Tribology and Mechanics of Coatings and Surfaces
Room Palm 3-4 - Session MC1-1-ThA

Friction, Wear, Lubrication Effects, & Modeling I

Moderators: Pierluigi Bilotto, TU Wien, Austria, **Julien Keraudy**, Oerlikon Balzers, Oerlikon Surface Solution AG, Liechtenstein

1:20pm **MC1-1-ThA-1 Tribological Behavior of New and Green Surface Treatments of Anodized Aluminum Alloys***, Marc Schmittbuhl [marc.schmittbuhl@ec-lyon.fr],* Ecole Centrale de Lyon - LTDS, France*; Gilles Auregan, Jacoboni Alex,* Safran Landing Systems, France*; Joffrey Tardelli,* IRT-M2P, France*; Marjorie Cavarroc-Weimer,* Safran Tech, France*; Vincent Fridrici,* Ecole Centrale de Lyon - LTDS, France

Light and high-performance aluminum alloys are widely used in aeronautical equipments manufactured by Safran Landing Systems. Many parts require sulfuric anodic oxidation surface treatments combined with a sealing step to protect them from corrosion during service. Compliance with chemicals regulations has led to the replacement of traditional sealing baths using chromates (hexavalent chromium) or nickel salts [1] with a combination of an impregnation bath consisting of trivalent chromium (Cr(III)) and fluorozirconates (Zr(IV)), followed by sealing bath with silicates additives [2]. Although these new treatments maintain good corrosion resistance, their tribological behavior differs and thus raises new issues, particularly with regard to friction in screw assemblies.

The objective of this study is to understand friction behavior and wear mechanisms of the new treatments through tribological tests and characterizations of the aluminum oxide layer.

Various configurations of surface treatments were studied, all on 2024 aluminum alloy oxidized by sulfuric anodization:

-Historical treatments sealed with water containing nickel salts

-New-generation treatments including Cr(III)/Zr(IV) impregnation and sealing with water containing silicate salts

-New-generation treatments including only the impregnation step or the sealing step

Flat samples are treated with each configuration and then tested in linear reciprocating tribological conditions in contact with the flat face of a cylindrical 100Cr6 steel pin. The experimental conditions are defined to approximate the conditions of screw fastening assemblies (number of cycles, contact conditions, kinematics, etc.).

The evolutions in friction coefficient for the different configurations are analyzed. Different features of the initial treatment and wear scars on both samples are characterized by means of topography (interferometry and roughness), microscopy (optical and SEM), chemistry (EDX and Raman spectroscopy), and mechanics (hardness). It allows us to identify the parameters influencing friction behavior and wear mechanisms.

Differences in coefficient of friction are related to changes in interface features. Examination of the wear tracks reveals different wear patterns, which can be explained by the effect of the impregnation of new generation treatments on friction.

[1] L. Hao, B. Rachel Cheng, "Sealing processes of anodic coatings – Past, present, and future". Metal Finishing, Vol. 98, p. 8-18, 2000.

[2] N. Chahboun, D. Veys-Renaux, E. Rocca, "Sealing mechanism of nanoporous alumina in fluorozirconate salt containing solutions". Applied Surface Science, Vol 541, 2021

1:40pm **MC1-1-ThA-2 Mapping Property Spaces of Combinatorially Deposited Nanocrystalline Alloy Coatings***, John Curry [jcurry@sandia.gov], Frank DelRio, Tomas Babuska, Justin Hall, Kyle Dorman, David Adams, Nathan Brown, David Montes de Oca Zapiain, Scotty Bobbitt, Michael Chandross,* Sandia National Laboratories, USA*; Filippo Mangolini, Camille Edwards,* University of Texas at Austin, USA **INVITED**

Nanocrystalline alloys continue to gain interest as a promising class of alloys with exceptional mechanical, tribological and catalytic properties among many other intriguing functional properties. Even within simpler binary metallic alloy systems, relative pairings and composition ratios of each alloy can be varied to produce a wide range of alloys with different microstructures/phases and performance characteristics. The ability to rapidly screen the properties and performance of these alloy systems enables the discovery of new alloy compositions tailored to diverse application spaces. This work outlines test methodologies and results for rapidly assessing friction coefficients, tribofilm/wear scar topography, alloy hardness/modulus, resistivity, composition, and structure/density of binary alloy systems. Pt-Au, Pt-Ni and Cu-Ag alloy systems are the focus of current studies, each deposited through combinatorial deposition methods with ~ 336 individual samples per alloy spanning their full range of binary composition space. DFT and EAM-X calculations of adsorption and segregation energies are also discussed. Results show many compositions exist with diverse mechanical properties, tribological performance and mechanochemical phenomena. Application of FAIR data principles during data generation and organization will also be discussed. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

2:20pm **MC1-1-ThA-4 From Green Lubricant to Liquid Precursor for Hard, Multi-Functional Coatings***, Mohammad Eskandari [mohammadeskandari@my.unt.edu], Diana Berman, Ali Zayaan Macknojia,* University of North Texas, USA

The development of sustainable, high-performance protective coatings via simple, scalable, and environmentally harmless methods is a significant challenge in materials science. This study introduces a new approach for surface engineering by polymerizing very-high viscosity Orychophragmus violaceus (OV) seed oil into a hard, multifunctional coating directly on a steel surface. OV seed oil, noted for its exceptional thermal stability, due to its unique triglyceride (TAG) estolide fatty acid structure, was used as a liquid precursor to form a hard protective film on 52100 bearing steel. The coating was synthesized in-situ through a simple, thermal curing process at moderate temperatures (200-250°C). Optimization of the steel-oil interface using surface activation was found to be advantageous for achieving excellent adhesion and film smoothness.

Comprehensive characterization revealed the formation of a uniform, amorphous, carbonaceous thin film with a controllable thickness. The coating exhibited a great hardness and an elastic modulus, as measured by nanoindentation, and demonstrated excellent adhesion through scratch testing. Under pin-on-disk reciprocal tribological testing against 52100 counterbody, the coating provided a low and stable coefficient of friction and specific wear rate, showing around an order of magnitude improvement in the tribological performance. Furthermore, potentiodynamic polarization tests in a 3.5% NaCl solution revealed a dramatic improvement in corrosion resistance compared to the uncoated 52100 steel.

This study presents a successful, cost-effective method for creating a hard, lubricious, and corrosion-resistant coating from a sustainable, green precursor. This in-situ formation process offers a promising alternative to conventional vacuum deposition techniques and opens new insight for the development of next-generation materials for high-performance lubrication and surface protection.

2:40pm **MC1-1-ThA-5 Promise and Pitfalls of Tribological Coatings in Electric Vehicle Applications***, Ali Erdemir [aerdemir@tamu.edu], Gugyeong Sung, Seungjoo Lee, Merve Komurlu, Henry Papesh, Cagatay Yelkarasi,* Texas A&M University, USA*; Leonardo Farfan,* Tecnologico de Monterrey, Mexico **INVITED**

Electric vehicles (EVs) hold great promise for a green, reliable, and economically viable mobility for this century and beyond [1]. However, their long-term reliability is threatened by significant challenges related to critical materials and severe tribological issues triggered by higher torque, load, speed, and temperature conditions [2]. In particular, the shift to a torque-centric drivetrain, combined with extreme contact pressures and shear forces, can accelerate wear, fatigue, and scuffing failures. This situation is further exacerbated by the presence of frequent electrical discharges at the rolling/sliding contact interfaces, which cause severe surface damage and lubricant breakdown. In this talk, we will give a comprehensive overview of these critical issues and stress the need for more advanced materials and coatings that can significantly improve tribological performance and, consequently, the reliability of future EV systems. Specifically, we will highlight the crucial roles of highly electrically insulating Diamond-Like Carbon (DLC) [3] and/or conducting transition metal nitride coatings in enhancing the friction, wear, and scuffing performance of future EV drivetrains.

[1] K. Holmberg and A. Erdemir, The impact of tribology on energy use and CO2 emission globally and in the combustion engine and electric cars, Tribology International, 135 (2019) 389-396.

[2] "Electric Vehicle Tribology: Challenges and Opportunities for a Sustainable Transportation Future", Leonardo Farfan-Cabrera and Ali Erdemir, Eds., Elsevier, Amsterdam, 2024, ISBN: 9780443140747

[3] L. I. Farfan-Cabrera, J. A. Cao-Romero-Gallegos, S. Lee, M. U. Komurlu, and A. Erdemir, 2023, Tribological behavior of H-DLC and H-free DLC coatings on bearing materials under the influence of DC electric current discharges, Wear, 522(2023)204709.

3:20pm **MC1-1-ThA-7 Behavior of Nb-Doped Molybdenum Disulfide Coatings Under Electrified Tribological Tests***, **Miguel Rubira Danelon [miguel.danelon@usp.br]**,* University of São Paulo, Brazil*; Newton Kiyoshi Fukumasu,* Institute of Technological Research, Brazil*; Roberto Martins de Souza, André Paulo Tschiptschin,* University of São Paulo, Brazil

Adaptive coatings have been shown to extend the lifespan of mechanical systems exposed to magnetic, thermal, and electrical disturbances by modulating their properties. In electric vehicle powertrains, stray currents are known to accelerate the degradation of bearings and gears. Coatings based on transition-metal dichalcogenides, such as molybdenum disulfide, provide excellent solid lubrication and wear resistance. However, structural defects can facilitate the formation of MoO_3in humid environments, thereby undermining low-friction performance. Doping TMDs with transition metals enhances their mechanical properties, promotes the formation of amorphous structures with greater integrity, and allows bandgap tuning, enabling modulation of their properties via an electric current. In this study, Nb-doped MoS_2 coatings were deposited onto H13 tool steel substrates using balanced pulsed DC magnetron sputtering. Tribological testing involving electro-stimulation employed a reciprocating ball-on-plane apparatus with an AISI 52100 sphere, a normal load of 30 N, a 5 mm stroke, and a frequency of 0.28 Hz. Three electrical conditions (positively and negatively charged, and no current) were evaluated under both continuous and intermittent current-contact modes, with applied currents ranging from 100 to 1500 mA. Coating morphology and composition were characterized by scanning electron microscopy with energy-dispersive spectroscopy (SEM/EDS), and Raman spectroscopy was used to analyze the films before and after testing. Mechanical properties were assessed through instrumented nanoindentation. Results indicated that passing current reduced the coefficient of friction under both continuous and intermittent modes, achieving reductions of up to 50% relative to the non-electrified condition. This reduction is attributed to recrystallization of Nb:MoS_2 during sliding with an electrified contact. Wear behavior, however, was influenced by current direction, with positively charged counterbodies exhibiting greater wear than negatively charged counterbodies. It is proposed that opposite current polarities induce distinct tribolayer formation and elemental segregation (Mo, S, Nb), which maintains low friction but differentially affects wear. Overall, Nb-doped MoS_2 demonstrates current-responsive tribological behavior characterized by friction reduction and polarity-dependent wear mechanisms.

4:00pm **MC1-1-ThA-9 Calibrated Friction Measurements Using a New Interferometric Atomic Force Microscope***, **Joel Lefever [joel.lefever@oxinst.com]**, Aleksander Labuda, Roger Proksch,* Oxford Instruments, USA

Measuring lateral force is critical for friction measurements on tribological materials ranging from bearings in engines to 2D materials. The atomic force microscope (AFM) is one important tool for frictional measurement on the scales of both microns and nanometers. Conventional optical beam deflection (OBD)-based AFMs are difficult to calibrate, with most calibration methods requiring cumbersome sample exchanges which may disturb the alignment of the chip and detection beam, while simultaneously introducing substantial uncertainty.

We introduce a method for performing lateral force measurements using an AFM with a quadrature phase differential interferometer (QPDI) detector in addition to a traditional optical beam detector (OBD), which furthermore provides a new means to perform a direct calibration of the lateral sensitivity. The detection spot may be placed on the centerline of the cantilever, using QPDI for height feedback while using OBD for friction measurement. In this configuration crosstalk from the lateral signal into the normal signal is eliminated, which reduces the effects of friction and topography on the applied load and is useful for macroscopic relief. Alternatively, by positioning the interferometric detection spot along one edge of the cantilever, the AFM takes advantage of the detector's low noise floor to observe stick-slip friction at scan rates that would be difficult or impossible with optical beam AFMs The results demonstrate clearly resolvable stick-slip friction over a range of tip speeds up to 2 µm/s and additionally show the variation of friction with applied load. Because this calibration technique can be performed *in situ* without sample exchanges, it also allows calibration to be performed in enclosed environments, for example to enable changing humidity. Furthermore, with some modifications, all of these methods can also be performed in liquid, which is useful for characterizing tribofilm growth and other phenomena.

4:20pm **MC1-1-ThA-10 Effects of Mo–N–Cu Doping on Microstructural, Mechanical, and Tribological Properties of Thick Ta-C Coatings for Cryogenic Applications***, **Young-Jun Jang [yjjang@kims.re.kr]**, Jae-Il Kim, Ji-Woong Jang, Jongkuk Kim,* Korea Institute of Materials Science (KIMS), Republic of Korea **INVITED**

The introduction of environmental regulations and the growing use of renewable energy have altered the operating temperature (111 K) of mechanical components used for transporting cryogenic fluids such as hydrogen, liquid nitrogen, and liquefied natural gas. In cryogenic environments, where lubrication fluids or special lubricants are unavailable, adhesive, abrasive, fatigue, and delamination wear can occur; hence, suitable materials for such conditions are essential. Various solutions have been proposed, including hybrid ceramic bearings combining hard ceramics and alloy steel, or protective coatings such as diamond-like carbon. Among these, tetrahedral amorphous carbon coatings exhibit excellent hardness and wear resistance, yet their performance in cryogenic environments is limited due to difficulties in forming low-friction tribo-films, which are hindered by thermal and chemical reactions in atmospheric conditions. Furthermore, ta-C coatings with surface hardness above 40 GPa can cause severe wear imbalance due to hardness differences with base materials (e.g., SUS 316L stainless steel, 1.75 GPa). The mismatch between the thermal expansion coefficients of the coating and substrate also increases delamination wear at lower temperatures. Excessive hardness additionally leads to reduced fracture toughness, low-temperature brittleness, fatigue, and fracture, thereby degrading coating functionality. For sliding components such as valves or bearings to maintain efficiency under cryogenic conditions, a modified ta-C coating that preserves the mechanical and tribological advantages of ta-C while accommodating thermal and structural stresses is required. This study explores Mo–N–Cu-doped tetrahedral amorphous carbon (Mo–N–Cu–ta-C) coatings synthesized using simultaneous filtered cathodic vacuum arc and unbalanced magnetron sputtering under air (296 K) and liquid nitrogen (77 K) environments. The resulting 1 µm-thick coating comprised nanocomposite Mo carbide and nanolayered Cu structures. Compared with undoped ta-C, Mo doping reduced counterpart wear by 82%, Cu doping enhanced fracture toughness by 22%, and decreased disk wear by 86%. Nitrogen addition promoted phase separation, strengthening the synergistic effects of Mo and Cu to achieve balanced wear. Cu and N_2 further minimized thermal expansion and strain mismatches between the coating and substrate at reduced temperatures, mitigating thermal stress and improving cryogenic reliability. At 296 K, the Mo–N–Cu–ta-C coating exhibited superior adhesion, controlled toughness, and stable wear behavior while maintaining reliable performance in LN_2.

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