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.

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