Tribology and Mechanics of Coatings and Surfaces
Room Town & Country C - Session MC3-1-TuM

Tribology of Coatings and Surfaces for Industrial Applications I

Moderators: Osman Eryilmaz, Argonne National Laboratory, USA, **Stephan Tremmel**, University of Bayreuth, Germany

8:00am **MC3-1-TuM-1 Bridging Research and Industrial Application: Advanced Coatings and Surface Treatments for Tribological Challenges***, **Andras Korenyi-Both [andy.korenyi-both@woodward.com]***, Woodward Inc., USA **INVITED**

Surface engineering and advanced coatings are critical for addressing complex tribological challenges across diverse industrial applications, from aerospace to manufacturing. This talk provides an overview of key advancements in coating technologies, spanning decades of research and development, with a focus on linking fundamental insights to real-world applications.Highlights include the investigation of faults and failures in sprayed MoS_2 coatings on the Galileo spacecraft, which informed the development of improved PVD MoS_2 coatings through doping and layering for enhanced performance transitioning to rocket engine turbo pump gears. The transition from PVD coatings to tribomechanical deposition applications is explored, leveraging techniques such as laser surface texturing and WAM testing to bridge laboratory results with production-scale implementation.Emerging technologies, such as autocatalytic in situ diamond-like carbon formation from hydrocarbons, are also discussed, showcasing their potential to enable self-lubricating surfaces in extreme industrial environments. The application of duplex and triplex treatments is highlighted as a powerful approach to solving complex tribological problems, combining multiple surface engineering techniques to optimize performance across diverse conditions.Additional contributions include the development of high-performance coatings for forging and die-casting applications, high-temperature plasma electrolytic oxidation combined with solid film lubricants and the use of nanoparticles in liquids to enhance lubrication. Case studies like the MISSE-to-production pipeline highlight the challenges of translating terrestrial -proven coatings to flight applications, addressing the "flight history conundrum."This work demonstrates the importance of combining advanced surface engineering strategies—ranging from thin-film deposition to hybrid treatment approaches—to tackle emerging challenges in multi-fuel and dry gas environments. Collectively, these efforts underscore the value of a multidisciplinary approach to the development, characterization, and deployment of coatings and surface treatments for solutions in transportation, manufacturing, and beyond. Closing remarks include the role of solid film lubricants towards environmental stewardship.

8:40am **MC3-1-TuM-3 DLC-Based Coatings with Enhanced Cavitation Resistance for Automotive Applications***, Kenny Bislin,* Oerlikon Surface Solutions AG, Liechtenstein*; Martin Bohley,* Oerlikon Balzers Coating Germany GmbH, Germany*; Christian Fleischmann,* ***Astrid Gies [astrid.gies@oerlikon.com]****, Theresa Huben, Kaushik Hebbar Kannur, Felix Oelschlegel, Stefan Moser,* Oerlikon Surface Solution AG, Liechtenstein*; Timea Stelzig,* Oerlikon AM Europe GmbH, Germany

Since several years, automotive manufacturers focus on enhancing the engine performance while reducing the fuel consumption and therefore emissions of gasoline internal combustion engines (ICE). Consequently, the usage of high-pressure direct injection systems, already known from diesel ICEs, is increasing. In these systems, the fuel is accumulated in a central high-pressure rail and injected via injectors into the cylinder. The injection pressure has increased over time; current state-of-the-art systems operate between 200bar and 500bar. By increasing the injection pressure from 200bar to 500bar, the particle emission of the engine can be reduced by 95%. In most of the high-pressure injection systems, the injector valves consist of a ball opening and closing against a seat. Any leakage between the ball and the seat must be avoided to guarantee the lifetime of the system. In most of the current systems, the components like for example the balls are often coated with diamond-like-carbon (DLC) based coatings in order to prevent any premature wear in the systems.

However, the constantly rising injection pressures, but also the use of different fuel blends with incorporation of certain amounts of ethanol and methanol for reduced CO_2 emissions lead to drastically increased loads on the different components, especially due to severe cavitation occurring inside the injectors, exceeding sometimes the mechanical strength of common DLC coatings. The resulting wear of the injectors causes fuel leakage into the combustion chamber and significantly reduces the lifetime of such systems.

In this study we compare the tribological performance as well as the cavitation resistance of a standard DLC coating optimized for tribological applications with a DLC coating with enhanced cavitation resistance. The tribological performance of the coatings is investigated using a translatory oscillating friction and wear test (SRV® from Optimol Instruments). To study the cavitation resistance of the coatings, a cavitation test bench (sonotrode tester) was employed using test procedures according to ASTM 32.

While the tribological performance of both coatings is similar, the standard DLC coating shows first indication of cavitation erosion after 90 minutes testing time, whereas the DLC coating with enhanced cavitation resistance shows first indications of cavitation resistance by a factor of 3 later and at a lower intensity. Therefore, this coating is more suitable for the application in high-pressure direct injection systems and enables the use of more environmentally friendly gasoline blends with higher ethanol or methanol share due to the drastically increased cavitation resistance.

9:00am **MC3-1-TuM-4 Surface Technologies for Geothermal Energy Applications***, **Oyelayo Ajayi [ajayi@anl.gov]**, Levent Eryilmaz, Aaron Greco,* Argonne National Laboratory, USA **INVITED**

Geothermal power systems rely on equipment that must perform in exceptionally harsh environments—high temperatures, high flow rates, chemically aggressive brines containing chlorides, CO_2 and H_2S, and suspended solids. These conditions make many components susceptible to surface-initiated or surface-related failure modes. Vulnerable systems include drilling tools, casing strings, valves and piping, and rotating equipment such as pumps, motors and turbines. Under these extremes, abrasive wear, particle erosion, corrosion and mineral deposit formation can rapidly degrade performance, shorten component life. Mitigating surface-related failures is therefore essential to reliable, cost-effective construction and operation of geothermal plants.Surface engineering offers a practical, cost-effective pathway to extend service life without wholesale changes to base materials. Incumbent surface technologies used in geothermal applications include hardfacing overlays with metal-matrix composite claddings (e.g., carbide-reinforced Ni/Co systems); thermochemical conversion treatments such as boriding/boronizing that create hard, wear-resistant diffusion layers; and thermal spray coatings—HVOF, plasma and arc spray deposition to apply corrosion- and erosion-resistant alloys, cermets and ceramics.This presentation will review where and how these technologies are applied, their benefits and limitations, and the practical technical considerations that determine success. Key property and performance attributes most relevant to geothermal service—hardness, fracture toughness, coating adhesion, erosion and slurry wear rates, corrosion resistance, scaling propensity, thermal stability will be discussed.Emerging advances in surface technologies, such as functionally graded coatings, nanostructured and amorphous metal overlays, high-entropy alloy and cermet systems, will be highlighted. Gaps where further development is needed: standardized test protocols representative of geothermal conditions, long-duration field data and models that bridge laboratory results to plant performance, coatings that resist silica-rich scaling while maintaining mechanical integrity will be discussed. Together, these insights aim to highlight opportunities for surface-engineered solutions across geothermal power systems.

9:40am **MC3-1-TuM-6 Tailoring Ice Adhesion Behavior of Erosion Resistant Coatings: Tuning Surface Chemistry and Physical Properties***, **Olayinka Abegunde [Olayinka.Abegunde@sdsmt.edu]**, Nathan Madden, Grant Crawford, Forest Thompson,* South Dakota School of Mines and Technology, USA*; Emily Asenath-Smith,* US Army Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH 03755, USA

The mitigation of ice accretion on critical infrastructure, including aircraft components and energy installations remains a significant challenge in cold and arctic regions. Conventional de-icing methods based on thermal and chemical approaches are widely used and have been explored extensively but are inherently energy-intensive and environmentally unsustainable. Thus, passive approaches which rely on the surface properties of a material to reduce ice adhesion strength, delay ice nucleation, or repel ice accretion have gained significant attention.

This study explores the design, deposition, and characterization of durable, erosion resistant coatings engineered to minimize interfacial adhesion strength with ice in cold environments by tuning their surface chemistry, physical properties, and surface microstructure. A series of nitride-based coatings were deposited using magnetron sputtering process. Deposition parameters were optimized to tailor key surface characteristics, including roughness, topography, surface energy, crystallographic texture, and Young's modulus.

The surface morphology and topography were examined using scanning electron microscopy (SEM) and atomic force microscopy (AFM), while grazing-incidence X-ray diffraction (GIXRD) was employed to identify crystalline phases. X-ray photoelectron spectroscopy (XPS) provided insights into the surface chemical states and contact angle goniometry was utilized to evaluate surface wettability. The sub-zero coefficient of friction and wear rate were assessed using a low-temperature tribometer. Ice adhesion strength was quantified through a shear-testing procedure which enabled controlled growth of ice on the durable coatings.

This work provides new insights into the structure–property–performance relationship governing ice adhesion and demonstrates a pathway for scalable fabrication of durable, low-adhesion coatings suitable for extreme service conditions in the aerospace and energy sectors.oi

10:00am **MC3-1-TuM-7 2D MXene Coatings – Combining Macro-Scalesuperlubricity and Durability***, Andreas Rosenkranz* ***[arosenkranz@ing.uchile.cl]****,* University of Chile **INVITED**

MXenes nano-sheets have experienced tremendous attention in the scientific community since their discovery in 2011. In the last 5 years, the tribological research community has started to explore their friction and wear performance when used as lubricant additives, solid lubricant coatings and reinforcement phase in composites. Especially when using MXenes for solid lubrication, promising results have been verified. MXene coatings tend to demonstrate an ultra-high wear resistance being particularly beneficial for the durability and longevity of these coatings. These beneficial properties are traced back to the formation of a thin MXene-rich tribolayer. Little is known about the structural and compositional properties of these tribolayers. The underlying kinetics and driving forces are yet to be explored. More knowledge about the involved mechanisms and kinetics is urgently needed, which is expected to significantly boost this entire research topic.

Therefore, we have designed tribological ball-on-disk experiments to understand the influence of the number of layers (few- versus multi-layers), the coatings thickness and the tribological testing conditions (normal load, sliding velocity and relative humidity) on the tribofilm formation. Combined with advanced materials characterization, these tests allow us to draw some important conclusions about the involved thermomechanical aspects and underlying kinetics of the layer formation.

Based upon the experiments conducted, we verify thermomechanical and kinetic aspects of the involved tribolayer formation, which align well with the respective temporal evolution of the coefficient of friction. When exceeding a critical value of the applied normal load (Hertzian contact pressure), the formation of a stable tribolayer with beneficial friction and wear properties is not possible. More importantly, the same conclusion can be drawn when exceeding a critical sliding velocity, which clearly shows the kinetic aspect of the involved layer formation. We also verify that increasing the respective thickness of the MXene coatings does not necessarily result in more beneficial effects (low friction, low wear, and long-lasting effects). Concerning energy application, the material of choice tends to go towards mono-layer MXenes. Regarding tribological research, no scientific study has systemically addressed whether it is more beneficial to use few- or multi-layer MXenes. This contribution also sheds some light on this open question, thus giving some important guidelines and recommendation for future tribological experiments using MXenes.

10:40am **MC3-1-TuM-9 Friction and wear of composite MXene/MoS_2 coating under low viscosity fuels under reciprocating sliding***, Ali Zayaan Macknojia* ***[alizayaanmacknojia@my.unt.edu]****, Mohammad Eskandari,* University of North Texas, USA*; Stephan Berkebile,* Army Research Laboratory, USA*; Andrey Voevodin, Samir Aouadi, Diana Berman,* University of North Texas, USA

Friction and wear-related failures remain major challenges in moving mechanical assemblies operating under various conditions. For example, the components of fuel systems made of AISI 52100 steel are susceptible to scuffing-induced wear when operated in fuel environment. This study demonstrates the decreased friction and wear characteristics achieved by spray-coating 52100-grade steel surfaces with solution-processed multilayer $Ti_3C_2T_x$-MoS_2 blends. Study analyzed performance of the coating in different fuels. Raman spectroscopy, scanning electron microscopy, and transmission electron microscopy results revealed the formation of an in-situ robust tribolayer responsible for the outstanding performance observed at high contact pressures and sliding speeds. This study has broad implications for the development of solid lubricants that can operate under extreme conditions and low viscosity fuel environment, inspiring further research and development in this field.

Tribology and Mechanics of Coatings and Surfaces
Room Palm 5-6 - Session MC2-1-TuA

Mechanical Properties and Adhesion

Moderators: Lin-Li Chia, Ming Chi University of Technology, Taiwan , **Michael Meindlhumer**, Montanuniversität Leoben, Austria, **Balila Nagamani Jaya**, Indian Institute of Technology, India

1:40pm **MC2-1-TuA-1 Mechanical and Interfacial Behavior of Liquid-Like Polymer Surfaces at Extremes***, **Megan J. Cordill [megan.cordill@oeaw.ac.at]**,* Erich Schmid Institute of Materials Science, Austrian Academy of Sciences, Leoben, Austria **INVITED**

Ice buildup presents significant obstacles for both power generation and air transportation in cold regions requiring effective ice protection strategies. Passive anti-icing methods, such as icephobic coatings have garnered increasing interest due to their cost-effectiveness and eco-friendliness. Effective passive ice removal requires very low ice adhesion strength values of less than 20 kPa so that the ice can be easily removed with natural forces such as wind and gravity. Recent studies have shown that liquid-like surfaces (LLS) with ice-shedding properties can be generated through the covalent attachment of linear polymer chains onto smooth substrates bearing sufficiently high hydroxyl group densities. The durable coating retains its slippery properties after exposure to laboratory conditions of icing/deicing and heating cycles, organic solvents, and acid treatment. However, little is known about mechanical stability and longevity of the LLS at relevant temperatures and wind speeds. Nanoindentation, both traditional and AFM-indentation, was used to measure the mechanical properties at various temperatures to establish a ductile to brittle transition of the coating. Additionally, scratch and wear testing were utilized to mimic scratch induced debris and removal of the LLS. As a final check, bulge testing was used to evaluate the adhesion of the ice-phobic coating to the aluminum substrate. These experiments were then compared to the same coatings subjected to various ice and wind tunnel experiments performed on a NACA 0012 aerofoil that would simulate actual conditions during take-off and landing. The combination of assessments demonstrates that the developed LLS coating is robust for wind turbine applications as well as to replace anti-icing fluids currently used for airplanes.

2:20pm **MC2-1-TuA-3 In Situ Observation of Multicracking in Thin Films and Nanostructures***, **Damien Faurie [faurie@univ-paris13.fr]**,* 99 avenue Jean-Baptiste Clément, France **INVITED**

Multicracking in brittle thin films on compliant substrates is a critical reliability issue in flexible electronics, optical coatings, and protective thin-film technologies. While characteristic fracture patterns have been reported for decades, the fundamental mechanisms governing crack initiation, spacing, and multiplication still remain unclear. Classical models link average crack spacing to film thickness, yet they do not account for the local stress heterogeneity and accumulation of damage that precede fracture.In this invited talk, we present an *in situ* experimental methodology that combines synchrotron X-ray diffraction with real-time optical imaging during controlled uniaxial and biaxial mechanical loading of brittle thin films (10–500 nm) supported on polymer substrates. This approach enables the simultaneous monitoring of stress evolution, diffraction peak broadening (FWHM), and crack nucleation. We show that variations in FWHM provide a quantitative diffraction signature of local stress concentration and correlate directly with the onset and multiplication of cracks. This establishes a direct link between microscopic stress heterogeneity and the formation of multicracking networks.Looking forward, we extend this methodology to lithographically patterned thin films, where periodic architectures (e.g., parallel wires, modulated-width structures, multilayered or architectured interconnects) offer new degrees of freedom to tailor stress distribution and confinement effects during deformation. We will discuss how such artificial architectures can promote or suppress crack formation, enable stress redistribution, and ultimately improve thin-film reliability.Overall, this work provides a new framework to understand and engineer multicracking in thin films and opens pathways toward mechanically robust architectured coatings and interconnects for next-generation flexible technologies.

3:00pm **MC2-1-TuA-5 Numerical and Experimental Evaluation of Cyclic Contact Loads on Titanium Borides***, Hugo Alberto Pérez Terán, GERMAN ANIBAL RODRIGUEZ CASTRO, ALFONSO MENESES AMADOR, **Felipe Nava Leana [felnaval@gmail.com]**,* Instituto Politécnico Nacional, Mexico*; Daybelis Fernández Valdés,* Tecnológico Nacional de México*; VICTOR MANUEL ARAUJO MONSALVO,* Instituto Nacional de Rehabilitación Luis Guillermo Ibarra Ibarra, Mexico

In this work a Ti6Al4V alloy hardened by the boriding process was evaluated by cyclic contact loads. Powder-pack boriding process was used to modify the alloy surface where two phases TiB and TiB_2 were obtained on the sample due to the boron diffusion into the substrate material. The thermochemical treatment was carried out at a temperature of 1100°C for 10, 15 and 20 h of exposure time. Titanium borides (TiB and TiB_2) formed on the surface of the Ti6Al4V alloy was confirmed by means of the XRD analysis.Berkovich nanoindentation test was conducted to determine both hardness and Young's modulus of the borided samples. Cyclic contact loads were applied on the borided sample using a MTS Acumen equipment to evaluate the quality of the titanium borides based on the damage caused on the sample surface. Finite element method was used to obtain the stress field due to cyclic contact loads. Results showed that the sample with thicker thickness because of longer treatment time showed the best mechanical behavior under cyclic contact loads.

4:00pm **MC2-1-TuA-8 Grain Boundaries and "Complexions" in Metallic Thin Films: New Insights on the Interplay of Atomic Structure, Chemistry and Material Properties***, **Gerhard Dehm [dehm@mpie.de]**,* Max Planck Institute for Sustainable Materials, Germany **INVITED**

Similar to surface reconstructions, grain boundaries in polycrystalline materials can undergo phase transformations (sometimes referred to as "complexion" in the literature), which alter the resulting properties. Temperature, stress, and chemical composition are the main driving forces for such transformations. Understanding and controlling such transformations allows additional control over the relationships between structure, processing, properties, and performance, especially in materials with a high content of grain boundaries.

The first part of the presentation shows examples of grain boundary phases and transitions in pure and alloyed metallic thin films. Surprisingly, grain boundary phase transitions are observed even in pure metals. The second part of the presentation focuses on electrical and mechanical properties. A workflow is presented that allows to investigate the contribution of individual grain boundary structures to electrical resistivity. The results show that the excess volume of a grain boundary is the main contributor to electron scattering in a pure fcc metal such as copper. However, impurities segregated at the grain boundary can significantly alter electron transport. This can be exploited positively, but can also be detrimental, as exemplified with two examples.

Also mechanical properties are strongly influenced by grain boundaries and their phases. While this has long been known for cases of grain boundary embrittlement, such as Bi in Cu or Ga in Al, the influence on strength and shear-coupled grain boundary motion has only recently been studied in detail and will be presented in the lecture. Finally, strategies to make use of grain boundary "complexions" for property design are discussed.

Acknowledgment: This work gas been partially supported by the ERC advanced grant GB-Correlate (Correlating the State and Properties of Grain Boundaries [https://www.mpie.de/3893203/GB-correlate]) and the German Science Foundation DFG within the SFB 1394 Structural and chemical atomic complexity – from defect phase diagrams to material properties. Fruitful interactions with many colleagues, especially T. Brink, C. Liebscher, L. Langenohl, K. Bhat, A. Kanjilal, J. Duarte, and H. Bishara are gratefully acknowledged.

4:40pm **MC2-1-TuA-10 Many-to-one Mapping Between Stress-Strain Curves and Spherical Indentation Load-Displacement Curves***, **Santosh Thapa [sth230@g.uky.edu]**, Yang-Tse Cheng, Madhav Baral,* University of Kentucky, USA

The stress-strain relationship is key to understanding material behavior, yet conventional tensile testing provides only bulk-averaged properties and fails to capture local heterogeneities. Instrumented indentation testing (IIT), particularly with spherical indenter, is often assumed capable of uniquely determining stress-strain relationships from a single load-displacement curve. However, our results challenge this assumption showing that different combinations of elastic modulus, yield stress, and work-hardening exponent can produce indistinguishable indentation responses, highlighting the non-uniqueness of the inverse problem of obtaining stress-strain relation from spherical indentation load-displacement curves. Thus, the quest for obtaining local mechanical properties from spherical indentation measurements continues.

5:00pm **MC2-1-TuA-11 Tribological Performance and Mechanistic Insights of Aluminium-Sic Composites Fabricated by Computerized Bottom-Pouring Stir Casting***,* ***Vishal Mehta [mehtavishalr@gmail.com]****,* Automobile Engineering Department, Parul Institute of Technology, India*; Anand Joshi,* Micro Nano Research and Development Center, Parul University, India*; Unnati Joshi,* 3Mechanical Engineering Department, Parul Institute of Engineering & Technology, India

The growing demand of lightweight structural material with enhanced wear resistance has accelerated the study of aluminium based metal matrix composites that are reinforced using ceramic particulates. The composites in the present research were Aluminium-Silicon Carbide (Al-SiC) produced by computerized bottom pouring type stir casting, which has a high level of control on the process parameters giving accurate dispersion of reinforcement and fewer defects in the casting. This work is devoted to the evaluation of the friction and wear properties of the developed composites in the dry sliding mode and to determine the prevalent wear mechanisms by means of the surface and compositional analyses.

In the present investigation, pure aluminium (Al) was considered as a matrix material due to easy availability. Pure Al was reinforced with 5 wt.% SiC having size of 40-50 microns. Rockwell hardness of the developed AMCs were measured and 13% higher values were observed as compared to unreinforced matrix. The pin-on-disc tribometer was used for a tribological test in wet conditions. The Al-SiC AMCs were found to have a significant decrease in the coefficient of friction and wear rate with those of the unreinforced aluminium matrix. The ability of the SiC particles to prevent direct contact between metal and metal contributed to the increased performance and was attributed to the bearing role of the particles. The smoother worn surfaces and reduced scars of adhesive wear were observed post-test SEM analysis, whereas the EDX spectra proved the absence of intermetallic Al_4C_3 in the developed composite with C/Al mass ratio value of ~0.176 referring to theoretical stoichiometric value for Al_4C_3 (~0.334). The EDS result confirms the defect free AMC development for the further applications. The wear mechanisms observed in SEM characterization indicates transition from adhesive wear in the base alloy to mild abrasive and oxidative wear in the reinforced composites.

These findings suggest that computerized bottom-pouring stir casting provides both an effective and quality production pathway to high-integrity Al-SiC AMCs with improved friction and wear properties and therefore promising in surface engineering, tribological finishes and other lightweight component applications.

Keywords

Aluminium matrix composites, Friction and wear, SEM, EDX, Stir casting, Tribology

Tribology and Mechanics of Coatings and Surfaces
Room Town & Country C - Session MC3-2-WeA

Tribology of Coatings and Surfaces for Industrial Applications II

Moderators: Osman Eryilmaz, Argonne National Laboratory, USA, **Stephan Tremmel**, University of Bayreuth, Germany

2:00pm **MC3-2-WeA-1 Tailoring and Designing High-Performance Carbon Coatings - Insides in Recent Developments and New Approaches for Tribological Applications***, DOMINIC STANGIER [dominic.stangier@oerlikon.com],* Oerlikon Balzers Coating Germany GmbH, Germany **INVITED**

The deposition of diamond-like carbon coatings is an established approach to enhance the service life of tribologically stressed components and tools for industrial applications. Due to today's challenges of reduced lubrication, increased thermal and tribological loads as well as the demand for improved performance and service life, conventional and standardized existing thin films solutions are often limited in their wear-resistance and therefore provide insufficient protection. To overcome these challenges, tailored and application-specific coating systems have gained enormous interest in the field of carbon coatings. On the one hand the efficient deposition of these coating designs requires often a combination of advanced plasma technologies, as well as on the other side the possibility of chemically doping the amorphous carbon network to adjust the property profile. In this regard, the deposition of ta-C coatings by cathodic arc evaporation was found to be an excellent solution, which allows the adjustment of mechanical properties in a broad range as well as offers the possibility to combine different plasma technologies for the deposition of functional multi-layer designs. However, the key challenge is the evaporation of the carbon cathode, which was conducted by an industrial scale arc source (APA evaporator) using a dynamic controlled electro-magnetic field generated by a coil system to steer the arc spot motion and control the deposition conditions. This technology enables the modification of the tribological properties for the running-in phase and the "stationary" wear behavior by adjusting the coordination of the carbon network (sp^3/sp^2-ratio) as well as the chemical composition. In addition, the results reveal the possibility of controlling the intrinsic residual stresses of ta-C coatings to improve the coating adhesion. Furthermore, tailoring the properties was conducted by doping small amounts of Si in ta-C coatings for increasing the thermal stability, which therefore extends the application field of the coating systems.

2:40pm **MC3-2-WeA-3 Advanced Coating and Surface Techniques in Modern Automotive Tribology***, **Sung Chul Cha [sungchul.cha@hyundai-kefico.com]**,* Hyundai Motor Group- Hyundai Kefico, Republic of Korea*; Kyoung Il Moon, Hae Won Yoon,* KITECH, Republic of Korea*; Jongkuk Kim,* KIMS, Republic of Korea

This paper presents low-friction coating technologies for automotive tribology applied over the past 20 years. In the era of eco-friendly vehicles, particularly electric vehicles (EVs), it is essential to develop suitable coating technologies. Hyundai Motor Group has forecasted mobility trends for 2035: strong HEVs will account for 23% in 2035 (16% in 2024), plug-in HEVs 26% (8%), and battery EVs 38% (13%). By 2035, eFuel capacity is expected to increase from 3 billion liters to 100 billion liters. Global coating companies are developing technologies using hybrid process, low temperature coating process for polymer material, high ionization and high speed. Oerlikon-Balzers has introduced ta-C coatings for polymer materials, as well as MoN and ta-C coatings for automotive components. As a major research institution, Fraunhofer IWS in Germany presented Si- and B-doped ta-C coatings for applications up to 500 °C. RWTH Aachen University's IOT developed coatings with a graded structure, consisting of S-rich and Mo-rich layers on CrAlN, to achieve low friction on plastic substrates. Recent developments in low-friction coatings presented at ICMCTF were analyzed, and the findings are included in this work. In Korea, R&D efforts focus on developing ultra-low friction coatings for extreme conditions, such as those found in EV components. Current coatings exhibit a coefficient of friction (CoF) of 0.05, while ultra-low friction coatings (CoF 0.01) include nitrides and ta-C doped with elements such as ZrCuSi, ZrMoTi, MoZrTiSi, and ZrMoTiCuSi. To address the corrosion issues of SiO-DLC caused by bioethanol fuels, ta-C coatings have been successfully applied, demonstrating high hardness (66 GPa), low friction (CoF 0.05), thermal resistance up to 500 °C, and excellent corrosion resistance. Furthermore, to enhance the frictional performance of coatings, electrochemical polishing technique (DLyte) has been employed, resulting in a significant reduction in surface roughness (Ra from 0.4 µm to 6 nm).

3:00pm **MC3-2-WeA-4 Development and Evaluation of TiAlVSiCN Coatings for Automotive Applications***, **Jianliang Lin [jlin@swri.org]**,* Southwest Research Institute, San Antonio Texas, USA

To increase the fuel efficiency of diesel engines or enhance the performance of racing vehicles, reducing the friction of moving components, such as piston rings and valvetrain parts, is critical, particularly at low engine speeds and loads. Therefore, there is a strong need to develop novel, low coefficient of friction (COF), and robust tribological coatings. In this research, low friction titanium–aluminum–vanadium–silicon–carbon–nitride (TiAlVSiCN) nanocomposite coatings were developed by sputtering Ti-6Al-4V targets in a reactive gas mixture using high power impulse magnetron sputtering (HiPIMS). The chemistry and microstructure of the TiAlVSiCN coatings were tuned by varying the gas flow rate. The tribological behavior of the coatings deposited on stainless steel coupons was evaluated using ball-on-disk and block-on-ring wear tests in SAE 10W-30 engine oil (no additives). The TiAlVSiCN coatings with thicknesses in the range of 6-10 µm exhibited tunable hardness in the range of 15–35 GPa, and the lowest COF of 0.03 and wear rate of $4.8x10^{-9}$ $mm^3N^{-1}m^{-1}$ under lubricated conditions. The optimized coating, offering the best combination of low COF and wear resistance, was deposited on piston rings and further evaluated using a TE 77 bench test. Its performance was compared with an OEM diamond-like carbon (DLC) coating and a traditional low friction TiSiCN coating. The TiAlVSiCN coating demonstrated superior performance compared to both the OEM DLC and TiSiCN coatings in terms of sliding friction, smooth run-in behavior, galling resistance, and wear resistance. The TiAlVSiCN coating was subsequently applied to piston rings and tested in an internal combustion engine. The results of the engine tests, in comparison with OEM DLC coatings, will be updated.

3:20pm **MC3-2-WeA-5 Combining laser-textured dimples and AlCrN coating to reduce wear on AISI M2 steel***, **Iker Alfonso [iker.alfonso@unavarra.es]**, Adrian Claver, Jose Antonio Garcia,* Universidad Pública de Navarra, Spain*; Iban Quintana,* Tekniker, Spain*; Iñaki Zalakain,* Universidad Pública de Navarra, Spain

Tool degradation remains a major challenge in precision metal forming, where punches and dies are exposed to high pressures and temperatures leading to accelerated surface wear. A common strategy to mitigate this is the application of hard ceramic coatings, such as CrN, TiN, AlCrN, or DLC, deposited by Physical Vapor Deposition (PVD). Additionally, Laser Surface Texturing (LST) has emerged as a promising technique to improve tribological behavior by creating micro-features like dimples, which can trap debris and act as lubricant reservoirs. The combination of both techniques has shown promising benefits, although further optimization is still required.

This work explores the combination of femtosecond laser surface texturing (LST) and AlCrN coating as a promising strategy to reduce wear on fine blanking tools. Dimple textures with a diameter of 50 µm, a depth of 15µm and a surface coverage of 10%, 15%, and 20% were fabricated on AISI M2 steel. After the fabrication of the textures an AlCrN coating of 1.5 µm thickness was deposited via HIPIMS. SEM images of the surface confirmed the proper coating coverage of the dimples and the study of the cross-section revealed a suitable film growth. Nanoindentation and scratch tests showed 33 GPa hardness and good adhesion. Contact angle measurements indicated that the as-prepared surfaces were oleophilic, while increasing the textured area density led to a progressive shift toward higher hydrophobicity. Ball-on-disk tests demonstrated that an initial lubricant supply of 0.05 mL was sufficient to maintain a stable separation lubricant film under loads of 10, 30 and 50 N, resulting in friction coefficients between 0.10 and 0.15 regardless of textured area density. Long-term tests performed for 20000 cycles revealed a clear improvement in wear resistance, with the wear coefficient k decreasing from 2.99E-06 m^3/Nm to 8.02E-08 m^3/Nm when applying the AlCrN coating on textured samples. SEM/EDX analysis of the wear tracks indicated reduced degradation of the dimples in the case of the AlCrN-coated samples, and no significant chemical interaction with the alumina ball. Results suggest that applying a tribological coating is the primary approach to mitigate wear, while further work is needed to explore the potential of surface textures as wear debris traps and lubricant reservoirs.

3:40pm **MC3-2-WeA-6 Evaluation of Boriding as a Post-Treatment to Improve the Thermal Stability and Tribological Performance of Weld-Repaired Tool Steels***, Cesar Resendiz Calderon [resendiz.cesar@tec.mx],*
Leonardo Farfan Cabrera, Tecnologico de Monterrey, Mexico*; Enrique Campos Silva,* Instituto Politecnico Nacional, Mexico*; Edgar Ravelo Santos, Mateo Roux Reyna, Sebastian Garcia Barragan,* Tecnologico de Monterrey, Mexico

Metal deposition processes for component repair are gaining attention as a practical alternative to replacement. Yet, welding-based methods can alter microstructures and reduce mechanical integrity, especially in high-carbon steels. Such effects are critical in components exposed to elevated temperatures and demanding service conditions. In this study, the effectiveness of boriding as a post-conditioning treatment to improve wear resistance and reduce tribological heterogeneity is investigated, with special attention to its stability under long-term high-temperature exposure. A repair process based on welding was simulated on AISI H13 tool steel. AISI 308L austenitic stainless steel and ERNiFeCr-2 alloys were used as filler materials for the restoration using the GTAW technique. After metal deposition, a pack-boriding treatment was applied to form a continuous boride layer over the repaired surfaces. Half of the borided samples were exposed to 700 °C for 240 h to evaluate their thermal stability. Surface hardness, coating adhesion, and tribological performance were characterized before and after thermal exposure, both in the repaired and non-repaired regions, using nanoindentation, scratch testing, and dry reciprocating sliding tests. Surface damage and wear mechanisms were analyzed by scanning electron microscopy, and the wear volume was quantified through optical profilometry. Boriding proved effective in reducing mechanical property mismatches between the base and repaired regions and in enhancing the tribological performance of repaired H13 steel, even after prolonged high-temperature exposure. The treatment was particularly beneficial for samples repaired with stainless steel filler metal.

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.

Tribology and Mechanics of Coatings and Surfaces
Room Golden State Ballroom - Session MC-ThP

Tribology and Mechanics of Coatings and Surfaces Poster Session

Moderators: Jaya Balila, Indian Institute of Technology Bombay, India, **Pierluigi Bilotto**, TU Wien, Austria, **Osman Eryilmaz**, Argonne National Laboratory, USA, **Stephan Tremmel**, University of Bayreuth, Germany

MC-ThP-1 Evaluation of Stress Field in a Borided Inconel 718 Superalloy Under Dry Sliding Wear, *Alan Daniel Contla Pacheco, Iván Campos Silva,* Instituto Politécnico Nacional, Mexico*; Arturo Ocampo Ramírez,* Universidad Veracruzana, Mexico*; Daybelis Fernández Valdés,* Tecnológico Nacional de México*; GERMAN ANIBAL RODRIGUEZ CASTRO,* ***Felipe Nava Leana [felnaval@gmail.com]****, ALFONSO MENESES AMADOR,* Instituto Politécnico Nacional, Mexico

In this work, the wear resistance of Inconel 718 superalloy hardened by the boriding process was evaluated by means of dry sliding. A powder-pack boriding process was used to modify the alloy surface in which nickel borides were obtained in the sample due to the boron diffusion into the substrate material. The thermochemical treatment was carried out at a temperature of 950 °C for 2 and 6 h of exposure time. The Ni2B, Ni4B3 and Ni3B intermetallic compounds formed on the surface of the Inconel 718 superalloy were confirmed by XRD analysis. Berkovich nanoindentation tests were conducted to determine both hardness and Young's modulus of the borided samples. The dry sliding wear tests were performed on the surface of the borided sample using an alumina ball with diameter of 6 mm, a constant load of 20 N and distances of 50, 100, 150 and 200 m. Wear coefficient was obtained by the Archard's model. The finite element method using mesh nonlinear adaptivity was used to obtain the stress field during the wear test. Results of the failure mechanisms over the worn tracks showed that the sample with thicker thickness had better wear resistance.

MC-ThP-2 Electro-Tribological Behavior of Borided Steels in Lubricated Sliding–Rolling Contacts, ***Leonardo Farfan-Cabrera [farfanl@tec.mx]****,* Tecnologico de Monterrey, Mexico*; Peter Lee, Carlos Sanchez,* Southwest Research Institute, San Antonio Texas, USA*; Cesar Resendiz Calderon,* Tecnologico de Monterrey, Mexico*; Ali Erdemir, Merve Uysal Komurlu,* Texas A&M University, USA

The electric vehicle drivetrains are subject to new tribological challenges caused by stray electricity leading to surface degradation and lubricant breakdown. This work explores the potentials of boridingtreatment as a dual-function approach to enhance not only the electrical but also tribological properties of rolling–sliding components under lubricated and electrified conditions. Recent studies have shown that borided layers can exhibit high hardness, chemical stability, and inherently low electrical conductivity, making them attractive candidates for the production of low-cost insulating gears and bearing systems; however, their traction behavior under lubricated and electrified conditions has not yet been explored. In this study, AISI 52100 bearing steel discs and balls were thermochemically borided to form Fe_2B/FeB layers and tested in a mini-traction machine (MTM) under slide-to-roll ratios from 0–20% and entrainment speeds between 0.001 and 3900 mm/s which are typical of bearing operating regimes. Each test matrix consisted of twelve consecutive runs (six speed and six traction tests) conducted at 20 °C and 75 °C under 0, 1.5, and 3 A DC using a PAO base oil and a fully formulated ATF. Surface characterization was performed by optical profilometry, SEM, Raman and XRD spectroscopy to examine the influence of electrification and lubrication on the tribochemical response of borided layers. Overall, this study provides a framework to assess the potential of boriding as an insulating surface treatment for bearings in next-generation e-mobility systems.

MC-ThP-3 Tribological and Corrosion Performance of Alloy 718 coated with WC/Co Applied by HVOF, ***Nathalia Kappaun Vieira [nathaliakapp@hotmail.com]****,* PUCPR, Brazil*; Steffen Aicholz,* Oerlikon Balzers, Brazil*; Michelle Sostag Meruvia, Paulo Soares, Ricardo Diego Torres,* PUCPR, Brazil

Nickel-based superalloys, such as Inconel 718 and Inconel 625, are widely used in oil and gas industry due to their mechanical and Chemical properties. The extraction and processing environments involve high temperatures, high pressures, and corrosive environments. Nickel alloys offer high mechanical strength at elevated temperatures, and excellent resistance to corrosion and oxidation, ensuring safety and a longer service life for components that use them. Inconel 718 has high corrosion resistance, but its application is limited due to low hardness and wear resistance. One method of solving this problem is to combine heat treatment with application of coatings. The present work carried out a comparative study of the tribological and tribocorrosive properties of nitride Inconel 718 and Inconel 718 with a WC/Co coating, applied by the HVOF method, which was chosen due to the obtention of a dense layer with low porosity, improving the wear resistance of the material. The surfaces were characterized using X-ray diffractometry (XRD), microhardness, and scanning electron microscopy (SEM) techniques. The tribological, tribocorrosive, and corrosive properties were evaluated in five environments: (a) Distilled water saturated with CO2; (b) distilled water with sodium chloride; (c) distilled water saturated with H2S; (d) distilled water with sodium chloride and saturated with CO2; (e) distilled water with sodium chloride, CO2and H2S. Where in the end the surfaces will be compared across three requirements: i) corrosion current and potential, ii) wear rate, iii) wear rate considering the synergistic effect of tribocorrosion.

MC-ThP-4 Influence of Coating Thickness and Bias Voltage on Cracking Behavior of TiAlCrN PVD Coating, *Kirsten Bobzin,* ***Christian Kalscheuer [kalscheuer@iot.rwth-aachen.de]****, Wenting Xu,* Surface Engineering Institute - RWTH Aachen University, Germany

Physical Vapor Deposition (PVD) TiAlCrN coatings show outstanding mechanical properties, thermal stability and oxidation resistance. Therefore, TiAlCrN coatings exhibit great potential to be deposited on cutting tools in order to minimize wear during cutting operations. Both the coating thickness and the bias voltage applied during the PVD process can influence the cracking behavior of the coating, which in turn affects the machining capacity and lifetime of the cutting tools. In this study, TiAlCrN coatings with thicknesses of s = ~ 2.2 µm, ~ 2.8 µm and ~ 3.8 µm were deposited on cemented carbide WC-Co substrates under a constant applied bias voltage of U_B = -80 V. In addition, TiAlCrN coatings were deposited with different applied bias voltages of U_B = -60 V, -80 V and -100 V at a constant thickness of s = ~ 2.8 µm. The cracking resistance was evaluated using nanoscratch tests with constant forces of F = 250 mN, 500 mN and 750 mN. A conical diamond indenter was used for the nanoscratch tests. Nanoscratches were analyzed for cracks on the surface and in cross-section for coating deformation using scanning electron microscopy (SEM). Additionally, the depth of the nanoscratches were measured with confocal laser scanning microscopy (CLSM). In this study, thicker coatings exhibit better cracking resistance. With increasing thickness, the permanent deformation is reduced. In addition, the coating deposited with a bias voltage of U_B = -100 V exhibits the lowest deformation. The results reveal valuable insights in the cracking behavior of TiAlCrN coatings. These findings can contribute to enhancing the machining performance and the lifetime of cemented carbide tools through targeted coating design.

MC-ThP-5 Enhancing Corrosion Resistance and Tribological Performance of Inconel 718 through Plasma Nitriding and CrAlN/DLC Coatings for Oilfield Applications, ***Heloísa Scalabrin [heloisa.scalabrin@pucpr.edu.br]****, Michelle Sostag Meruvia, Paulo Soares, Ricardo Diego Torres,* Pontifícia Universidade Católica do Paraná (PUC-PR), Brazil

Oil and gas environments are highly corrosive due to the presence of H_2S, CO_2, and chloride ions, which accelerate material degradation through both chemical and mechanical mechanisms. This study investigates the impact of plasma nitriding on the tribological performance, adhesion, and corrosion resistance of CrAlN/DLC coatings deposited on Inconel 718 substrates. The goal is to develop an alternative surface treatment suitable for extreme oilfield conditions.

The Inconel 718 specimens were aged at 760 °C for 6 hours. Three groups were analyzed: (i) nitrided Inconel 718, (ii) nitrided Inconel 718 with CrAlN/DLC coating, and (iii) Inconel 718 with CrAlN/DLC coating without nitriding. Characterization was conducted using nanoindentation to assess mechanical properties, pin-on-disk testing for wear evaluation, and scratch testing for adhesion. The tribocorrosion performance was evaluated in a simulated oilfield environment. Structural and phase integrity of the coatings were analyzed using Raman spectroscopy and X-ray diffraction (XRD), while surface morphology and failure mechanisms were examined via scanning electron microscopy (SEM).

Plasma nitriding enhances surface hardness and promotes the formation of a diffusion layer, which improves coating adhesion and compatibility with the substrate. This combination reduces friction and wear under tribocorrosive conditions. Additionally, DLC deposition lowers friction coefficients and wear rates, further enhancing resistance to tribocorrosion. Preliminary results indicate that nitriding significantly increases surface hardness and coating adhesion. XRD analysis confirms the structural integrity of CrAlN/DLC coatings after exposure, supporting the proposed surface treatment as a multifunctional solution for harsh oilfield environments.

MC-ThP-6 High Temperature Stability of Different Diamond-Like Carbon Thin Films*, **Daniel Pölzlberger [daniel.poelzlberger@tuwien.ac.at]**,* Institute of Materials Science and Technology, TU Wien, Austria*; Julien Keraudy, Klaus Böbel,* Oerlikon Balzers, Oerlikon Surface Solutions AG, Liechtenstein*; Tomasz Wojcik, Philip Kutrowatz,* Christian Doppler Laboratory for Surface Engineering of High-performance Components, TU Wien, Austria*; Carsten Gachot,* Institute of Design Engineering and Product Development, Research Unit Tribology, TU Wien, Austria*; Helmut Riedl,* Institute of Materials Science and Technology, TU Wien, Austria

The transition to a more energy-efficient world requires innovative solutions, with materials science and tribology playing critical roles. Improving lubrication and reducing wear are essential for lowering the carbon footprint, conserving energy, and meeting climate targets. While conventional liquid lubricants perform well under many conditions, extreme environments, such as high or cryogenic temperatures, high contact pressures, vacuum, or radiation, demand the use of solid lubricants combined with advanced materials. However, many solid lubricants, including MoS_2, MXenes, and graphite, oxidize rapidly above approximately 400 °C, limiting their applicability. Developing self-lubricating materials that also provide excellent corrosion and wear resistance is, therefore, crucial. Among solid lubricating coatings, diamond-like carbon (DLC) is one of the most established. Yet, its performance at high temperatures above 400 °C remains questioned, as DLC coatings are suspected to degrade under such conditions. A systematic comparison and extreme condition testing that links tribological performance to coating properties is still missing.

This study investigates different DLC-based thin film materials, classifying them by dominant mechanisms, application ranges, and performance. Several DLC coatings are compared, including non-hydrogenated DLC (a-C), hydrogenated DLC (a-C:H), hydrogenated DLC with an oxide former (a-C:H:Si:O), and tetrahedral amorphous carbon (ta-C). These coatings, which vary in mechanical properties and sp_2/sp_3 ratios, were tribologically tested at different temperatures and loads. Subsequent surface characterization included nanoindentation, Raman spectroscopy to analyze the effects of graphitization after thermal exposure, and X-ray photoelectron spectroscopy. Further insights into the limits of carbon as a solid lubricant are provided through high-resolution characterization techniques such as high-resolution transmission electron microscopy.

In summary, this work highlights the potential of advanced DLC coatings for solid lubrication. It highlights the need for a deeper understanding of their mechanisms and the design of innovative coatings to enable future high-performance applications.

MC-ThP-7 The Impact of Nitriding Parameters on the Tribological and Corrosion Behavior of Inconel 718*, Gabriel Queiroz Carara, Heloisa Scalabrin, Cesar Neitzke, Michelle Meruvia, Paulo Soares, **Ricardo Torres [ricardo.torres@pucpr.br]**,* PUCPR, Brazil

The mechanical and tribological properties, along with the corrosion resistance of plasma-nitrided Inconel 718, were evaluated at nitrided treatment temperatures of 400°C and 500°C. The treatments varied in duration, lasting 1 hour, 2 hours, or 4 hours, and utilized gas compositions of 5% N_2 / 95% H_2 and 25% N_2 / 75% H_2 at a pressure of 530 Pa. Microstructural characterization was conducted using X-ray diffraction. For mechanical characterization, Vickers hardness measurements were performed using a force of 245.2 mN. The tribological properties were assessed through a reciprocating wear test involving an Inconel 718 and cemented ball pair, from which the wear rate was determined. Corrosion resistance was evaluated through potentiodynamic polarization testing. The results indicated that treatment at 400°C led to the formation of the expanded austenite phase, while the samples nitrided at 500°C formed the CrN phase. As anticipated, increasing the nitriding parameters resulted in a progressive increase in sample hardness—from 4.5 GPa for untreated samples to 9.75 GPa for those treated at 500°C with 25% N_2 for 4 hours. A notable reduction in the coefficient of friction was observed in all nitrided samples compared to the non-nitrided sepecimen, with the samples treated at 500°C exhibiting the lowest friction coefficient values. Additionally, the wear rate saw a significant decrease when comparing nitrided samples to non-nitrided ones.

MC-ThP-8 Microstructural and Mechanical Characterization of Plasma-Nitrided Mig-Welded h13 Tool Steel*, **Gabriel Ossovisck [gabriossov@gmail.com]**, Gelson de Souza,* Universidade Estadual de Ponta Grossa, Brazil*; Hipolito Carvajal-Fals,* Universidade Tecnológica Federal do Paraná, Brazil*; Guilherme Valadão,* Universidade Estadual de Ponta Grossa, Brazil*; Anderson Pukasiewicz,* Universidade Tecnológica Federal do Paraná, Brazil*; Roger Verástegui,* Universidade Tecnológia Federal do Paraná, Brazil*; Milton Polli,* Universidade Tecnológica Federal do Paraná, Brazil*; Francisco Serbena,* Universidade Estadual de Ponta Grossa, Brazil*; Higor Prochno,* Universidade Tecnológica Federal do Paraná, Brazil

This study investigates the effects of plasma nitriding (400 °C, 3 h, 50% N_2–50% H_2) on MIG-welded H13 tool steel, comparing the microstructural and phase evolution between the weld zone and the base metal. Specimens with dimensions of 10 mm × 10 mm × 20 mm were prepared through precision grinding, polishing and ultrasonic cleaning prior to nitriding.

After nitriding, optical microscopy investigations revealed a clear microstructural distinction between the base and welded regions, with structures typically associated with the high cooling rates in weld beads. The nitrided layers were characterized by X-ray diffraction (XRD) to identify the phases formed during treatment. The analysis confirmed the presence of characteristic nitrided phases (γ'-Fe_4N, ε-Fe_3N, CrN, and Cr_2N) in both regions, though significant differences in nitrogen retention were observed. The Fe_4N and CrN peaks were markedly more intense in the weld region, suggesting enhanced nitrogen incorporation.

Elemental mapping (EDS) of both the weld and base regions after nitriding revealed the presence of silicon- and chromium-rich intermetallic precipitates, as well as a distinct nitrogen diffusion profile characterized by a steep concentration gradient. Nitrogen-rich zones, when compared with the iron maps, indicated that the coexistence of nitrogen, chromium, and molybdenum promotes the formation of compounds with reduced iron content.

This altered diffusion behavior is consistent with the presence of retained austenite in the weld region compared with the base material — a consequence of the rapid cooling during welding — which enhances nitrogen penetration depth while reducing near-surface concentration. These findings are corroborated by comparative EBSD phase analyses.

Nanoindentation measurements confirmed differences in the mechanical behavior of the nitrided layers between the base and welded samples. In both cases, the surface hardness was significantly higher than the untreated substrate, reaching values of approximately 1,313 HV for the welded region and 1,400 HV for the base material.

Tribology and Mechanics of Coatings and Surfaces
Room Palm 3-4 - Session MC1-2-FrM

Friction, Wear, Lubrication Effects, & Modeling II

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

8:00am **MC1-2-FrM-1 Electro-Tribometers and Beyond: Experimental Routes to Assess Materials and Lubricants under Mechanical and Electrical Loadings***, **Leonardo Farfan Cabrera [farfanl@tec.mx]**,* Tecnologico de Monterrey, Mexico*; Ali Erdemir,* Texas A&M University, USA*; Peter Lee,* Southwest Research Institute, San Antonio Texas, USA **INVITED**

The global energy transition, driven by the rapid electrification of mobility, wind power systems, and other advanced energy technologies, demands a deeper understanding of how electrical loading influences friction, wear, and tribochemical film formation in electrified contact interfaces. Bearings, gears, and electrical contacts in these systems are increasingly exposed to stray currents that accelerate surface degradation, lubricant breakdown, and coating failure. To address these challenges, traditional tribometers have been redesigned into electro-tribometers that integrate precise control of mechanical, electrical, and environmental parameters. This presentation highlights different platforms developed to study materials and lubricants under electrical conditions: (1) the electrified four-ball test, used to evaluate current-induced wear and lubricant degradation in concentrated point contacts; (2) the electrified pin-on-disk test, operated under controlled gas atmospheres (air, nitrogen, argon, or humidified conditions) to investigate electro-tribochemical reactions and film growth with high reproducibility; (3) the electrified Mini-Traction Machine (MTM), designed to examine traction and mixed-lubrication behavior under simultaneous rolling, sliding, and current flow; (4) the block-on-ring test, adapted to simulate and study the combined effects of mechanical loading, sliding contact, and electrical current on tribological interfaces; and (5) the electrified ball-cratering (micro-abrasion) test, adapted for localized wear and debris characterization of materials and coatings under electrical bias. Together, these experimental routes establish a unified framework for probing electro-tribochemical mechanisms, coating durability, and lubricant stability, paving the way toward standardized testing of materials, coatings, and lubricants for electromobility, wind power, and other energy conversion systems.

8:40am **MC1-2-FrM-3 Tribological Performance of Sputter-Deposited MoS_2 Coatings with Varying Process Gases***, **Tomas Babuska [tfbabus@sandia.gov]**, Alexander Mings, Steven Larson, John Curry, David Adams,* Sandia National Laboratories, USA

Sputter-deposited molybdenum disulfide (MoS_2) coatings have been used for decades in aerospace applications due to their ultra-low steady-state coefficients of friction ($\mu_{ss} < 0.05$). Developing MoS_2 coatings for demanding applications with predictable and reliable performance over time (i.e., high-quality) requires tuning the coating microstructure through process variations. In this work, we explore process-structure-property-performance relationships of pure MoS_2 solid lubricant coatings where coatings are sputter deposited using different process gases. Helium, kypton, neon, argon and xenon are used to sputter deposit MoS_2 of varying morphologies, and the impact on critical performance traits such as initial friction, run-in, and aging resistance are studied. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

9:00am **MC1-2-FrM-4 Effect of Ta Content in ta-C:Ta Coatings on the Machining Performance of Aluminum Alloy***, **Kosuke Suzuki [kousukes@mmc.co.jp]**,* Mitsubishi Materials Corporation, Japan*; Takayuki Tokoroyama, Ruixi Zhang, Noritsugu Umehara,* Nagoya University, Japan*; Shun Sato, Kenji Yumoto,* Mitsubishi Materials Corporation, Japan **INVITED**

In recent years, demand for lightweight materials in the automotive and aerospace industries has increased, leading to a growing need for machining aluminum alloys. In aluminum alloy machining, Diamond-Like Carbon (DLC) coatings—especially hydrogen-free tetrahedral amorphous carbon (ta-C) coatings—are widely used due to their excellent wear resistance and low friction, which help suppress material adhesion and tool wear caused by hard Si particles in the alloy.

However, under more severe machining conditions, further improvements in coating performance are required to extend tool life, especially in terms of wear resistance and delamination resistance. One of the representative approaches for such performance enhancement is the addition of transition metal elements to DLC coatings, and numerous studies have been reported in this area. Among these, tantalum (Ta) is known to form strong covalent bonds with carbon and is expected to achieve both mechanical strength and improved adhesion strength through the reduction of residual compressive stress.Nevertheless, studies on its influence on machining performance remain limited.

In this study, tantalum-doped ta-C (ta-C:Ta) coatings with varying Ta contents were fabricated, and the correlation between Ta content and coating properties, as well as its effect on the drilling performance of aluminum alloy (ADC12), was systematically evaluated.

For each coating, microstructural analysis and residual stress measurements were conducted, along with ball-on-disk friction tests and scratch tests. Additionally, aluminum alloy cutting tests were performed to evaluate wear resistance and cutting force. As a result, the friction coefficient and specific wear rate tended to increase with higher Ta content in the friction tests. On the other hand, the scratch tests showed an increase in critical load, and a correlation between critical load and residual compressive stress was confirmed. Observations of the scratch marks revealed that ta-C:Ta coatings exhibited smaller delamination areas compared to undoped ta-C coatings. The dispersed structure of TaC nanocrystals observed in the ta-C:Ta coatings is suggested to suppress delamination propagation and contribute to improved toughness.

In the cutting tests, the coating containing 1.1 at.% Ta demonstrated the best wear resistance and lowest cutting force by significantly suppressing chipping while maintaining resistance to abrasive wear. These results suggest that controlling residual stress through appropriate Ta addition and enhancing toughness via fine TaC structures are effective strategies for improving tool life in aluminum alloy machining.

9:40am **MC1-2-FrM-6 Tailoring Titanium Nitride Thin Film on Magnesium Substrate to Improve Adhesion and Tribological Performance***, **Thiago Gontarski [thiago.gontarski@pucpr.edu.br]**, Bruno Pereira,* Pontifícia Universidade Católica do Paraná, Brazil*; Richard Chromik,* McGill University, Canada*; Ricardo Torres, Paulo Soares,* Pontifícia Universidade Católica do Paraná, Brazil

Magnesium (Mg) alloys are attractive materials for biomedical, automotive, and aerospace applications due to their low density and high specific strength. However, their poor wear and corrosion resistance remain major limitations for long-term use. In this work, titanium nitride (TiN) thin films were deposited on Mg-Y-RE magnesium alloy using magnetron sputtering to improve adhesion and tribological performance. Two main variables were investigated: (i) the substrate bias voltage, comparing DC and pulsed modes, and (ii) the presence of a graded TiN interlayer. The coatings were characterized by X-ray diffraction (XRD) to analyze the crystalline structure, scanning electron microscopy (SEM) for surface morphology, and energy-dispersive spectroscopy (EDS) for chemical composition. Mechanical properties were evaluated by nanoindentation to determine hardness and elastic modulus, while adhesion was assessed through scratch testing. Tribological performance was examined using a ball-on-plate tribometer, and the wear scars were quantified by white light interferometry (WLI) to calculate the wear volume. The results indicate that the optimal configuration for enhancing both adhesion and tribological properties is the combination of pulsed bias with a graded TiN architecture. These findings highlight the importance of tailoring both bias voltage and film architecture to optimize the mechanical and tribological behavior of TiN-coated magnesium alloys.

10:20am **MC1-2-FrM-8 Mxene Based Functionalisation of Ceramic Coatings Produced by Plasma Electrolytic Oxidation of Light Alloys***, **Tess Knowles [tess.knowles@manchester.ac.uk]**, Aleksey Rogov, Nicolas Laugel, David Lewis, Aleksey Yerokhin,* University of Manchester, UK

Plasma electrolytic oxidation (PEO) is an advanced surface treatment method used to produce stable barrier oxide coatings on light alloys. This coating technique is advantageous due to its simplicity and environmental benefits compared to relative methods such as anodising and promising for applications across many sectors including aerospace, automotive and biomedical. However, conventional PEO coatings have limitations to many areas of performance as they can only do so much as a passive protective layer. For this reason, it is important to further engineer the coating system to enhance the most beneficial behaviours and improve coating functionality.

An area that PEO is often used is for enhancement of wear resistance of aluminium alloys in sliding contact applications. PEO coatings must be modified to adapt tribological behaviour to changing environment, temperature and loading conditions. In these situations the main option is to add adaptive lubricants to the oxide coating to reduce friction and improve the overall performance of the component, some common examples being graphite or molybdenum disulphide based solid lubricants. These are capable of vastly reducing the friction coefficients [1] but encounter limitations under increased loading as they can delaminate due to weak interlayer bonding [2], with detrimental effects on coating longevity.

To address this problem, we investigate the application of MXene based solid lubricants on PEO coated Al alloys. MXenes are an innovative class of 2D inorganic materials with increased bonding strength between the layers of transition metal compounds making up their structure. To improve the compatibility between the PEO base and MXene top layer, in the first part of our work, we optimise the surface characteristics and properties of the PEO coating, adapting the surface texture and porosity to allow for better adherence and retention of the dry lubricant in sliding tribological contacts. Subsequent experiments include reciprocating sliding wear tests against steel and ceramic substrates, under hertzian contact pressures up to 1 GPa in dry and wet environments. The tribological behaviour and wear mechanisms are investigated by confocal microscopy, Raman spectroscopy and cross-sectional microanalysis. The key factors influencing the adaptive tribological performance of MXene-functionalised PEO coating systems are discussed with recommendations on further research directions made.

References

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[2] M. Lin, *et. al.*, *Tribology International*, **2021**,*154*, 106723.

10:40am **MC1-2-FrM-9 Experimental Investigation of Friction, Wear, and Dielectric Behavior of Hybrid Polymer Nanocomposites for Insulated Bearings with Machine Learning Assisted Optimization***, **Unnati Joshi [unnatiajoshi@gmail.com]**, Anand Joshi, Vishal Mehta, Jaivik Pathak, Pranav Rathi,* Parul University, India

The present research reports the development and comprehensive investigation of polymer based hybrid nanocomposites composed of Graphene Oxide (GO) and Copper Oxide (CuO) nanoparticles reinforced Polyether ether ketone (PEEK), designed for multifunctional efficacy in advanced high speed electromechanical system applications, including insulated bearings. The objective was to improve the friction-wear characteristics and dielectric properties of the base PEEK polymer. The suitability of the hybrid nanocomposites for insulated bearing applications were evaluated by examining the dielectric constant, dielectric loss, wear rate, and coefficient of friction. Structural and morphological properties were characterized using SEM, EDS, XRD, and FTIR. In this study, the friction, wear and dielectric properties of PEEK based nanocomposites containing 5 wt% Graphene Oxide and varying Copper Oxide nanoparticle contents (1 to 5 wt%) were experimentally investigated. Among all the compositions that were examined, the nanocomposite containing 5 wt.% GO and 5 wt.% CuO nanoparticles demonstrated the highest R^2 value of 88% for wear resistance and 93% for coefficient of friction, thereby validating its optimal performance level and operational stability. The simultaneous enhancements that result from the combination of CuO and GO are indicative of improved surface strength. Furthermore, the machine learning regression models, including Random Forest, XGBoost, and Extra Tree, have exhibited exceptional predictive capabilities for wear and friction forces. The Extra Tree model, in particular, achieved near-perfect accuracy (R^2 = 0.9999) and identified load as the most influential factor. Also, the dielectric constant (ε') and dielectric loss (ε") were predicted and modelled using these machine learning models. The analysis demonstrated that the highest ε' was achieved at 2 wt% Copper Oxide as a result of increased interfacial polarisation, while the most stable dielectric loss (ε") was achieved at 3 and 4 wt% Copper Oxide. The Extra Trees algorithm consistently exhibited superior predictive accuracy and generalisation capability among all the models. This demonstrates that the wear resistance, coefficient of friction, and dielectric behaviour of the composites, were substantially influenced by the synergistic interaction between Graphene Oxide and Copper Oxide nanoparticles. This research advances durable, high performance insulating materials for next-generation electromechanical systems, supporting SDG 9. It also promotes SDG 12 by supporting the design of affordable, durable materials that reduce material waste and enhance industrial component energy efficiency.

Tribology and Mechanics of Coatings and Surfaces
Room Town & Country B - Session MC3-3-FrM

Tribology of Coatings and Surfaces for Industrial Applications III

Moderators: Osman Eryilmaz, Argonne National Laboratory, USA, **Stephan Tremmel**, University of Bayreuth, Germany

8:00am **MC3-3-FrM-1 High-performance ta-C-based coatings for tribological applications deposited by laser-arc technique***, **Volker Weihnacht [volker.weihnacht@iws.fraunhofer.de]**, Frank Kaulfuss, Stefan Makowski, Falko Hofmann, Fabian Härtwig, Martin Zawischa,* Fraunhofer IWS, Germany **INVITED**

Tetrahedral amorphous carbon (ta-C) coatings are increasingly used in tribological contacts and can be found in numerous industrial applications due to their wear resistance caused by super hardness in combination with generally low friction. Fraunhofer IWS has developed a deposition technique for stable industrial coating processes for ta-C using a pulsed, laser-triggered arc discharge on graphite cathodes. The laser-arc technique can be combined with plasma filtering to reduce the density of particle-induced defects in the ta-C coatings. In addition to the further development of plasma filter technology, IWS has currently focused on the development of doped ta-C(:X) coatings by using graphite composite cathodes. In this contribution, it will be shown how doping affects the deposition behavior as well as the structure and properties of the grown ta-C:X coatings. Special emphasis is placed on the tribological properties using various engine oils and alternative, environmentally friendly lubricants.

8:40am **MC3-3-FrM-3 Effect of Boriding on the Surface Hardness and Wear Resistance of Low Carbon Steel Fabricated by Wire Arc Additive Manufacturing (WAAM)***, **Abraham Molina-Sanchez [A01363512@tec.mx]**, Cesar David Resendiz-Calderon, Leonardo Israel Farfan-Cabrera, Christian Ricardo Cuba-Amesquita,* Tecnológico de Monterrey, Mexico

Wire and Arc Additive Manufacturing (WAAM) enables the production of large-scale, geometrically complex components at a significantly lower cost compared to other additive manufacturing (AM) technologies. It offers extensive material availability, including low-carbon steel, which is widely used in mechanical and structural components. However, due to its low hardness and corrosion resistance compared to other steels, its use is limited in high-demand environments. This study evaluates the effect of boriding on the surface hardness and wear resistance of low-carbon steel fabricated using the WAAM technique. WAAM-built low-carbon steel plates were printed layer by layer to complete 60 layers per sample using ER70S-6 steel wire (0.8 mm diameter). The parameters included a welding voltage of 19.7 V, 67 A current, 5 mm/s travel speed, and a shielding gas of 100% CO_2 supplied at 15 L/min. These samples were subjected to a boriding process wherein a sealed container with Ekabor 2 powder as the boron donor was used, heated at 950°C for 3 hours, and cooled at room temperature. A boride layer with an average thickness of 93.5 ± 32.6 μm composed of FeB and Fe_2B phases was formed, as confirmed by X-ray diffraction (XRD). The adhesion of the boride layer on the as-built (AB) samples was evaluated using a progressive scratch test, and nanoindentation revealed an increase in hardness with no significant changes along the material deposition direction. Dry-sliding tests measured the coefficient of friction (CoF) between AB and borided samples, and a considerable wear volume decrease of 20% was observed with the boride layer, as measured by optical profilometry. These results demonstrate no significant changes along the build direction in phase composition, hardness, or tribological behavior, indicating that boriding is an effective surface treatment for enhancing wear resistance in WAAM-fabricated low-carbon steel.

9:00am **MC3-3-FrM-4 Tribological Performance of Epoxy Coatings for Semi-Rigid Packaging Applications***, **SIDDHANT VYAVAHARE [siddhant.vyavahare@adityabirla.com]**, AKSHTA VAISH, HARSHADKUMAR PANDIT,* Hindalco Industries Ltd, India

Epoxy-based coatings play a critical role in the performance and reliability of semi-rigid packaging containers, where they must endure both mechanical forming stresses and tribological contact during service. This study examines the balance between coating brittleness, moulding stresses, and frictional behaviour, with the objective of improving coating solutions for industrial packaging applications.

Formulations were developed using bisphenol-A-based epoxy resin and phenolic resin cured with amine hardeners, with tailored additives to optimize flexibility and hardness. Coatings were applied and thermally cured under industrially relevant processing conditions. Mechanical performance was evaluated through bend, cupping, crosshatch adhesion, and impact resistance tests, simulating forming and handling stresses encountered in production. Results demonstrated that higher crosslink density, while enhancing hardness, increased brittleness and led to premature microcracking during deformation.

Tribological evaluation, performed using a multi-tribometer under dry sliding, revealed a strong correlation between brittleness and increased wear rates, with stiffer coatings exhibiting elevated coefficients of friction (COF) due to reduced surface compliance. Post-test analyses by profilometry and SEM confirmed brittle fracture-driven wear mechanisms such as micro-spallation and delamination.

These findings highlight the need for epoxy coatings engineered with a balance of hardness and flexibility, enabling them to survive forming operations while maintaining low wear and stable friction during service. The outcomes provide practical design guidelines for coating engineers to develop next-generation epoxy systems that improve both manufacturing reliability and end-use performance in semi-rigid container applications.

Keywords — Epoxy coatings, Tribology, Semi-rigid packaging, Industrial coatings.

9:20am **MC3-3-FrM-5 The Development of Amorphous-Based Multi-Component Alloys for the Nanocomposite Coatings and their Properties***,* ***Kyoung Il Moon [kimoon@kitech.re.kr]****, Gi hoon Kwon, Hae Won Yoon, Byoungho Choi, Kyong jun An,* Korea Institute of Industrial Technology, Republic of Korea*; Sung Chul Cha,* Hyundai Motor Group-Hyundai Kefico, Republic of Korea

While modern industries are becoming more sophisticated, diversified, and globalized, they requires the development of smart materials have multi-functionality, high mechanical properties, and extreme durability. Also they could be prepared environmentally friendly and energy efficiently. At the same point of view, the smart coating materials capable of simultaneously expressing various mechanical properties or opposite properties such as high hardness with high toughness, high electricity with high corrosion resistance are attracting attentions as an versatile and useful materials in the future. In particular, there is an urgent needs to develop a novel coating materials capable of stably maintaining microstructures and mechanical properties in various external environments, unlike conventional coating materials whose properties and structures are easily changed by the some harsh environments. To get this kinds of objects, the coating material with multi-components are essential. But if the materials should be prepared with one phase with multi components, they could have only one properties. So, nano-composites with various phases should be formed to realize the various properties. So, it is necessary to develop a coating layer composed of various components those could be formed various phases and more complex structures with multifunctional properties.

In this study, various single alloy target materials with various compositions based on the Zr-Cu amorphous materials have been prepared by powder metallurgy methods such as atomization, mechanical alloying, and Spark Plasma Sintering (SPS). The various nanocomposite coatings could be prepared by using single alloying targets. The most important property is the composition of the target material could be transferred to the coating layers. The properties of as-prepared nanocomposite coatings will be summarized in this present including the coating's performance under conditions that simulate EV drivetrain environments.

9:40am **MC3-3-FrM-6 Enhancement of Tribological Properties of Graphene Oxide/MoS2 Composite Coatings Prepared on Textured Biomedical Implants by Electrophoretic Deposition Method***,* ***Madhusmita Mallick [mmallick@iitbbs.ac.in]****,* IIT Bhubaneswar, India

Graphene oxide exceptional solid lubrication properties, arising from its low shear strength and mechanical properties, make it an ideal material for tribological enhancement in biomedical implant surfaces. This study focusses on deposition of graphene oxide-molybdenum disulfide (MoS_2) composite coatings on laser-textured biomaterials such as commercially pure titanium and Nitinol substrates using the electrophoretic deposition (EPD) technique. Before EPD coating, substrates were treated with femtosecond laser texturing to produce both circular and bio-inspired micro-grooves morphologies, aimed at optimizing surface functionality. The tribological performance of the coated substrates were evaluated under dry sliding conditions using a ball-on-disc tribometer facility, while microstructural characterization were performed using SEM, EDS, XRD and Raman spectroscopy before and after wear testing. The results revealed that laser surface texturing significantly improved coating adhesion due to mechanical interlocking and enhanced tribological behavior, particularly in the case of bio-inspired patterns owing to better retention of graphene/MOS2 coating in the micro-grooves pattern. Additionally, EPD-prepared graphene oxide–MoS_2 composite coatings reduced the coefficient of friction to as low as 0.036 and markedly decreased wear rates compared to bare and EPD-coated GO/ MoS2 substrates. These findings demonstrate the strong potential of combining femtosecond laser texturing with graphene oxide -MoS_2 hybrid coatings to achieve ultra-low friction, high wear resistance, and durable biocompatible surfaces for advanced load-bearing biomedical implant applications.

Keywords: Biomedical Implants; Electrophoretic Deposition; Graphene oxide Nanoplatelets, MoS_2; Femtosecond laser texturing; Tribological property

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Rogov, Aleksey: MC1-2-FrM-8, 11
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Roux Reyna, Mateo: MC3-2-WeA-6, 6
Rubira Danelon, Miguel: MC1-1-ThA-7, **8**
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Sanchez, Carlos: MC-ThP-2, 9
Sato, Shun: MC1-2-FrM-4, 11
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Schmittbuhl, Marc: MC1-1-ThA-1, **7**
Serbena, Francisco: MC-ThP-8, 10
Soares, Paulo: MC1-2-FrM-6, 11; MC-ThP-3, 9; MC-ThP-5, 9; MC-ThP-7, 10
Sostag Meruvia, Michelle: MC-ThP-3, 9
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Stelzig, Timea: MC3-1-TuM-3, 1
Sung, Gugyeong: MC1-1-ThA-5, 7
Suzuki, Kosuke: MC1-2-FrM-4, **11**
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Tardelli, Joffrey: MC1-1-ThA-1, 7
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Thompson, Forest: MC3-1-TuM-6, 1
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Torres, Ricardo: MC1-2-FrM-6, 11; MC-ThP-7, **10**
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VAISH, AKSHTA: MC3-3-FrM-4, 12
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Weihnacht, Volker: MC3-3-FrM-1, **12**
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Yoon, Hae Won: MC3-2-WeA-3, 5; MC3-3-FrM-5, 13
Yumoto, Kenji: MC1-2-FrM-4, 11
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Zalakain, Iñaki: MC3-2-WeA-5, 5
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