Tribology and Mechanics of Coatings and Surfaces
Room Town & Country B - Session MC3-2-ThM

Tribology of Coatings and Surfaces for Industrial Applications II

Moderators: Nazlim Bagcivan, Schaeffler Technologies GmbH & Co. KG, Germany, **Stephan Tremmel**, University of Bayreuth, Germany, **Martin Welters**, KCS Europe GmbH, Germany

8:00am **MC3-2-ThM-1 Interactions between Coatings/Surfaces and Lubricants: How to Manage the Tribochemical Wear in ZDDP-lubricated DLC Coatings?**, ***Maria Isabel De Barros (maria-isabel.de-barros@ec-lyon.fr)***, Laboratory of Tribology and System Dynamics Ecole Centrale de Lyon, France **INVITED**

Solid and liquid lubrication play a key role in reducing energy consumption and wear behaviour of mechanical parts. Regarding the high importance of Diamond-Like-Carbon (DLC) coatings in the transportation and wind energy sectors, it is necessary to investigate their friction and wear mechanism in lubricated conditions. For these DLC films, mainly carbon and hydrogen are known to have a high chemical inertia under static conditions towards their environment. But in a lubricated sliding contact, a kind of complex "chemical reactor" is operating under severe dynamic conditions. The reason based on mainly the possibility of breaking of C-H and C-C bonds under the effect of shear, which leads to the emergence of C° free radicals or "dangling bonds" on the rubbed surface of thecoatings. A wide variety of tribochemical reactions with the lubricant molecules follow at the contact asperities, areas subjected to high pressure.

It was recently showed that very hard sp3-hybridized hydrogen-free amorphous carbon (ta-C) lubricated in the presence of the ZDDP (zinc-dialkyldithiophosphate) additive shows significant wear, associated with the absence of phosphate- type tribofilm formation. The wear is related to a preferential reactivity between the sulphur atoms released by the ZDDP and the reactive carbon atoms formed on the ta-C surface. In contrast, the softer DLCs, hydrogenated DLC and non-tetrahedral a-C, show much lower wear rates and the formation of ZDDP-derived tribofilms with higher coefficients of friction. Thus, the decomposition of ZDDP appears to be governed primarily by contact pressure at the bearing asperity scale, but the surface and subsurface sulphur transport that leads to tribofilm formation or significant wear and, results in a change in material properties at the nanoscale, depends on both stiffness and surface chemistry. In this context, the understanding of the reactivity of different DLC coatings representative of the variety of DLC found on the market and industrial applicationsin terms of H content and mechanical properties, and the interplay of mechanical and chemical contributions is of primary importance. Ultimately, itis targeting to optimize "multi-functional DLC surfaces", combining mechanical properties and surface chemistry, to better control their friction and wear performances in application.

8:40am **MC3-2-ThM-3 Coating of Plastic Parts with Tetrahedral Amorphous Carbon for Wear Protection Using Laser-Arc Technology**, *B. Gebhardt, M. Holzherr, M. Kopte, H. Pröhl, R. Seifert,* ***Marc Tobias Wenzel (Wenzel.MarcTobias@vonardenne.com)***, VON ARDENNE, Germany; *F. Kaulfuß, F. Härtwig,* Fraunhofer IWS, Germany

Laser-arc technology is a well-established method to produce hydrogen free ta-C coatings. Such coatings are known to provide outstanding wear properties and reduced friction for a variety of applications like piston rings, tappets, motorcycle chains or cutting tools.

Plastic components are ubiquitous in industry and everyday life. The use of plastic parts instead of metal components enables savings in cost, weight, and energy. Yet, coating of plastics with ta-C poses challenges due to the low hardness and limited temperature resistance of the substrates.

Injection molded plastics are shown to be suitable for ta-C coating on industrial scale using laser-arc. Reinforced and non-reinforced parts of PA12 and PEEK have been coated and investigated. The promising coating variants were transferred to a gear system. In dry operation the ta-C coating increased the lifetime by a factor of five.

In addition, we will present an up-scaled laser-arc module allowing increase of productivity and reduction of coating cost.

9:00am **MC3-2-ThM-4 Investigation of the Mechanical and Tribological Properties of TiBCN Thin Films**, ***Cennet Yıldırım (cennetyildrm@gmail.com)***, Turkish Energy, Nuclear and Mineral Research Agency – Boron Research Institute / Istanbul Technical University, Türkiye, Turkey; *Ö. Kısacık, H. Doyuran, C. Eseroğlu,* Turkish Energy, Nuclear and Mineral Research Agency – Boron Research Institute, Türkiye, Turkey; *E. Kaçar,* Hakkari University, Türkiye, Turkey

Recently, coatings with a nanocomposite structure have become increasingly significant compared to monolithic coatings, owing to their advantageous properties such as high hardness and wear resistance. Particularly, the impact of boron and carbon on coating hardness has led to a growing application of boronrich and carbide-rich nanocomposite coatings. In the scope of this study, nanocomposite films with a TiBCN structure were produced on M2 HSS using titanium and B_4C magnetron targets. To enhance adhesion on steel surfaces, Cr-CrN bond layers were deposited using the cathodic arc physical vapor deposition (CaPVD) technique, and films with different compositions were subsequently produced by varying the power of titanium and B_4C targets. Cross-sections of the produced films were examined using electron microscopy, and surface morphologies, as well as film thicknesses, were determined. Phases formed were analyzed by XRD, Raman, and FTIR, and changes in bond structures and depth profiles were identified using XPS. The hardness of the produced films was measured using the nanoindentation method, and adhesion was examined through scratch tests. Wear behaviors against alumina balls were investigated at different temperatures ranging from room temperature to 600 °C. Wear volumes were determined using optical profilometry, and wear rates and friction coefficients were calculated. The formed tribo-films were characterized using XPS analysis. It was observed that the amount of boron and carbon incorporated into the films had an influence on hardness and wear behaviors.

9:20am **MC3-2-ThM-5 Investigating the Influence of B, C, and N on the Tribo-mechanical Properties of the Chemically Complex TiSiBCN Thin Film using Design of Experiments**, *W. Tillmann,* ***Julia Urbanczyk (julia.urbanczyk@tu-dortmund.de)***, *A. Ebady, A. Thewes, G. Bräuer, N. Lopes Dias,* TU Dortmund University and TU Braunschweig University, Germany

TiSiBCN thin films show promising properties like high hardness and improved tribological behavior. Adjusting the chemical composition can tailor the properties of these thin films. To investigate this influence, usually one element is varied. However, the interplay and influence of especially the light elements B, C and N on the tribo-mechanical properties of chemical complex TiSiBCN thin films remain unclear. Therefore, a Design of Experiment using a Central Composite Design (CCD) was employed to investigate the influences of these light elements on the tribo-mechanical properties of TiSiBCN thin films. TiSiBCN with varying chemical compositions were grown in a magnetron sputtering process by adjusting the cathode power of $TiB_2/TiSi_2$ composite targets and the gas flow rates of C_2H_2 and N_2.

X-ray diffraction (XRD) analysis revealed crystalline phases based on Ti, TiN, TiC, and TiB_2, with varying degrees of crystallinity dependent on the chemical composition. Depending on the chemical composition, the TiSiBCN thin films demonstrate a broad spectrum of mechanical properties, with hardness and elastic modulus ranging from 20.2 to 39.7 GPa and from 222.3 to 405.0 GPa, respectively. Notably, the B content significantly affects the mechanical properties, with the highest hardness and elastic modulus observed at 46.0 at.–% B. In tribometer tests against Al_2O_3 under dry friction at room temperature, the TiSiBCN thin films also exhibit a broad spectrum of tribological properties, with the coefficients of friction (CoF) between 0.62 and 0.89 and wear rates between 6.4×10^{-5} and 12.2×10^{-5} mm^3/Nm. The lowest CoF of 0.62 with a wear rate of 7.7×10^{-5} mm^3/Nm is obtained for TiSiBCN with high amounts of 31.1 at.-% C and 33.5 at.–% N, while high 31.7 at.–% C and low 11.2 at.–% N contents favor the lowest wear rate of 6.4×10^{-5} mm^3/Nm with a CoF of 0.74. The tribological results reveal the significant influence of C and N on friction and wear, with TiSiBCN displaying reduced friction and wear tending to have lower hardness. Consequently, TiSiBCN thin films with either high hardness or enhanced friction and wear performance are attainable by adjusting the chemical composition.

Depending on the application requirements, the content of the light elements is decisive for the properties of TiSiCN thin films. The CCD provides insights into the intricate interplay between the chemical composition and tribo-mechanical performance of TiSiBCN. Adjusting the concentrations of B, C, and N within TiSiBCN is crucial for tailoring the tribo-mechanical behavior to meet the specific requirements of applications.

9:40am **MC3-2-ThM-6 Effect of Alloy Modification on the Wear Protection Coatings Made of Ni- and Co-Based Materials and Surface Machinability via Ultrasonic Milling Process**, ***Maraike Gräbner (maraike.graebner@tu-clausthal.de)***, Clausthal University of Technology, Institute of Welding and Machining, Germany; *M. Giese,* Federal Institute for Materials Research and Testing, Germany; *K. Treutler,* Clausthal University of Technology, Intitute of Welding and Machining, Germany; *S. Lorenz, V. Wesling,* Clausthal University of Technology, Institute of Welding and Machining, Germany; *D. Schröpfer, T. Kannengießer,* Federal Institute for Materials Research and Testing, Germany

The development of technologies for climate-neutral energy generation is an important contribution to the reduction of greenhouse gases, whereby the efficient use of material systems is a key factor. Wear-resistant coatings are required for highly efficient and economical steel components in plant, process and power plant engineering to withstand the high corrosive, tribological, thermal and mechanical stresses. Co alloys are utilized as wear protection coatings for steel components that are customized to the specific application. The research area of interest is the substitutability of Co alloys with Ni-based wear protection systems. This research endeavour considers the price and supply uncertainties as well as the escalating demands on corrosive load-bearing capacity at elevated temperatures.

The wear-resistant alloys NiMoCrSi (Colmonoy C56) and CoMnCrSi (Tribaloy T400) have been modified through various alloying additions and subsequently applied to a carbon-manganese steel S355 using the Plasma Arc Transferred Arc (PTA) welding process. The influence of the alloying additions on the microstructure as well as on the formation of the hard phases of the build-up welds is compared. The inclusion of the alloying element Nb, for instance, results in the formation of a more refined hard phase and reduces the machining force required for the C56 and T400. The incorporation of Al results in an enhancement of the cutting forces for the C56, as the hard phases exhibit more needle-like structures. Al reduces the cutting forces of the T400. The wear potential of the modified build-up welds of the C56 and T400 is also being examined In the industrial sector, there is a growing demand for functional surfaces of superior quality. Therefore, it is imperative to ensure the machinability of the wear protection layers to achieve clearly defined contours. The machinability of the build-up welds is investigated using ultrasonic milling. The optimization of the demanding machining conditions through alloy modifications of the Co- and Ni-based alloys without impairing the wear protection potential and using the ultrasonic-assisted milling process is a joint project of BAM and ISAF at Clausthal University of Technology (Fosta P1550/IGF 21959 N).

10:20am **MC3-2-ThM-8 An Alternative Thermal Route to Improve an Aluminum Alloy Mechanical and Tribological Properties through Deposition of NiP Coating**, *R. Davies,* Pontificia Universidade Católica do Parana, Brazil; *M. Soares,* Universidade Tecnologica Federal do Parana, Brazil; *F. Amorim, P. Soares, C. Neitzke,* ***Ricardo Torres (ricardo.torres@pucpr.br)***, Pontificia Universidade Católica do Parana, Brazil

This research aims to improve the main limitations of aluminum alloys: mechanical and wear resistance through the deposition of the nickel-phosphorus (NiP) coating. Due to the natural formation of a dense oxide layer on the aluminum surface, the NiP deposition process often becomes more costly. Furthermore, it is common for NiP coatings to undergo a post-heat treatment to increase hardness due to crystallization and Ni3P precipitation and further increase adhesion through the interdiffusion layer with the substrate. Finding an adequate interdiffusion temperature is challenging, as aluminum significantly decreases its mechanical properties. It would probably soften or even melt if subjected to an interdiffusion temperature of around 400 ºC. This work aimed to find a suitable process for depositing an autocatalytic nickel-phosphorus coating on AlCu4Ti aluminum alloy in an alternative thermal route using the aluminum typical aging temperature and time treatment to create an interdiffusion layer between NiP and aluminum substrate in a single step. The typical aging temperature of the alloy was investigated, i.e., 200 ºC, as well as the minimum temperature for the beginning of Ni3P precipitation, i.e., 250 ºC. The SEM and EDS analyses showed a NiP layer of about 40 µm, well adhered, homogeneous, without substrate exposure, and a high phosphorus content (≈ 10%) formed in the aluminum alloy surface. The interdiffusion and aging treatment condition at 250ºC/16h resulted in the highest hardness of both aluminum and NiP coating.

10:40am **MC3-2-ThM-9 High-Temperature Tribology of Cathodic Arc Deposited Altin Protective Coating**, ***Aljaž Drnovšek (aljaz.drnovsek@ijs.si)***, *P. Šumandl,* Jožef Stefan Institute, Slovenia; *Ž. Gostenčnik,* jožef Stefan Institute, Slovenia; *J. Kovač, M. Čekada,* Jožef Stefan Institute, Slovenia

The AlTiN coating is a popular hard coating for high-temperature applications. However, the most commonly used method for depositing this coating on cutting tools, cathodic arc evaporation, can result in a relatively rough surface due to micro-droplet emission. This roughness and embedded droplets in the coating matrix can significantly affect the coating's wear and friction properties.

Our objective was to assess the wear and friction properties of the AlTilN coating during both the running-in and steady-state periods under varying temperature conditions. To evaluate the performance of the AlTiN hard coating, we conducted tribological tests using a high-temperature ball-on-disc tribometer. The tests were conducted using an Al_2O_3 ball as a counter body at different temperatures. We varied the test duration at specific temperatures, ranging from 50 up to 140,000 cycles, to examine the effect of test length on the coating's wear and friction properties.

The results indicated that the coating experienced the highest wear during the room temperature test. Conversely, the wear during the running-in phase and steady-state friction were the lowest at 250°C. As the temperature increased, the wear rate rose, which we attributed to increased tribo-oxidation and fatigue caused by the high test lengths. Ultimately, the coating delaminated from the WC-Co substrate at the highest temperature. The asperities on the coating surface due to micro-droplets played a significant role in friction and wear behaviour, as they were a primary source of wear particles and the first spots of oxidation on the coating. We show that the running-in phase depends mainly on the surface condition (asperities density) at room temperature tests. In contrast, at high temperatures, the formation of a stable tribo-oxide layer in the wear track elongates this period.

We conducted detailed 3D profilometry, SEM and FIB analyses on numerous samples to determine the wear mechanisms at different stages of high-temperature wear. In addition, we conducted secondary-ion mass spectrometry (SIMS) and X-ray photoelectron spectroscopy studies to evaluate the extent of oxidation and identify different species present in the oxide layer.

The combination of these analyses allowed us to gain a comprehensive understanding of the wear mechanisms and behaviour of the AlTiN coating at high temperatures. We could identify the dominant wear mechanisms and how they evolved over test length by analysing the samples at different wear stages.

11:00am **MC3-2-ThM-10 Nanomechanical and Tribological Properties of Conversion Coatings for Railway Rolling Bearing Applications**, ***Esteban Broitman (esteban.daniel.broitman@skf.com)***, *A. Ruellan,* SKF - Research and Technology Development, Netherlands; *R. Meeuwenoord,* SKF Research and Technology Development, Netherlands; *D. Nijboer, V. Brizmer,* SKF - Research and Technology Development, Netherlands

In this study, different conversion coatings have been compared in terms of friction performance based on a single-contact oil-lubricated tribometer and on a grease-lubricated double row bearing friction test rig ran under relevant operating conditions for a railway application. Conversion layers like zinc-calcium-phosphate, manganese-phosphate and tribological black-oxide deposited onto AISI 52100 bearing steel have been compared to uncoated steel in terms of nanomechanical and tribological properties.

Our results demonstrate that the optimum tribological black-oxide conversion layer can reduce friction by more than 25% on rolling/sliding raceway contacts (ball-on-disk) and up to 80% on the sliding flange contacts (roller-on-disk), which share a significant portion of power losses in roller bearing units. Results at the bearing level demonstrate that the same optimum conversion layer can reduce the running torque by approximately 30% compared to the current products both at low and intermediate speeds relevant to intercity trains.

Reference

Broitman, E.; Ruellan, A.; Meeuwenoord, R.; Nijboer, D.; Brizmer, V. *Comparison of Various Conversion Layers for Improved Friction Performance of Railway Wheel-End Bearings*. Coatings **13** (2023) 1980.

11:20am **MC3-2-ThM-11 Impact of Fiber Orientation and Oxidation on Wear Performance of Carbon-Carbon Composites***, Hamid Mohseni* ***(Hamid.Mohseni@prattwhitney.com)****, X. Fang, L. Dawag, C. Winder,* Pratt & Whitney, USA

Carbonaceous matrix reinforced with continuous or discontinuous carbon-based fibers comprises the building block of carbon-carbon (C/C) composites, one of the prominent and versatile aerospace materials. The range of constituents in C/C composites, such as carbonaceous matrix, oxidation resistant impregnation, fiber types, size, volume, orientation, weaving pattern, lay-ups, and densification method, potentially allows to achieve a unique combination of properties. This design flexibility presents numerous opportunities to achieve application-specific and novel wear resistant composites. In this investigation, two class of C/C composites each with three different fiber orientations in non-oxidized and pre-oxidized (to 5 and 10 % weight loss) condition were subjected to a reciprocating sliding wear test against Inconel 718 plates at 375°C. Whereas the average wear depth was in the 10^{-2} mm range for all the samples regardless of non-oxidized or oxidized conditions, the samples with fiber orientation perpendicular to the reciprocal sliding exhibited almost 75% higher wear. Microstructural investigation of worn and unworn samples using SEM/EDS revealed severe cracking at the interface of fibers and carbonaceous matrix that resulted in fiber pull-out and evolution of wear debris. Raman spectroscopy revealed higher D/G band intensity for the worn area that indicated higher concentration of defects induced by reciprocating sliding at the interface of perpendicular fibers and carbonaceous matrix. Presence of pre-existing porosities was found to be the precursor for wear-induced cracking and formation of wear debris. Furthermore, carbonaceous solid-lubricant transfer film was discovered on the Inconel 718 plate that justified the significantly lower average wear depth (10^{-3} - 10^{-4} mm) compared to the corresponding C/C composite samples.

12:00pm **MC3-2-ThM-13 Cr Doping Modification for Tribological Behavior of Cr/a-C Multilayer Coatings Against PEEK Under Diverse Operational Conditions***, Xiaohui Zhou* ***(zhouxiaohui@nimte.ac.cn)****,* Key Laboratory of Marine Materials and Related Technologies, Zhejiang Key Laboratory of Marine Materials and Protective Technologies, Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, China

Considering the increasing demands for wear-resistant materials used for various frictions with dynamic sealing parts, we employed hybrid magnetron sputtering technology to fabricate Cr/a-C multilayered coatings with and without Cr-doping modification for comparison. The tribological behaviors of coatings when paired with Polyether ether ketone (PEEK) balls was focused under different friction environments evolving atmosphere, NaCl solution, olyalphaolefin (PAO) oil, and water-in-oil (W/O). The results demonstrated that the tribological properties of all friction pairs was strongly influenced by the surrounding environment. In the atmosphere and NaCl solution, the addition of Cr promoted the formation of a-C transfer film, thereby yielding the stable and low friction characteristics. However, the dominant factor contributing to the tribological performance shifted from the coatings themselves to the PAO oil film with PAO medium. In the case of W/O solution, both the facile reactivity of Cr and the intrinsic instability of W/O mixture accelerated the existence of Cr_2O_3, which caused the more severe wear. The current observations not only identified the tribological failure mechanism of Cr/GLC coatings with and without Cr doping modifications in conjunction with PEEK counterparts, but also addressed the importance of designing and fabrication of adaptive lubricant coatings for harsh multi-environment applications.

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