Tribology and Mechanics of Coatings and Surfaces
Room Town & Country B - Session MC3-1-WeA

Tribology of Coatings and Surfaces for Industrial Applications I

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

2:00pm **MC3-1-WeA-1 Tribological Coatings to meet Future Requirements for Green Mobility**, ***Steffen Hoppe (steffen.hoppe@tenneco.com)***, Tenneco Powertrain, Product & Technology, Germany **INVITED**

The global transportation industry is taking on the challenge of decarbonizing propulsion with the goal of achieving climate-neutral mobility. Hydrogen-powered internal combustion engines (H_2-ICEs) are the mix of applicable and complementary technology solutions. This technology can drive decarbonization on a broad scale, especially in commercial truck, off-highway and industrial applications. Non-fossil fuels like ammonia, methanol or e-fuels are required to achieve net-zero-CO2 emissions in marine and aviation markets.

The introduction of non-fossil fuels has a significant impact on the tribology systems in ICEs. Due to the significant differences in physical and chemical properties of hydrogen, ammonia, and methanol compared to gasoline and diesel fuel, the combustion strategies need to be adapted to these fuels. Advanced coating solutions are required for ICEs components to address the impact on the tribological systems caused by higher combustion temperatures, oil dilution or deterioration, and water entrapment.

This paper will show how the critical tribological system of piston rings can be optimized by developing high performance coatings. Hydrogen free DLC coatings, advanced thermal spray coatings and new electrochemical coatings are applied to achieve robust tribological systems in decarbonized propulsion systems.

2:40pm **MC3-1-WeA-3 Current-Induced Friction and Graphitization Effects in Amorphous and Tetrahedral Amorphous Carbon Coatings on M2 Steel: An Electro-Tribological Investigation**, *A. Khodadadi Behtash,* ***Ahmet T. Alpas (aalpas@uwindsor.ca)***, University of Windsor, Canada

In electric vehicles, protecting bearings from shaft voltages and bearing currents is key to avoiding premature wear and failure. Diamond-like carbon (DLC) coatings, with their low friction and insulating properties, could extend bearing life and reliability. This study assesses how electrical current affects the frictional behaviour of M2 steel coated with non-hydrogenated diamond-like carbon (a-C) and tetrahedral amorphous carbon (ta-C), by comparing their coefficients of friction (COF) against an AISI 52100 steel counterface under varying currents but the same loading conditions using a ball-on-disk tribometer. The uncoated M2 steel exhibited COF values ranging from 0.55 to 0.62, suggesting frictional instability and a tendency towards oxidation with sliding under electrical currents (Figure 1). The a-C coatings maintained a stable coefficient of friction under 0.15 up to currents of 1200 mA. In contrast, the ta-C coatings showed variable COFs, starting at 0.20 and rising above 0.60, indicating less stability under electrical currents. Micro-Raman analyses revealed graphene formation within the wear tracks of a-C samples upon exposure to induced current (Figure 2a). This current-induced graphitization within the wear tracks correlates with the a-C coating's low and stable COF. In contrast, ta-C coatings, with a higher sp^3 content, underwent less graphitization and more oxidation (Figure 2b) at the steel interface when subjected to the same electrical current. The increase in D peak intensity within wear tracks of a-C samples at higher currents suggested a rise in defect density in graphene layers formed. The mechanisms underlying these observations, including the interplay between graphitization and electrical current, as well as their implications for electro-tribological systems, will be discussed in the presentation.

3:00pm **MC3-1-WeA-4 Compositionally Graded MoS_2-WC Spray Coatings for Robust Tribological Protection in Low Viscosity Fuels**, ***Euan Cairns (euancairns@my.unt.edu)***, *J. Decker,* University of North Texas, USA*; S. Dixit,* Plasma Technology Inc., USA*; S. Berkebile,* Army Research Laboratory, USA*; D. Berman, S. Aouadi, A. Voevodin,* University of North Texas, USA

Increased usage of low carbon emission fuels, such as ethanol and dodecane, are driving a critical need for advanced lubricious materials to extend the wear life of fuel pump components. Solid lubricants are traditionally employed in applications where liquid lubrication is insufficient if not impossible. We demonstrated that molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2) films spray-coated onto 52100 steel and WC-17Co surfaces decreased friction and wear during sliding in hydrocarbon fuels. Solid lubricant coatings were substantially more robust while sliding in non-polar dodecane fuel, where friction coefficients of less than 0.1 were maintained for thousands of sliding cycles. Meanwhile, in polar ethanol fuel, low friction was only kept for a few hundred cycles before sharp failure of the coatings, due to oxidation and removal of the lubricant from the wear track.

In this study, we propose to further enhance the wear resistance of crucial components in fuel pumps via designing compositionally graded MoS_2-WC coatings. The microstructure and wear data were evaluated using scanning electron microscopy (SEM) equipped with an energy dispersive spectrometer (EDS). Analysis of worn surfaces was performed using optical profilometry and Raman spectroscopy to analyze the chemical evolution inside the wear track across multiple fuel chemistries. Insights gained from this study offer valuable information for the development of robust lubrication solutions in the realm of low carbon emission fuel applications.

3:20pm **MC3-1-WeA-5 Tribological Behavior of DLC Coatings: Wear Map of Oil Lubricated Contacts in a Three-Pins-on-Disc Test Configuration***, J. Keraudy, N. Manninen, F. Rovere,* ***Klaus Boebel (Klaus.Boebel@oerlikon.com)***, Oerlikon Surface Solutions AG, Liechtenstein

Diamond-like carbon (DLC) coatings have emerged as a promising coating solution able to combine high wear resistance and low friction coefficient. In fact DLC coatings comprise a family of different carbon based coatings which can show a broad range of properties based on the fraction of sp3/sp2 bonds and also on the amount of incorporated hydrogen or metal dopants.

In the present study different DLC coating variants were tested regarding their tribological performance.The coatings were tested in three pin-on-disc configuration under additive oil (ZDDP) lubricated conditions. Different pressure x velocity (P.V) conditions were tested during endurance tests in order to identify the coatings performance over a broad range of P.V conditions. The lubrication regimes were identified by Stribeck curves in order to determine the lubrication regimes for the different test parameters. The coatings were analyzed by scanning electron microscopy (SEM), profilometry and optical microscopy after the tribological tests, in order to evaluate the wear mechanisms. The coatings were characterized regarding their topography and morphology (by means of SEM analysis), roughness (by profilometry analysis) and hardness (by nanoindentation). The coatings chemical properties, roughness and hardness are strongly correlated with the tribological performance.

3:40pm **MC3-1-WeA-6 Structural and Tribo-mechanical Properties of AlCrVYON Thin Films with Varying O Contents Sputtered from Either AlCrVY or AlCrY and V Targets***, W. Tillmann,* ***Finn Ontrup (finn.ontrup@tu-dortmund.de)***, *D. Aubry,* TU Dortmund University, Germany*; E. Schneider, M. Paulus, C. Sternemann,* Fakultät Physik/DELTA, TU Dortmund University, Germany*; N. Lopes Dias,* TU Dortmund University, Germany

The incorporation of Y and V into AlCrN has previously proven effective in enhancing oxidation resistance and tribological properties at elevated temperatures. As this improvement stems from the oxide formation of these elements, depositing O-containing AlCrVYN presents a promising approach for directly synthesizing thin films with enhanced tribo-mechanical properties for high-temperature applications. Therefore, AlCrVYON with varying O contents were deposited using a hybrid dcMS/HiPIMS process in two distinct approaches. In a reactive process, AlCrVYON was either sputtered from two AlCrVY targets or co-sputtered from AlCrY and V targets. For both configurations, the O_2 flow rate was varied from 0 to 20 sccm.

Sputtering from AlCrY+V targets results in higher O contents from 1.4 to 31.3 at.–% compared to the other target setup which achieves up to 20.7 at.–%. High-resolution x-ray diffraction using synchrotron radiation reveals a cubic CrN phase for all thin films, independent of the O content and target configuration. Nanoindentation tests show that the hardness stays at a high level above 40 GPa for an O content of up to 6.5 at.–% for AlCrVYON sputtered from AlCrVY targets and up to 14.7 at.–% for those sputtered from AlCrY+V targets. However, for higher O concentrations the hardness for both AlCrVYON variants decreases. Due to a constant decrease in the elastic modulus with an increasing amount of O, a maximum in the H/E ratio is observed for the aforementioned O contents. Furthermore, the tribological properties were analyzed using a high-temperature tribometer. No significant reduction of the coefficient of friction is noted at room temperature and only a slight improvement is visible in the higher temperature range for all AlCrVYON thin films, except the ones with the maximum *H*/*E* ratio. Annealing the thin films deposited from two AlCrVY targets for 2 h at 500, 600 and 700 °C demonstrates a high oxidation resistance for all AlCrVYON of at least 6.5 at.-% O, as no decrease in hardness, nor an increase in O content could be identified post-annealing. However, the thin films sputtered from AlCrY+V targets perform different in this regard, as the hardness decreases for all thin films after annealing at 600 °C.

In summary, the AlCrY+V target configuration produces AlCrVYON with higher O contents, resulting in a significantly different oxidation resistance. Other than that, both configurations show similar trends, demonstrating the advantage of adding small amounts of O into AlCrVYN. Thus resulting in a maximum of the *H*/*E* ratio for explicit O contents, depending on the target configuration.

4:00pm **MC3-1-WeA-7 Development and Process Optimization of Suspension Plasma Spray Coating to Enhance the Frictional Properties and Wear Resistance**, ***Yong-Jin Kang (free83@kims.re.kr)***, *Y. Yoo, S. Lee, D. Kim,* Korea Institute of Materials Science, Republic of Korea

Chromium oxide (Cr_2O_3) coating produced by the atmospheric plasma spray (APS) process is widely used in industrial fields such as anilox rolls, doctor blades in the paper-making industry, pump sleeves, and break discs that require resistance to sliding wear and corrosion. However, due to its low mechanical properties and high surface roughness and porosity, the development of alternative coating processes such as suspension plasma processes(SPS) is required. Accordingly, in this study, we developed a chromium oxide coating with low surface roughness, high hardness, and excellent wear resistance through a suspension plasma spray (SPS) process. By optimizing the stand-off distance, feedstock powder size, and power during SPS process, dense Cr_2O_3 coating with a porosity less than 2% was achievable. Microstructures and mechanical properties of as coated samples were characterized by SEM, XRD, surface profiler. Then, tribological properties, such as friction coefficient and wear rate, were evaluated by ball on disk test. The wear resistance of Cr_2O_3 coatings via SPS and APS processes was compared with their intrinsic microstructure and mechanical properties.

4:20pm **MC3-1-WeA-8 Excellent Tribological and Anticorrosive Properties of Nanocomposite Coating Based on Polyvinyl Alcohol/NiFe LDH/Tannic Acid**, ***Dieter Rahmadiawan (n18127046@gs.ncku.edu.tw)***, National Cheng Kung University (NCKU), Taiwan, Indonesia; *S. Chen Shi,* National Cheng Kung University (NCKU), Taiwan

This study investigates the effects of incorporating tannic acid into a polyvinyl alcohol (PVA)/MXene film. The composite was characterized for its mechanical, corrosion resistance, and tribological properties. The addition of tannic acid was found to enhance the mechanical strength of the composite, attributed to its crosslinking capabilities and interactions with the MXene nanosheets. Corrosion resistance was significantly improved, as tannic acid acted as a corrosion inhibitor, forming a protective layer on the composite surface. Tribological tests revealed reduced wear rates and improved frictional behavior, indicating the effectiveness of tannic acid in enhancing the lubricating properties of the PVA/MXene system. The comprehensive analysis presented in this study underscores the potential of PVA/MXene/Tannic Acid composites for applications demanding superior mechanical performance, corrosion resistance, and tribological efficiency.

4:40pm **MC3-1-WeA-9 Effects of Various Al/Cr Composition and Deposition Conditions on Surface Properties, Mechanical and Tribological Properties of AlCrN Coatings**, ***SHINICHI TANIFUJI (tanifuji.shinichi@kobelco.com)***, *M. NAKAMURA, R. TAKEI, S. KUJIME, T. TAKAHASHI,* Kobe Steel, Ltd., Japan

The environment in which tools and molds are used in production is becoming harder and harder year by year. Therefore, coatings applied by physical vapor deposition are required to have high hardness and oxidation resistance in order to extend the lifetime of tools and dies. Typical examples of coatings with such properties are AlTiN and AlCrN coatings. The oxidation resistance of coatings is attributed to the Al content of the coating, and it is known that the higher the Al content, the higher the oxidation resistance. On the other hand, the hardness of the coatings differs, with AlTiN and AlCrN coatings showing maximum hardness at 67 at% and 77 at% Al content, respectively. It is known that when the Al content in both coatings exceeds these levels, a decrease in hardness occurs due to the precipitation of soft AlN in the coating.

At last year's conference, KOBELCO introduced its new Cathodic arc evaporation system, AIP-iX. Using the new μ-Arc evaporation source installed in the system, KOBELCO reported on the surface properties of AlCrN coating with 75% Al content as observed by scanning electron microscopy, the coating hardness as measured by nanoindentation test, and the crystal structure of the coating by X-ray diffraction method. The results of the crystal structure of the coatings were also reported by the X-ray diffraction method. The results of the nanoindentation test and the crystal structure of the coating by X-ray diffraction are also reported. The surface smoothness of the coating is superior to that of the conventional cathodic arc deposition coating, and the cubic crystal structure is confirmed, indicating that a hard coating can be formed.

On the other hand, one of the main characteristics of μ-Arc is that it has fewer surface macro-particles than conventional coatings, but the effect of the surface properties of the coating on the tribological properties of the coating has not yet been clarified. In order to meet the needs of industrial applications, it is important to clarify the relationship between tool and die performance and the properties of the coatings. In this report, we describe the results of our studies of AlCrN coatings prepared under various compositions and deposition conditions, and the effects of these conditions on surface properties, mechanical and tribological properties, as well as the relationship of these coatings to tool and die performance.

5:00pm **MC3-1-WeA-10 Effect of Multilayer Architecture on Mechanical Properties and Cutting Performance of AlTiBN/AlCrBN Coatings**, ***Chung-En Chang (abcd0214milk@gmail.com)***, *Y. Chang,* National Formosa University, Taiwan

Ti-6Al-4V alloy is a currently popular material known for its high fracture toughness and hardness, making it a preferred choice for industries like aerospace and automotive due to its excellent processing properties. However, during the machining of Ti-6Al-4V, substantial heat is generated due to its relatively low elastic modulus and thermal conductivity. This excess heat accelerates tool wear and can lead to tool failure. In recent years, AlTiN and AlCrN hard coatings have become widely used for cutting tools. Machining difficult-to-cut materials has become a trend, and to enhance the properties of the coatings for processing these materials. Appropriate amounts of Boron (B) elements can be added to improve hardness, toughness, thermal stability, and wear resistance of the AlTiN and AlCrN coatings. The addition of Boron (B) atoms promotes the formation of a nano-composite structure, which includes AlTiBN and AlCrBN solid solutions, surrounded by an amorphous BN phase. In this study, the influence of AlTiBN/AlCrBN coatings with different multilayer architectures on the wear behavior and cutting performance of the carbide cutting tools was investigated in machining of Ti alloys. The multilayer thickness and alloy content of the deposited coating were correlated with the evaporation rate of cathode materials. Glancing angle X-ray diffraction was used to characterize the microstructure and phase identification of the films. The microstructure of the deposited coatings was characterized by using a field emission scanning electron microscope (FESEM) and a high-resolution transmission electron microscope (HRTEM) equipped with energy-dispersive X-ray spectroscopy (EDS). A Rockwell indentation tester and a scratch tester were used to evaluate the adhesion strength between the coating and the substrate. The coating hardness and the elastic modulus were measured by nanoindentation. The design of multilayered AlTiBN/AlCrBN coatings is anticipated to inhibit the grain growth, and leads to grain refinement effect, which expected to increase the mechanical properties and cutting performance of coatings.

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