Tribology and Mechanical Behavior of Coatings and Engineered Surfaces
Room Town & Country B - Session E1-2-WeM
Friction, Wear, Lubrication Effects, and Modeling II

Moderators: Noora Manninen, Oerlikon Balzers, Oerlikon Surface Solutions AG, Liechtenstein, **Dr. Michael Chandross**, Sandia National Laboratories, USA, **Prof. Dr. Andreas Rosenkranz**, Universidad de Chile

8:20am **E1-2-WeM-2 Coatings and Composites for Extreme Environments Lab (CE)2***, **Achyuth Kulkarni**, T. Ansell,* Naval Postgraduate School, USA

The Aluminum (6xxx.x) series alloys have gained widespread use across several industries, including aerospace, marine, structural, and automobile, primarily due to their impressive characteristics, such as low density, high specific strength, formability, and good corrosion resistance. However, despite these advantages, these alloys are susceptible to poor mechanical strength and wear resistance when exposed to challenging environmental conditions. To tackle these shortcomings, the development of Aluminum Metal Matrix Composites (MMC) has emerged as a crucial advancement in improving the properties of commercial Al alloys without compromising the ductility of their substrate material. The use of MMCs offers the potential to enhance the mechanical properties of Al alloys significantly, including tensile strength, hardness, wear resistance, and fatigue strength, thereby expanding their application range in harsh environments. Moreover, the incorporation of various reinforcing materials, such as ceramic particles, whiskers, fibers, and nanotubes, into the Al matrix can further augment its mechanical properties.

This study presents the synthesis of novel nanocomposite aluminum-based coatings reinforced with boron carbide (B_4C) microparticles and Graphene Nanoplatelets (GNPs) using a dual-reinforcement approach. The combination of the two reinforcing materials activates synergistic interactions between particles, resulting in improved dispersion and enhanced strengthening efficacy. To evaluate the efficiency of the dual-reinforcement approach, coatings containing 4 vol.% of GNPs and 4 vol.% B_4C are compared with unreinforced Al coatings and coatings reinforced with either 4 vol.% BNNT or 4 vol.% B_4C. The mechanical properties of the coatings are evaluated using adhesion testing, and nanoindentation. The structural characterization is done using Optical Microscopy, and Field Emission Scanning Electron Microscope (FE-SEM). Moreover, the elevated temperature (300ºC) dry sliding wear characteristics are studied. The worn surfaces are further analyzed using FESEM and a 3-D non-contact type optical profilometer. These findings have significant implications for the development of high-performance nanocomposite coatings in various industries, including aerospace, automotive, and structural applications.

8:40am **E1-2-WeM-3 Tribological Behavior of Mos_2 Based Coatings Under Different Sliding to Rolling Lubricated Contact Conditions***, **Newton Fukumasu**, I. Machado,* University of São Paulo, Brazil*; R. Rego,* Aeronautics Institute of Technology, Brazil*; A. Tschiptschin, R. Souza,* University of São Paulo, Brazil

Powertrain components, such as gears and bearings, are used in a variety of sectors, including automotive, aerospace, energy conversion and manufacturing. These parts are subjected to high torque, cyclic loading and variable sliding to rolling ratio (SRR), which can induce sliding wear and/or rolling contact fatigue damage. Strategies to mitigate those failures include the use of advanced 2D coating materials, such as molybdenum disulfide, which may exhibit excellent solid lubrication properties under high contact stresses and pure sliding conditions. In principle, higher SRR conditions would demand coatings with higher hardness to mitigate sliding wear while lower SRR conditions would require more ductile coatings to improve RCF life. Given those demands, adaptive coatings that can change their properties in response to local contact conditions would improve component performance and durability. One mechanism to provide such local adaption is the shear-induced crystal orientation (SCO) promoted by high contact sliding condition, in which the highly oriented stresses and elevated local temperatures may lead to the formation of nanocrystalline regions on the surface of the material, resulting in improved mechanical properties, including increased hardness, fracture toughness and/or lower friction. In this work, MoS_2 based coatings were deposited by pulsed direct current magnetron sputtering technique and submitted to 1 GPa contact pressure under variable SRR (10% and 100%) to evaluate conditions more prone to promote the SCO mechanism. SAE 52100 steel discs were coated and tested in a ball-on-disc configuration using a Mini Traction Machine (PCS Inc.) equipment, in which both disc and ball tangential velocities were controlled to provide different SRR levels, maintaining a low average velocity to provide a boundary lubrication condition. Numerical simulations of tested configuration, using the Finite Element Method, indicated no significant correlation between shear stress developed at contact region and SRR values, while shear stress peak values were obtained for higher coefficient of friction. Experimental results indicated elevated coefficient of friction in the running in part of the test for all SRR conditions, decreasing to a lower stable COF along the test. The lower COF was achieved for highest SRR condition, in which Raman spectroscopy indicated the existence of a crystalline MoS_2 phase inside the wear track, not present initially in the as-deposited condition. These results support the SCO mechanism, adapting local coating properties that may improve wear and RCF resistance.

9:00am **E1-2-WeM-4 Catalytic Transformation of Lubricants to Wear-Protective Tribofilms on Selected Steel Surfaces During Sliding***, **Yip-Wah Chung**, A. Khan, J. Ahmed, T. Martin, S. Liu,* Northwestern University, USA*; S. Berkebile,* Army Research Laboratory, USA*; Q. Wang,* Northwestern University, USA

We report here the impact of different alloying elements in steels on friction and wear behavior by performing ball-on-flat lubricated reciprocating tribotesting experiments on 52100 ball on steel flats with different compositions heat-treated to give similar hardness and microstructure, with polyalphaolefin (PAO-4) and/or *n*-dodecane as the lubricant. The major observation is that steels containing high concentrations (>= 5 wt.%) of Cr, Mo, V, or Cu/Ni give rise to markedly reduced wear compared with 52100 or plain carbon steels, with D2 steel, which contains 11.5 wt.% Cr, as the major alloying element being the most wear-resistant. The wear resistance is strongly correlated with the efficiency of formation of carbon-containing oligomeric films at surfaces as determined by Raman spectroscopy. Given the strong affinity of chromium to oxygen, chromium should exist as Cr_2O_3 at the steel surfaces during testing. We have performed molecular dynamics simulation on Cr_2O_3 and demonstrated its ability to catalyze the formation of carbon-containing oligomeric films from hydrocarbon molecules, consistent with its known catalytic activity in other hydrocarbon reactions. We believe that chromium-containing alloys, such as D2, and coatings, such as CrN, derive their wear resistance in part from the efficient *in-situ* formation of wear-protective carbon tribofilms at contacting asperities.

9:20am **E1-2-WeM-5 Aromatic Compounds as Sustainable Lubricants for Iron***, **Sophie Loehlé**,* TotalEnergies, France **INVITED**

The present work will focus on one type of aromatic compound, Hypericin, as a nature constituent of St. John's wort, which is commonly known as anti-depressant, anti-virus, and anti-biotic agents. Besides its functions in medical treatment, the present work reveals its potential as an original friction modifier. Indeed, amazing tribological properties were observed by adding hypericin to glycerol in order to lubricate a steel/SiC tribopair. A hypericin concentration as low as 0.3% reduces friction coefficient (CoF) from ~ 0.02 to a value below 0.01 (the so-called superlubricity regime) under boundary lubrication. The excellent friction reduction property of hypericin derives from its hydroxygen functionalized carbopolycyclic structure, which achieves surface protection by forming a nanometer-thick hypericin-like tribofilm on both steel and SiC surfaces. The tribologically-induced polymerization of the molecules into graphene is detected by high resolution transmission electron microscopy (HRTEM) on a focused ion beam cross-section. First-principles calculations elucidate the thermodynamic driving force for the process, monitored in real time by *ab initio* and classical, molecular dynamics simulations. This work suggests an exciting and unconventional way to promote the formation of graphene by mechanical stresses and uncovers the great potential of many aromatic molecules derived from the pharmacopoeia, such as hypericin, as lubricants for industrial applications.

11:00am **E1-2-WeM-10 How Efficient Is the Self Adaption Concept for Low Friction with TMD-Based Sputtered Coatings***, **Albano Cavaleiro**,* University of Coimbra, Portugal **INVITED**

In last decades a huge amount of research was dedicated for further improvement of the frictional behaviour of sputtered coatings based on transition metal dichalcogenides (TMD). It is currently accepted that the low friction achieved with this type of coatings is based on the development of a tribolayer in the contact formed by a self-adaption process. The sliding process gives rise to the establishment of contact conditions which are able, by a reorientation / recrystallization process, to transform the material in the contact leading to the formation of a tribolayer with the required low friction characteristics. Whatever are the initial structure and phase composition in the sputtered deposited coatings, the transformation can occur in the contact if specific conditions of sliding exist.

In this talk, the conditions for activating the self adaption process will be presented and discussed. Sliding and contact parameters such as, the number of cycles, the temperature and the contact pressure, will be related with the type of TMD-based sputtered coatings and antagonist materials with the supporting of several practical examples. Tribological testing, using different experimental rigs, and detailed characterization of the materials in the contact are in the basis of the interpretation of the results to be presented.

11:40am **E1-2-WeM-12 Self-Lubricating Titanium Alloys: Design and High Temperature Tribological Performance Up to 800 °C***, H. Torres, K. Pichelbauer, S. Budnyk,* AC2T Research GmbH, Austria*; T. Schachinger, C. Gachot,* TU Wien, Austria*; **Manel Rodriguez Ripoll,*** AC2T Research GmbH, Austria

Titanium and its alloys are extensively used in aerospace and biomedical applications thanks to their high strength-to-weight ratios, excellent corrosion resistance or good biocompatibility. However, a general widespread of these alloys to other applications, such as machine elements is severely limited by their poor tribological properties.

With the aim of improving the performance of titanium alloys and spreading their applicability to new fields, the present work deals with the development of self-lubricating titanium alloys, with an emphasis on high temperature applications performance. The alloy developed is deposited by means of laser melting using a direct diode laser system, as laser deposition processes can be readily used for additive manufacturing techniques that offer a great flexibility and efficiency compared to traditional subtractive manufacturing processes.

A mixture of Bi with Ni powder (70:30) is pre-placed on a Ti6Al4V plate and melted with the direct diode laser. The melting process results in the presence of a 300 µm thickness coating on top of the Ti6Al4V plate. The microstructure and phase composition of the deposited self-lubricating titanium alloy coating is characterized using X-ray diffraction, scanning and transmission electron microscopy. The results reveal the presence of three distinct phases, a Ti6Al4V matrix with Bi-Ti-rich inclusions that are surrounded by a Ni-Ti-rich phase. Afterwards, the friction and wear performance of the developed self-lubricating coating is evaluated using high temperature tribological tests at temperatures ranging from room temperature up to 800 °C. The tribological experiments are performed against Ti6Al4V pins in reciprocating sliding.

The results reveal that the self-lubricating laser deposited titanium alloy is able to significantly decrease friction in the 400 to 800°C range, when compared to conventional Ti6Al4V. In terms of wear, the resulting self-lubricating alloy was also able to clearly outperform the reference Ti6Al4V in all the evaluated temperature ranges, from RT to 800°C. The friction reduction mechanism in the 400 to 600°C temperature range has been linked to the transfer and smearing of bismuth-rich phases to the counter body. At the highest temperature of 800°C, friction reduction could be linked to the formation of the ternary oxide $BiVO_4$, which could act as an effective solid lubricant. This overall tribological performance makes the presented self-lubricating alloy a potential candidate for numerous high temperature applications in the aerospace and energy sectors.

12:00pm **E1-2-WeM-13 Electrodeposited of Silver Nano-Particules Plant Based to Improve Lubrication of Composite Films***, **Pierre-Antoine Gay,*** Haute Ecole Arc Ingénierie, Switzerland*; I. Markovic Milosevic,* HEPIA Institut inSTI, Switzerland*; T. Journot,* HE ARC Ingénierie, Switzerland*; J. Maurer,* Faculty of Biology and Medicine. Clinical pharmacology, Switzerland

Electrodeposition of silver and nanoparticles plant based like TiO_2 and Al_2O_3 has been successfully demonstrated for the first time in silver electrodeposit composite films. Their tribological properties and wear resistance were investigated by a pin-on-disk type friction testing using an electrical system to also measure the resistivity of the composite coatings.

The friction coefficient of silver/TiO_2composite films decreased with increasing TiO_2content. Plating parameters, nanoparticles concentration and zeta potential were systematically investigated in order to found a relationship between incorporation rate *Vp and* friction coefficient. Ag – $TiO_2$with 60g/L of nanoparticles composite film showed the minimum friction coefficient value, with wear resistance 40% better. A comparaison with electrodeposit composit coatings was discussed with traditional nanoparticles.

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