based on the theory of elastic hydrodynamic lubrication. Firstly, the hydrodynamic pressure effect of ceramic corundum grinding wheel under different grinding fluids is studied. Secondly, comparison and analysis with and without the influence of thermal effect. Finally, the effect of surface topography on the hydrodynamic pressure effect in grinding area is analyzed. The results show that the emulsion is chosen as the grinding fluid when considering various factors. The pressure and film thickness are reduced when considering the thermal effect. The amplitude of roughness has a greater influence on the hydrodynamic pressure effect in the grinding area. The larger the amplitude, the larger the pressure, the smaller the film thickness, while the wavelength is not significant.

### Transient TEHL Numerical Analysis of Spur Gears Under Fluid Ferrofluid Lubrication

**Jing-jing Zhao, Qingdao University of Technology, Qingdao, Shandong, China**

The thermal elastohydrodynamic lubrication model of fluid ferrofluid involute spur gears is established to carry out the numerical simulation with multigrid method based on the Reynolds equation considering thermal effect. The transient oil film thickness, pressure profile distribution, oil temperature rise and frication coefficient with different based fluid ferrofluid are compared. The further research of ester-based H01 fluid ferrofluid is studied and the influence of the speed and load on lubrication film are discussed. Results show that the pressure at inlet region and the film thickness of H01 fluid ferrofluid is smallest. The frication coefficient and oil temperature rise are decreased with the increase of speed and the pressure peak and the film thickness are increased with the increase of speed. The pressure peak, friction coefficient and oil temperature rise are increased with the increase of load and the film thickness are decreased with the increase of load.

### Decreasing Radial Contact Area Results in a Higher Coefficient of Friction on Articular Cartilage

**Hannah Himmelmann, Robert Jackson, Reid Hanson, Auburn University, Auburn, AL**

Joints are well known for their ability to withstand high loads with minimum damage. Articular cartilage is a main element providing lubrication in joints. Multiple lubrication mechanisms are observed within joints. It is important to understand how joint friction works for disease purposes. Measuring the coefficient of friction (COF) of a sample of cartilage under specific conditions can help explain friction mechanisms in a joint. There were two hypothesis for this study: A smaller radial contact area on the articular cartilage will produce a higher COF under varying pressures and constant force, and a smaller radial contact area on the articular cartilage will produce a higher COF under varying force and varying pressure.

### Influence of Fluctuating Water Supply Pressure on the Elastohydrodynamic Lubrication of Water-Lubricated Hybrid Bearing during Acceleration

**Yinong Xie, Qingdao University of Technology, Qingdao, China**

The elastohydrodynamic lubrication (EHL) model of the water-lubricated hydrostatic bearing during the acceleration process was established. The different fluctuation modes of the water supply pressure and the change of the water supply pressure were considered. The numerical simulation of the process was carried out and the elastohydrodynamic lubrication was analyzed. The results show that the fluctuation trend of the water supply pressure is the same as that of the contact zone film thickness, while the pressure change of the contact zone is opposite. When the water supply pressure is low, the fluctuation with 0° phase is more favorable for lubrication, and the fluctuation with 180° phase makes the film formation difficult, and even the bearing is in dry contact state. Simultaneously, the greater the frequency of the fluctuation, the more failure of the bearing. Within a certain range, accelerating under a large water supply pressure is more conducive to lubrication.

## Measuring Lubricant Viscosity at a Surface Using Shear-horizontal Surface Acoustic Waves

**Georgios Tyreas, Rob Dwyer-Joyce, University of Sheffield, Sheffield, United Kingdom, Rai Notai, John Durham, Lubrizol Limited, Hazelwood, United Kingdom, Oliver Smith, Alexander Michlberger, Lubrizol Corporation, Wickliffe, OH**

Engine oil experiences conditions of high shear, temperature, and pressure; understanding the properties of the oil film under such conditions would help in lubricant design. Shear-horizontal surface acoustic waves (SH-SAW) are being investigated for measuring lubricant properties in an engine journal bearing. SH-SAW cause in-plane shear as they travel along the surface. Wave attenuation depends on the viscosity of the liquid in contact with this surface. Testing was carried out on flat steel surfaces with various lubricant samples and deposited films. Viscosity measurements were determined from SH-SAW attenuation and good agreement found with results obtained using a conventional viscometer. It also proved possible to detect viscosity changes in micron-thick polymer films deposited on a steel surface. Finally, the approach was implemented on a multi-layer bearing shell in preparation for application in a running engine. The poster will present the results obtained during this project.

## Clarifying the Role of Transfer Films by Removing Them

**Istiaque Alam, David Burris, University of Delaware, Newark, DE**

The fact that tribological performance correlates strongly to transfer film morphology is interpreted either as evidence that high quality transfer films cause low friction and wear or evidence that low friction and low wear sliding causes high quality transfer films. This work aimed to elucidate this causal relationship for a particularly well-studied material family by eliminating its transfer film. Alumina-PTFE composites were subjected to indexed reciprocation to eliminate the transfer film; standard reciprocation was used as a control. Three distinct alumina fillers known to produce low wear, moderate wear, and high wear when added to PTFE were used to gain insight into how each affects debris creation, debris size, counterface abrasion, transfer film morphology, tribochemistry, and other attributes of interest. Given the orders of magnitude differences in the wear rates reported for these materials, we observed surprising similarities.

## Experimental Validation of Topology Optimization for Composites Undergoing Linear Wear

**Tomas Grejtak, Xiu Jia, Lehigh University, Bethlehem, PA, Florian Feppon, Centre de Mathématiques Appliquées, Palaiseau, France, Sam Joynson, Annaliese Cunniffe, Yupin Shi, David Kauffman, Natasha Vermaak, Brandon Krick, Lehigh University, Bethlehem, PA**

Predicting and optimizing the wear performance of tribological systems is of great interest in many mechanical applications. Wear modeling based on elastic foundation models can be used to predict the wear behavior of composite materials. Topology optimization has previously been used to improve the wear performance of a bi-material composite surface without direct experimental validation. In this work, three multi-material composite wear surfaces are presented and fabricated that are the product of topology optimization. The wear surfaces were designed for optimal wear performance including minimized run-in wear volume lost. The designs are evaluated with high-accuracy simulations prior to fabrication. Extensive testing is conducted including for wear volume, wear rate, surface height distribution and profile measurements throughout the wear process. Experimental results confirm that the wear models utilized for optimization are accurate and consistent with the testing conditions.

## Tribological Behaviors of Graphene-based Lubricant on Titanium Alloy (Ti-6Al-4V)

**Christopher Goralka, Muhammad Jahan, Mark Sidebottom, Zhijiang Ye, Miami University, Snowmass Village, CO**

Being a difficult-to-cut material, the machining of Ti-6Al-4V imposes significant challenges due to strong adhesion and high friction. This study aims to improve the machinability of Ti-6Al-4V using graphene nano-lubricants. The tribological behavior of water-based graphene lubricants was evaluated using a pin-on-disk tribometer with tungsten carbide and Ti-6Al-4V contacts. The friction performance of graphene-water solutions ranging from 0.05 wt.% graphene to 0.15 wt.% graphene was characterized. The effect of surface roughness on friction was also investigated. Wear tracks were analyzed using a scanning electron microscope (SEM) with energy dispersive x-ray spectroscopy (EDS) attachment to measure track diameter and characterize surface elements. Our results show that graphene nanolubricants reduce friction and wear by 71% and 47% compared to dry conditions, with 0.10 wt.% graphene providing the lowest friction and wear.

# Early Career Posters

## Formation of White Etching Areas/Cracks on a Four Disk Rig–Influence of Electrical Current and Slip

**Adrian Mikitisin, Central Facility for Electron Microscopy, Aachen, Germany, Florian Steinweg, RWTH Aachen University, Aachen, Germany**

White Etching Cracks (WEC) are currently discussed as a common cause for premature failure of roller bearings in various applications. The formation mechanism of WEC is still under debate in published literature however it is emphasised that varying additional loadings, like electrical current or hydrogen, have an amplifying effect on the formation of WEC. In this work, the formation of WEC under the influence of electrical current was investigated. The testing was conducted on a four-wheel test rig using rollers made from the steel SAE 52100. These rollers were tested utilizing different electrical polarities, current intensities and slide roll ratios with the objective to obtain thresholds for WEC formation for the varied testing parameters. Detailed microstructure analysis using SEM, EBSD and TEM have been conducted, to investigate the effect of electrical current, polarization and slide roll ratio on the WEC damage pattern.

## Oil-flooded Fluoropolymer-coated (OFF) Surfaces for Mitigating Ice Adhesion

**Mitchell Ishmael, Active Energy Systems, Knoxville, TN**

Ice adhesion to surfaces causes problems ranging from mere nuisances (scrapping off a car windshield) to extremely dangerous (icy roads). In applications where heat exchange is important, such as thermal energy storage, ice growth on surfaces severely reduces the overall system performance. Oil-flooded fluoropolymer-coated (OFF) surfaces mitigate ice adhesion for heat transfer applications. In this work, the adhesion force between frozen water and various fluoropolymer coatings submerged in varied lubricant oils is presented and compared to commercial icephobic coatings and state-of-the-art coatings.