Tribology and Mechanical Behavior of Coatings and Engineered Surfaces
Room Royal Palm 4-6 - Session E1-2

Friction, Wear, Lubrication Effects, and Modeling

Moderators: Albano Cavaleiro, University of Coimbra, Carsten Gachot, Vienna University of Technology, Nazlim Bagcivan, Schaeffler Technologies GmbH & Co. KG, Germany

2:10pm **E1-2-3 Physical Mechanisms for Nanoscale Friction of a-C:H/D Thin Films**, *F Echeverrigaray, S de Mello,* UCS, Brazil*; F Alvarez,* UNICAMP, Brazil*; A Michels, **Carlos Figueroa**,* UCS, Brazil

The friction forces are originated in energy dissipation events owing to the lost work of non-conservative forces. The surface structure of hydrogenated/deuterated amorphous carbon thin films in air, which plays an important role in nanoscale friction, is constituted by hydrogen and/or deuterium terminated bonds and physisorbed oxygen, nitrogen, and water molecules. In spite of friction models were well established to explain the tribological behaviour of carbon-based thin films in different atmospheres, the fundamental physical understandings of these phenomena remain open. In this work, we report the friction behaviour of a diamond spherical dome sliding on different amorphous carbon thin films containing different amounts of hydrogen and/or deuterium inspecting at the nanoscale indentation. Three different experimental setups are reported. Firstly, for samples where hydrogen was replaced by deuterium in the thin film bulk, the friction coefficient decreases with the increasing of deuterium content. Secondly, for samples where hydrogen content is increased at the surface, the friction coefficient decreases with the increasing of the ratio H/C at the surface. Thirdly, for samples where the ratio H/C was fixed, the friction coefficient increases with the increasing of the relative humidity, effect that can be tuned by an external electrical field. Finally, we discuss three different physical mechanisms describing these experimental results: dissipation effects associated with phonon coupling, van der Waals forces, and orientation of water dipoles determining the friction behaviour of a-C:H/D for the above described experimental setups.

2:30pm **E1-2-4 Relocation Profilometry of Micro-tribology Experiments of Uncoated and DLC Coated Steel***, M Gee, J Nunn, L Crocker,* National Physical Laboratory, UK*; K Holmberg,* VTT Technical Research Centre of Finland Ltd, Finland*; L Li,* City University of Hong Kong, Hong Kong*; G Stachowiak,* Curtin University, Australia*; C Gachot,* Vienna University of Technology, Austria*; **Tony Fry**,* National Physical Laboratory, UK

Relocation profilometry was used to evaluate the damage that occurred in micro-tribology experiments on a range of DLC coated and uncoated steel samples. Three roughness conditions were tested ranging from a ground surface to a smooth surface for both the coated and uncoated materials. The effect of varying orientation of the micro-tribology experiments with the directionality of the finished surfaces. The micro-tribology experiments were carried out using single pass scratch tests using a diamond indenters. The same areas were examined with an Olympus Lext confocal microscope which gave image and height maps from each area examined. The same areas were examined before and after scratching, and the resulting pairs of height maps registered and subtracted using Image J. The true volume of damage was thereby calculated for all experiments. Friction measurements were also made. This enabled the energy dissipated in the damage formation to be calculated.

Little effect of orientation on the damage was observed. What was quite surprising was that there was also no effect of roughness on the damage that was observed.

2:50pm **E1-2-5 Microstructural Design of Self-lubricating Laser Claddings for use in High Temperature Sliding Applications***, **Carsten Gachot**,* TU Wien, Austria*; M Rodríguez Ripoll, H Torres,* AC²T Research GmbH, Austria*; B Prakash,* Lulea University of Technology, Sweden

Nickel-based self-lubricating claddings with the addition of Ag and MoS_2 were prepared by means of laser cladding on stainless steel substrates, aiming at their implementation in metal forming applications involving demanding tribological conditions at high temperature. The novelty of our approach relies in the addition of MoS_2 with the aim achieve a uniform silver distribution within the resulting cladding by means of an encapsulation mechanism, preventing it from floating to the surface during the deposition process and being subsequently lost during surface preparation. The role of Ag and MoS_2 concentration on the encapsulation process is discussed in terms of phase composition and resulting microstructures. The tribological behaviour of the resulting laser claddings was evaluated at high temperature under unidirectional sliding. The encapsulation of Ag led to outstanding tribological properties while keeping the amount of Ag used at lower concentrations, thus increasing the economic feasibility of the claddings. The improvement in terms of both friction and wear was observed for the self-lubricating claddings compared to the reference alloy, making them good candidates for use in high temperature applications such as metal forming.

3:10pm **E1-2-6 Fretting Wear Behavior of Duplex PEO-Chameleon Coating on an Al Alloy***, **Andrey A. Voevodin**,* University of North Texas, USA*; Y Liu,* University of Leeds, UK*; A Yerokhin,* University of Manchester, UK*; A Korenyi-Both,* Tribologix, Inc., USA*; M Lin,* University of Manchester, UK*; J Zabinski,* Army Research Laboratory, USA*; A Matthews,* University of Manchester, UK*; T Liskiewicz,* University of Leeds, UK

Plasma electrolytic oxidation (PEO) is an attractive technology for improving wear resistance and environmental protection of aluminum alloys. PEO results in the hard alumina based ceramic coatings of up to 100-150 micrometer thickness which are well adhered to the surface with morphology graded from a dense region near the coating-substrate interface to a porous outer region [1]. Such properties may provide PEO as 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, however the relevant work is scarce. This study investigates the fretting wear behavior and adaptive mechanisms for the PEO produced Al_2O_3 surface of about 11-12 GPa hardness with a top layer of an MoS_2-Sb_2O_3-C chameleon solid lubricating coating, which is named such for its ability to self-adapt tribological contact surface and provide friction and wear reduction in variable humidity [2]. Coupons of AA 6082 alloy were coated by the PEO process and then were over-coated by a burnishing process with a MoS_2-Sb_2O_3-C chameleon coating to prepare such duplex coating combination. The coated surfaces were then subjected to over 10,000 cycles of fretting wear against steel and alumina balls with variable amplitude (0 to 100 micrometers) and loads (10-100 N) in both humid air and in dry nitrogen, including cycled (air/nitrogen) environment conditions. The tests demonstrated low friction coefficients, considerable reduction in critical amplitude for the stick-slip transition, and self-adaptive tribological behavior in the cycled environment tests. Friction coefficients of the order of 0.10 to 0.15 in humid air and 0.06 to 0.09 in dry nitrogen were recorded and linked with the surface self-adjustment from graphite to MoS_2 lubrication, respectively. Raman, SEM and cross-sectional FIB/SEM/EDX analysis of the wear tracks were used to investigate the mechanisms of the adaptation and fretting wear performance. The study demonstrate the effectiveness of the adaptive PEO-Chameleon coating system performance for the fretting wear mitigation in changing environment.

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

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

3:30pm **E1-2-7 Lubricant/Coating Interactions and Their Effect on Tribological Performance: In-situ XAS Analysis of a Dynamic Lubricated Interface***, **Ardian Morina**,* University of Leeds, UK **INVITED**

The ability to model and predict friction and wear performance in boundary-lubricated conditions is limited by the lack of qualitative and quantitative information on transient tribochemical reactions between the lubricant additives and surfaces. It is these reactions that define tribofilms ' physical and chemical properties, essential for friction and wear performance of industrial boundary lubricated systems, such as valve train, piston ring/liner and pumps. In addition to tribofilm formation, recent work has shown that some of the lubricant additives, such as Molybdenum dialkyl dithiocarbamate (MoDTC), can have a detrimental impact on hydrogenated Diamond-Like-Carbon (DLC) coating durability.

In the current paper, a bespoke tribometer has been designed to be coupled with the Raman spectroscopy and synchrotron X-ray Absorption Spectroscopy for in-situ study of the tribochemical reactions between the lubricant additives and the surface. The focus will be on two typical lubricant additives: Zinc dialkyl dithiophosphate (ZDDP) used as an anti-wear, and MoDTC used as a friction modifier additive. The growth of tribofilms on heat-treated and DLC coated surfaces, in relation to friction and wear performance, will be discussed in detail.

4:10pm **E1-2-9 Friction and Wear Mechanism of MoS_2/C Composite Coatings under Atmospheric Environment**, ***Peiling Ke***, *S Cai, A Wang,* Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, China

Tribological properties of MoS_2/C coatings with different carbon contents (44.7~84.3 at.%) deposited by magnetron sputtering were systematically investigated under atmospheric environment. During tribological tests, the coating with the least MoS_2 content exhibited the lowest friction coefficient and wear rate, while coating with the most MoS_2 showed the worst performance. To understand friction and wear mechanism, multiple analytical tools such as SEM, EDS, Raman, XPS and TEM were applied to investigate the composition and structure. TEM and SEM characteristics proved that the tribofilm with multilayered structure was formed on the tribo-pair. The C rich layer adhered to the tribo-pair and the top layer was well-ordered MoS_2 tribofilm, and the dominated amorphous MoS_2 was found between the two layers. It suggested that the shear plane was mainly made of well-ordered MoS_2 transfer film, while carbon improved the mechanical properties of the coatings, served as a lubricant and also inhibited the oxidation of MoS_2.

4:30pm **E1-2-10 Adhesion and Mechanical Properties of Ti Films Deposited by DC Magnetron Sputtering**, ***RobertoCarlos Vega-Morón***, *G Rodríguez-Castro,* Instituto Politecnico Nacional, Surface Engineering Group, Mexico; *D Melo-Máximo,* Tecnológico de Monterrey-Campus Estado de México, Mexico; *J Méndez-Méndez,* Instituto Politécnico Nacional, Mexico; *L Melo-Máximo,* Instituto Tecnológico y de Estudios Superiores de Monterrey, Mexico; *J Oseguera,* Tecnológico de Monterrey-Campus Estado de México, Mexico

Titanium (Ti) films were deposited by DC Magnetron Sputtering by changing deposition times and substrate temperature on AISI 316L steel to evaluate different thicknesses and its properties. Cristal orientation was determined by grazing angle X-ray diffraction (XRD). Scanning electronic microscope (SEM) was used to determine the surface composition and deposition characteristics through elemental analysis, and also to measure film thickness. Ellipsometry measurements were performed to compare film thicknesses estimated with SEM. Surface topography was obtained by atomic force microscope (AFM). Using nanoindentation test with a spherical indenter, mechanical properties were estimated. Furthermore, failure mechanisms and critical loads were determined by progressive load scratch tests. Wear behavior was studied through pin-on-disk tests with a 6 mm-diameter WC ball. SEM and optical profilometry were used to examine wear tracks; wear rates and coefficient of friction were analyzed.

4:50pm **E1-2-11 Tribology of New Surface Modifications for Cold Rolling Mill Rolls**, ***Henara Costa***, Universidade Federal do Rio Grande, Brazil; *J Gonçalves Jr., J de Mello,* Universidade Federal de Uberlandia, Brazil **INVITED**

The present work analyzed the tribological behavior of coatings/surface modifications traditionally used in cold rolling mill rolls and new coatings/surface modificationswith potential to replace the carcinogenic hard chrome. The study started with identification of wear mechanisms occurring in real coldrollingmill rolls. Due the high cost and dimensions of the rolls, thereplication technique was used. Replicas were obtained from 4 different rolling millBrazilian companies before and after a normal rolling campaign. Initial sliding tests were conducted using spherical and cylindrical counter bodies in order to verifywhichtribological conditions allowed to reproduce the wear mechanisms found in the replicas. These tests indicated the use of reciprocating sliding tests with cylindrical counter bodies (line contact), normal load of 100 N, and test times of and 1 h and 5 h. Different surface modifications were carried out on samples produced from a fragment of a rolling mill roll. The specimens were heat treated and ground on both sides. After, some specimens were surface textured by electrical discharge texturing (EDT). For both groups (ground and EDT), subsequent treatments of chromium plating, electroless NiP coating and plasma nitriding were carried out. The results of the reciprocating tests showed that specimens with electroless NiP coating presented the lowest friction coefficients, while plasma nitrided specimens showed the highest. In general, previous surface texturing before the coating/surface modification increased the wear of the counter bodies. Oneexception was for EDT with subsequent electroless NiP coating, which presented the lowest counter bodies wear rate. The samples withelectroless NiP coating promoted a tribolayer consisting of Nickel, Phosphorus and Oxygen on both the specimens and thecounter bodies, which was apparently responsible for the reduction of friction coefficient and wear rate. The increase of the test time reduced the wear rate of the samples, apparently due the stability of the tribolayers formed, except for the nitrided samples. For the textured specimens, NiP coating showed the best performance in maintaining the surface topography of the specimens after the sliding tests

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