Tribology and Mechanics of Coatings and Surfaces
Room Town & Country C - Session MC3-2-WeA

Tribology of Coatings and Surfaces for Industrial Applications II

Moderator: Dominic Stangier, Oerlikon Balzers Coating Germany GmbH, Germany

2:00pm **MC3-2-WeA-1 Effect of Electrical Current Application on the Tribological Properties of Soft and Hard ta-C Coatings on HSS Substrates***, Amir Masoud Khodadadi Behtash,* University of Windsor, Canada*; Woo-Jin Choi, Jongkuk Kim,* Korea Institute of Materials Science, Korea (Democratic People's Republic of)*; **Ahmet T. Alpas [aalpas@uwindsor.ca]**,* University of Windsor, Canada

As electric vehicles (EVs) become more widespread, managing electrical current effects on friction and wear in moving components is crucial for enhancing durability and efficiency. Diamond-like carbon (DLC) coatings, known for their low friction and insulating properties, show potential in these applications. This study investigates the tribological characteristics of two types of tetrahedral amorphous carbon (ta-C) coatings -soft (51 GPa) and hard (69 GPa)- on high-speed steel (HSS) substrates under the electrical current application. The soft ta-C coating was deposited at 150 °C, while the hard ta-C coating was deposited at room temperature with a -100 V substrate bias, both using filtered cathodic vacuum arc (FCVA) with a Ti interlayer deposited by magnetron sputtering. The average surface roughness (R_a) values were 17.1 ± 0.3 nm for the soft ta-C coating and 20.3 ± 0.9 nm for the hard ta-C coating. Friction and wear resistance were evaluated using a modified ball-on-disk tribometer with an AISI 52100 steel counterface, under electrical currents from 0 to 1500 mA. Under non-electrified conditions, both hard and soft ta-C coatings displayed low wear rates of 4.5 and 5.27 × 10^{-7} mm^3/m.N, respectively. With applied electrical currents, however, notable differences emerged. The hard ta-C coating demonstrated coefficient of friction (COF) values ranging from 0.11 to 0.44 under electrical currents between 0 and 500 mA. In comparison, the soft ta-C coating exhibited lower COF values, ranging from 0.11 to 0.29, across a broader current range of up to 1500 mA. The wear rate of the hard ta-C coating increased significantly to 1.6 × 10^{-5} mm^3/m·N at 300 mA, whereas the soft ta-C coating maintained a much lower wear rate of 1.05 × 10^{-6} mm^3/m·N at the same current and reached only 6.17 × 10^{-6} mm^3/m·N at 1200 mA. These results indicate that the electrical current carrying tribological performance of ta-C coatings on HSS substrates can be tailored by heat treatment to enhance their response. Raman spectroscopy and electron microscopy are utilized to delineate the mechanisms underlying these structural changes and will be presented at the conference.

2:20pm **MC3-2-WeA-2 Impact of Electrification on the Tribological Performance of Metal Doped a-C Coatings***, **Miguel Rubira Danelon [miguel.danelon@usp.br]**, Newton Kiyoshi Fukumasu, Roberto Martins de Souza, André Paulo Tschiptschin,* University of São Paulo, Brazil

Amorphous carbon (a-C) coatings, composed of sp^2 and sp^3 hybridizations of carbon, may enhance the surface properties of materials. These coatings are commonly used as solid lubricants, improving tribological performance by forming a tribolayer that reduces the coefficient of friction by graphitization. In many systems, a-C coatings offer the potential to lower frictional energy losses and wear, improving efficiency and durability. Specific phenomena are anticipated for electric vehicles (EVs), since, from one side, electric current can affect surface wear in electrified systems by promoting accelerated oxidation or arc formation. On the other hand, electrical current flowing through an a-C coated contact can induce carbon crystallization, benefiting EV engine performance. Pure a-C lacks the conductivity needed for this crystallization effect, which can be improved by doping the a-C with metallic elements. Using copper or nickel as dopants can reduce electrical resistivity and catalyze carbon nanostructure formation, further reducing friction. This study investigates the tribological behavior of metal-doped a-C coatings under electrified ball-on-plane tests. Me:a-C coatings were deposited on glass substrates using pulsed DC balanced magnetron sputtering. Ni and Cu were used as dopants, with different concentrations, to improve electrical conductivity. Tribological tests involved a ball-on-plane setup with a 10 N normal load, 5 mm stroke, and 0.28 Hz frequency, applying 30 V in four current flow modes: current flowing from ball to plane, from plane to ball, no current, and intermittent on-off cycling every minute. The coatings' microstructure and composition were analyzed using Scanning Electron Microscopy with Energy-dispersive X-ray spectroscopy (EDS). Raman spectroscopy was used to evaluate carbon structure, while instrumented indentation tests allowed the characterization of mechanical properties. Results showed that doping a-C is essential to promote a direct response to electrical stimulation. Increasing the metal content of the amorphous-carbon coating increases the conductivity but decreases the wear resistance, due to a higher metal content. In contrast, reducing the metal content leads to insufficient conductivity, hindering the electrical current's effect on carbon graphitization. Current flow promoted friction coefficient variations, which were not influenced by thermal effect, since no significant temperature increase was observed. Instead, COF variations were related to instant changes in current flow during contact. The wear resistance has also been influenced by the current, with different outcomes depending on the current direction.

2:40pm **MC3-2-WeA-3 Graphene-Related Materials: Bridging Fundamental Tribology and Industrial Applications Across Multifarious Environments***, **Mingi Choi [ds602847@gmail.com]**, Ji-Woong Jang,* Pusan National University, Republic of Korea*; Anirudha Sumant,* Argonne National Laboratory, USA, India*; Ivan Vlassiouk,* Oak Ridge National Laboratory, USA, Russian Federation*; Jae-Il Kim,* Korea Institute of Materials Science, Republic of Korea*; Young-Jun Jang,* Korea Institute of Material Science, Republic of Korea*; Songkil Kim,* Pusan National University, Republic of Korea

Solid lubricants play a crucial role as alternatives to liquid lubricants in extreme environments and as solutions for enhancing mechanical system performance under ambient conditions at the macroscale. Among these, graphene, a representative two-dimensional nanomaterial, has attracted significant attention due to its exceptional nanoscale tribological properties. However, its application as a solid lubricant for macroscale industrial systems remains a challenge. Recent studies have highlighted that tailoring graphene's properties through functionalization, oxidation, can significantly enhance its performance. This underscores the strong correlation between the tribological behavior of graphene-based materials and their elemental and compositional properties.

In this work, we demonstrate the versatility of graphene-related materials as solid lubricants by engineering their structural and compositional properties. Under ambient conditions, we developed a heterogeneous structure of graphene oxide layered on pristine graphene, achieving over 100 times greater durability (>10 km) compared to pristine graphene (~100 m) while maintaining its low COF. In contrast, under humidity- and oxygen-free environments, pure graphene oxide exhibited a super low coefficient of friction (COF). Remarkably, in an argon environment, the COF approached the superlubric regime (COF < 0.01), while in vacuum, the COF gradually increased to 0.07. By unveiling the intrinsic lubrication mechanisms of graphene oxide in these environments, we highlight the potential of graphene-based materials as solid lubricants for diverse engineering applications, bridging fundamental understanding with industrial relevance.

4:00pm **MC3-2-WeA-7 Structure and Tribo-Mechanical Properties of Si-Containing ta–C Thin Films Grown by Cathodic Arc Evaporation***, **Nelson Filipe Lopes Dias [filipe.dias@tu-dortmund.de]**,* TU Dortmund University, Germany*; Domic Stangier,* Oerlikon Balzers Coating Germany GmbH, Germany*; Julia Urbanczyk, Gabriel Brune, Jörg Debus, Wolfgang Tillmann,* TU Dortmund University, Germany

Among various types of diamond-like carbon, tetrahedral amorphous carbon (ta-C) thin films have attracted considerable attention due to their high hardness of up to 70 GPa, low friction, and high wear resistance. This property profile makes ta-C a particularly promising thin film system with broader application potential compared to the well-established hydrogen-free amorphous carbon (a-C) and hydrogenated amorphous carbon (a-C:H). For both a-C and a-C:H, thin film properties are typically tailored by incorporating modification elements to meet specific application requirements. In this context, silicon (Si) is widely used to improve the thermal stability and reduce friction under dry sliding conditions. As a result, the modification of ta-C by Si lies within the focus of recent research to tailor its thin film properties.

A key challenge in the synthesis of ta-C:Si is the precise incorporation of low Si concentrations into the thin film without significantly reducing the high fraction of sp^3-coordinated carbon (C) bonds, which would compromise the superior hardness of ta-C. To overcome this, Si-containing graphite with 2.5 and 5 at.% Si as well as pure graphite were used as cathode materials and were mounted on an array of cathodic arc evaporators arranged vertically. By positioning AISI M2 steel substrates at different heights in front of the evaporators, Si-containing ta-C thin films with low Si concentrations were successfully deposited.

This vertical cathode arrangement allows for tailoring the Si content gradually decreases from top to bottom and for reaching a Si-free ta-C thin film at the lowest height. The hardness of ta-C:Si decreases with increasing Si content but remains above 40 GPa even at the highest Si concentrations. Notably, a high hardness exceeding 60 GPa is achieved at the lowest Si content. To correlate the mechanical properties with the structural characteristics, Raman spectroscopy with UV laser excitation was performed for precise structural analysis of the sp^3-coordinated C bonds. Additionally, tribometer tests were conducted to evaluate the influence of Si content on the friction and wear behavior at room temperature. The results highlight the potential of depositing low Si-containing ta-C:Si thin films with superior tribo-mechanical properties using cathodic arc evaporation and low Si-containing graphite cathode materials.

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