Tribology and Mechanical Behavior of Coatings and Engineered Surfaces
Room San Diego - Session E3-WeM

Tribology of Coatings for Automotive and Aerospace Applications

Moderators: John Curry, Sandia National Laboratories, USA, **Christian Greiner**, Karlsruhe Institute of Technology (KIT), Institute for Applied Materials (IAM), **Oliver Hunold**, Oerlikon Balzers, Oerlikon Surface Solutions AG

8:00am **E3-WeM-1 Self-assembly of Ultra-high Strength Nanoporous Metals for Multifunctional Coatings and Free-standing Films***, **James Pikul,*** University of Pennsylvania, USA*; N Argibay, J Curry,* Sandia National Laboratories, USA*; Z Hsain,* University of Pennsylvania, USA **INVITED**

This talk will describe the fabrication and characterization of nickel-based cellular materials which have the strength of titanium and the density of water. These materials can be made free-standing or as thin film coatings by electroplating metal through self-assembled particles. The gap between self-assembled particles confines the dimension of the metal struts to diameters as small as 17 nm. The nanoscale confinement increases the local yield strengths of the nickel struts to 8 GPa, which exceeds that of bulk nickel by up to 4X. The mechanical properties of this material can be controlled by varying the nanometer-scale geometry, with strength varying over the range 90-880 MPa, modulus varying over the range 5-40 GPa, and density varying over the range 880 – 14500 kg/m^3. In addition to characterizing the mechanical strength of these nickel-based cellular materials, I will discuss their wear performance when the pores are infiltrated with solid lubricants. These materials present a new class of films that can achieve high wear resistance while also maintaining high thermal conductivity, electrical conductivity, or other tailored properties.

8:40am **E3-WeM-3 Elevated Temperature Sliding Wear of PEO-Chameleon Duplex Coating***, **Andrey A. Voevodin**, A Shirani,* University of North Texas, USA*; A Yerokhin,* The University of Manchester, UK*; A Korenyi-Both,* Tribologix Inc., USA*; D Berman,* University of North Texas, USA*; J Zabinski,* Army Research Laboratory, USA

Plasma electrolytic oxidation (PEO) is an attractive technology for improving wear and corrosion resistance of aluminum and titanium alloys exposed to different temperature and environment.. PEO results in formation of 50-150 micrometer thick hard ceramic (AlSiO and TiSiO) coatings with good adhesion to the substrate and with morphology gradient from a dense region near the substrate interface to a porous outside region [1]. Such properties potentially make a PEO coating an ideal underlying layer for the application of solid lubricants which can be entrapped in outside porous and provide reservoirs for the tribological contact lubrication. In this study we investigate the wear behavior of the PEO –based coatings during sliding in air at elevated temperatures. The PEO produced 11-12 GPa hardness AlSiO and TiSiO coatings are covered with a top layer of an MoS_2-Sb_2O_3-graphite chameleon solid lubricant, the composition of which was previously reported to self-adapt in variable humidity environments resulting in friction and wear reduction [2]. Coupons of aluminum and titanium alloys were coated by the PEO process and then were over-coated by a burnishing process with a MoS_2-Sb_2O_3-graphite chameleon coating to prepare such duplex coating combination. The coated surfaces were then subjected to sliding wear tests against silicon nitride counterparts with variable normal loads (2- 10 N) and temperatures (room to 400 °C). At room temperature, the humid air friction coefficients were of the order of 0.10-0.15, which is typical for graphite lubricant in humid air. However, when the temperature was increased first to 100°C and then up to 400 °C, the coefficient of friction was reduced to about 0.03-0.05 level which was linked with removing the water and promoting lubrication with the MoS2 chameleon coating component. Raman, SEM and cross-sectional FIB/SEM/EDX analyses of the wear tracks were used to investigate the mechanisms of the temperature adaptation and sliding wear performance. The study demonstrate the effectiveness of the PEO-chameleon coating system performance for the sliding wear mitigation and friction reduction.

[1] A.L. Yerokhin et al., Surface and Coatings Technology, 122 (1999) 73.

[2] J.S. Zabinski et al., Tribology Letters, 23 (2006) 155.

9:00am **E3-WeM-4 Formation Mechanisms of Zn, Mo, S and P Containing Reaction Layers on a DLC Coating***, K Bobzin, T Brögelmann, C Kalscheuer, **Matthias Thiex**,* Surface Engineering Institute - RWTH Aachen University, Germany

Environmental restrictions on the climate-damaging CO_2 emissions in the field of mobility are increasingly tightened due to political requirements. Thus, there are requirements on saving fossil resources in tribological contacts, e.g., by reducing friction and wear as well as the amounts of additives and lubricants. A successful approach is the application of diamond-like carbon (DLC) coatings on components such as pistons, piston rings and bearings in lubricated tribological contacts due to their significant effects in friction and wear reduction. Lubricants and additives nowadays are designed for tribological steel/steel contacts, whereby the knowledge on tribochemical layer formation on steel surfaces is comprehensive in contrast to the physical-chemical interactions between DLC coatings, lubricants and additives. That is in contradiction to the increasing usage of DLC coated components in tribological applications. Within this study, the formation mechanisms of Zn, Mo, S and P containing reaction layers on a Zr modified DLC coating a–C:H:Zr (ZrC_g) in lubricated tribological DLC/DLC contacts were studied by means of pin-on-disc (PoD) tribometer. Motivated by the loading conditions in applications, the tests were conducted by varying the distances in a range 200 m ≤ s ≤ 5,000 m under boundary and mixed friction conditions at a temperature T = 90 °C and a Hertzian contact pressure p = 1,300 MPa. The synthetic base lubricant poly-alpha-olefin (PAO) was formulated using the anti-wear (AW) and extreme pressure (EP) additive zinc dialkyldithiophosphate (ZnDTP), PAO/ZnDTP, the friction modifier (FM) additive molybdenum dialkyldithiophosphate (MoDTP), PAO/MoDTP, as well as a combined additivation of MoDTP and ZnDTP at a ratio of 1:3, PAO/MoDTP/ZnDTP/1:3. Based on the results of confocal laser scanning microscopy (CLSM), tribochemical layers form inside and at the edge region of the wear track. The chemical and structural formation process can also be influenced by increasing the sliding distance s in PoD tests. Hereby, the thickness of the tribochemical layers increases too. The chemical composition of the tribochemical reaction layers (Zn,Mo,S,P) and molybdenum disulphide (MoS_2) determined by energy-dispersive X-ray spectroscopy (EDX) and Raman spectroscopy differs by changing the additivation and sliding distance s. Similar conclusion can be made considering the structure and texture of the tribochemical reaction layers, which differ significantly in size and appearance for all analyzed tribological contacts. Hereby, the results show the importance of a differentiated consideration of the interaction between DLC coating, lubricant and additive.

9:20am **E3-WeM-5 ta-C Coatings for Tribological Applications***, J Becker,* Oerlikon Balzers Coating Germany GmbH, Germany*; N Beganovic, **Astrid Gies**, J Karner,* Oerlikon Balzers, Oerlikon Surface Solutions AG, Liechtenstein*; J Vetter,* Oerlikon Balzers Coating Germany GmbH, Germany

Diamond Like Carbon (DLC) coatings and in particular the hydrogenated a-C:H coatings are widely used where friction and wear reduction is required. However, a-C:H coatings have a limited thermal stability and start to graphitize at temperatures higher than about 300°C. Depending on the contact pressure, graphitization might even occur at much lower temperatures. In addition, the tribological performance of a-C:H coatings can be negatively influenced by different lubricants and additives.

To overcome the drawbacks of a-C:H coatings hydrogen-free DLC coatings like ta-C and a-C are currently investigated as a possible solution. ta-C shows a significant higher coating hardness than a-C:H coatings and due to the lack of hydrogen a different surface chemistry which results in a different behaviour under lubricants. ta-C is usually deposited by high-energy deposition processes like arc evaporation; the arc evaporation is possible with or without filtering. Inherent to these processes is the generation of coating defects like droplets. A suitable post-treatment is mandatory to reduce the roughness to an acceptable level. High roughness in combination with a high coating hardness would lead to significant counter body wear.

In this work, ta-C coatings were submitted to tribological testing in a wide temperature range (room temperature to 480°C) in dry running conditions under air. Surprisingly the maximum operation temperature in dry running systems was not as high as expected. The results were compared to those obtained in the past for a-C:H coatings [1]. The investigations were completed by Raman measurements for a better understanding of the tribological behavior of the coatings. In addition, we investigated the compatibility of ta-C with different lubricants and additives and compared it to a-C:H.

[1] J. Becker et al., Thermal effects influencing stability and performance of coatings in automotive applications, Surface & Coatings Technology 284 (2015), pp. 166-172

11:00am **E3-WeM-10 Titanium Nitrides Coatings for Hard Chromium Replacement***, **Marjorie Cavarroc,*** Safran Tech, France*; B Giroire, L Teulé-Gay, D Michau, A Poulon-Quintin,* ICMCB, France

High-power impulse magnetron sputtering (HIPIMS or HiPIMS, also known as high-power pulsed magnetron sputtering, HPPMS) is a method for physical vapor deposition of thin films which is based on magnetron sputtering deposition. Very high power densities (of the order of a few $kW \cdot cm^{-2}$) are applied in very short pulses (few tens of microseconds) at low duty cycle (< 10%).

HIPIMS allows reaching a high ionization degree of the sputtered material around several tens of percent versus a few percent for conventional magnetron sputtering. The ionization and dissociation degree increase as a function of the peak cathode power. The limit is determined by the transition of the discharge from glow to arc phase. In the system we used, a continuous voltage is applied to the discharge in order to maintain continuously the plasma and increase its stability.

Work was focused on Titanium Nitride (TiN) deposition on steel coupons. After optimizing parameters for Titanium sputtering, the following parameters were chosen: 1 Pa total pressure, gas mixture 5% N2 diluted in 95% Ar. High power pulses of 20 µs @ 200 Hz were delivered with a voltage comprised between 800V and 900V and a continuous voltage comprised between 90V and 150V. In those conditions, maximum intensities around a few tens of amperes are observed.TiN coatings we obtained exhibit a cubic crystalline structure, with a low film texturation and nanometric crystallites.

Coatings are continuous and fully covering the substrate. TiN morphology and roughness are directly linked to the substrate's ones. Coatings are homogeneous in all the thickness: micro-stress, crystallite size and chemical composition are the same from the surface to the interface with the substrate.

We will present the influence of deposition parameters on the coating microstructure (crystallinity, stoichiometry, grain size and interface). Tribological properties will also be discussed.

11:20am **E3-WeM-11 Tribological Coating Solutions and Lubrication Strategies for Gas Turbine Engines***, **Pantcho Stoyanov,*** Pratt & Whitney, USA

The advancement of durable gas turbine engine components depends heavily on the development of high-performance materials that can withstand extreme environmental and contact conditions (e.g. large temperature ranges, high contact pressures, and continuous bombardment of abrasive particles, all of which degrade the physical properties). In particular, due to the large number of complex contacting and moving mechanical assemblies in the engine, the lifetime of certain structures is limited by the tribological performance of the employed materials and coatings. This talk will provide an overview of tribological solutions and lubrication strategies employed in several sections of gas turbine engines. After a general review of aircraft engine tribology, the talk will focus on tribological coatings and materials used to minimize fretting type of wear. A series of studies on the friction and wear behavior of Ni-based and Co-based superalloys at elevated temperatures will be presented. Emphasis will be placed on the correlation between the third body formation process (e.g. oxide layer formation, transferfilms) and the tribological behavior of the superalloys. This talk will conclude with the future strategies of tribological coating solutions in gas turbine engines.

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