Tribology and Mechanical Behavior of Coatings and Engineered Surfaces
Room Royal Palm 4-6 - Session E1-3

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

8:00am **E1-3-1 A Study on the Tribological Behavior of the AISI 316L Steel Exposed to Boriding to Reduce its Friction Coefficient and Enhance its Wear Resistance***, **Enrique Hernández- Sánchez,*** Instituto politécnico Nacional-UPIBI, Mexico*; J Velazqez,* Instituto Politécnico Nacional-ESIQIE, Mexico*; A Chino-Ulloa,* Instituto politécnico Nacional-UPIBI, Mexico*; I Torres-Avila,* Instituto Politecnico Nacional-UPIBI, Mexico*; J Castrejón-Flores,* Instituto politécnico Nacional-UPIBI, Mexico*; H Herrera-Hernández,* Universidad Autónoma del Estado de Mexico, Mexico

The AISI 316L stainless steel is well known by its high resistance to corrosion and its low response to the human fluids. Those are the main reasons that make it considered as a steel alloy suitable to medical applications. This study is on the application of the boriding process to an AISI 316L steel to evaluate its effect on the tribological behavior of it. The boride layers were achieved by applying the powder pack boriding process. The treatment time was set in 2, 4 and 6 h at temperatures of 900, 950 and 1000 °C. The morphology of the layer was evidenced by Scanning Electron Microscopy and nature of the boride layers was analyzed by X Ray Diffraction. The mechanical properties were evaluated by both instrumented nanoindentation and Vickers micro hardness test. The tribological behavior of the layers was evaluated by means of a sand/rubber apparatus by following the limits of the ASTM G-65 standard. The friction coefficient of the borided layers was estimated by means of the tribological pin-on-disk tests. The results showed a clear influence of the experimental parameters on the thickness of the boride layers. Also the mechanical properties were affected by the parameters of treatment especially by the temperature. The wear resistance of the layers tended to increase as the layer thickness increased according to the treatment conditions. However, wear mechanisms such as adhesion and micro-fatigue were mainly observed in the samples exposed to 6 h and 1000 °C. Finally, the friction coefficient was diminished from values of 0.7 for the as-received material to 0.2 for the borided samples.

8:20am **E1-3-2 Immersion Time-affected Tribocorrosion Behavior of Cr/GLC Multilayer Coating in Artificial Seawater***, **Lei Li**, L Liu, P Ke, A Wang,* Chinese Academy of Sciences, China

A chromium/graphite-like carbon (Cr/GLC) multilayer coating was deposited onto 316L stainless steel by direct current (DC) magnetron sputtering technique to enhance the tribocorrosion resistance of the substrate in marine environment. Taking into account intermittent use of some friction components accompanying long-time immersion in seawater, the influence of immersion time varying from 4 h to 48 h on the tribocorrosion behavior of Cr/GLC multilayer coating was studied in artificial seawater by a reciprocating ball-on-plate tribometer and an electrochemical workstation. The results of tribocorrosion tests after different time of immersion showed that the friction coefficient of Cr/GLC multilayer coating continuously increased from 0.070 to 0.085 with prolonged immersion time, while wear rate firstly decreased and reached its minim value of 5.20×10^{-7} mm^3/Nm at 12 h then gradually increase as the immersion time was in the range of 12 h to 48 h. Eectrochemical impedance spectroscopy (EIS) analysis, before and after the tribocorrosion test, clearly demonstrated that the corrosion resistance of Cr/GLC multilayer coating varied with immersion time, which is associated with the competitive effects of corrosion products blocking the micropores and contact stress promoting microcrack initiation and propagation. Such varying corrosion resistance led to time-affected tribocorrosion behavior of Cr/GLC multilayer coating, thus, more attention should be paid to the performance variation of protective coatings for tribocorrosion applications after long-term exposure to corrosive environments.

8:40am **E1-3-3 A Comparison of the Galling Wear Behaviour of PVD Cr and Electroplated Hard Cr Thin Films***, **Jaimie Daure**, P Shipway, G McCartney,* The University of Nottingham, UK

PVD chromium coatings exhibit good mechanical properties and are a possible replacement to electroplated hard chromium (EPHC) in various applications. Electroplated Cr is widely used but there is need to find an alternative to EPHC due to environmental legislation. One possibility is to use PVD Cr thin films as a replacement. However, insufficient information exists on the behaviour of PVD Cr. Therefore, the aim of the study was to compare the behaviour of two PVD Cr films deposited by different processes and compare with EPHC. Galling testing was selected as it is a useful method for testing the wear resistance and adhesion of a coating under high stresses.

Two PVD chromium coatings of approximately 8 µm thickness were investigated and compared to electroplated chromium of ~9.8 µm. The two PVD coatings were deposited by magnetron sputtering and electron beam physical vapour deposition (EBPVD). Coatings were deposited on 316 stainless steel substrates. Samples were characterised by SEM, XRD, EDX and profilometry. Mechanical testing consisted of nanohardness (ISO 14577-4), scratch testing (ASTM C1624-05) and galling testing (ASTM G98-02).

The nanohardness and surface roughness of the two PVD coatings were similar (around 5 GPa and 300 nm Ra respectively), the values were roughly double for the EPHC. All coatings exhibited similar scratch behaviour. Galling tests revealed that the EBPVD provided no improvement in galling resistance compared to self-mated stainless steel (22 MPa). The magnetron sputtered PVD and 9.8 µm EPHC failed at almost six times the stress of the EBPVD (125 Mpa).

Top surface SEM revealed the two chromium PVD coatings to have distinctly different microstructures. XRD revealed the EBPVD chromium coating had a strong preferred orientation in the {2 0 0} planes, whereas the magnetron sputtered chromium coating had preferred orientations in the {1 1 0} and {2 1 1} planes. The electroplated chromium revealed low intensities of crystalline peaks suggesting a lack of crystalline order or an orientation effect.

Overall, the hardness and surface roughness of the coatings appeared not to be a dominant factor in galling resistance. The crystal orientation of the PVD chromium coatings appears to play a large role in galling resistance. As BCC materials contain slip planes of type {1 1 0} in the <1 1 1> direction, the coating with a preferred orientation in the {1 1 0} planes is expected to provide better wear resistance due to the slip planes parallel to the surface. In the presentation, mechanisms for galling will be discussed and related to future development of thin Cr coatings for galling resistance.

9:00am **E1-3-4 Microstructural Evolution of Cold-sprayed Copper Coating during Reciprocating Sliding Wear***, **Yinyin Zhang**,* McGill University, Canada*; C Greiner,* Karlsruhe Institute of Technology (KIT), Institute for Applied Materials (IAM), Germany*; D Chern, R Chromik,* McGill University, Canada

Cold-sprayed Cu is characterized by various deformed microstructures including nano- and submicron-grains due to dynamic recrystallization, coarse grains containing dislocation forests, as well as deformation bands, deformation twins. When those microstructures were subjected to sliding wear loading, they turned into equiaxed micrometric recrystallized grains below the topmost tribofilm that consisted of nanocrystalline grains. The present work focuses on microstructural evolution mechanisms of the subsurface layer, i.e. grain boundary migration of the nano- and submicron-grains under tribological loading.

First, sliding wear tests were carried out on the as-sprayed and annealed Cu coatings and the subsurface microstructure before and after sliding were observed and analyzed by electron backscattered diffraction (EBSD) maps. This allows, firstly, to compare the difference between thermal-driven and stress-driven grain growth, and secondly, to explore the role of internal energy on microstructural evolution during sliding, given that annealing at different temperatures (i.e. 200 °C, 300 °C, 400 °C, and 500 °C) was to decrease the stored energy gradually. It was found that thickness of the sliding-induced grain growth layer deceased with annealing temperature and disappeared in the 400 °C-annealed specimen. Microstructural features (e.g. grain size, geometrically necessary dislocation density, texture, etc.) of this layer with increase in annealing temperature were discussed based on the EBSD maps. Nanoindentation was used to measure the hardness of the subsurface microstructures. The hardness profiles of the subsurface indicated lower hardness of the grain-growth layer compared to the initial microstructure and this layer became thinner with increase in annealing temperature and eventually disappeared at 400 °C. These results suggest a stored energy criterion probably existed, above which the grain boundary migration occurred under tribological loading.

9:20am **E1-3-5 Scratch Adhesion Resistance of Nickel Boride Layers on Inconel 718 Superalloy**, *I Campos-Silva, **Alan Contla-Pacheco**, A Ruiz-Rios, J Martínez-Trinidad, G Rodríguez-Castro, A Meneses-Amador, W Wong-Angel,* Instituto Politecnico Nacional, Surface Engineering Group, Mexico

New results about the scratch adhesion resistance of nickel boride layer on Inconel 718 superalloy were estimated in the present study. The nickel boride layer was developed on the surface of Inconel 718 superalloy by means of the powder-pack boriding process conducted at 1173 K with 2, 4, and 6 h of exposure. The microstructure of the nickel boride layer was analyzed from optical microscopy, X-ray diffraction and energy dispersive spectroscopy (EDS) in order to verify the presence of Ni_4B_3, Ni_2B, Ni_3B and the distribution of alloying elements along the depth of the layer; the thicknesses of the nickel boride layer + diffusion zone were established between 23 to 40 micrometres for all the set of boriding conditions. Furthermore, and before the scratch tests, indentation properties of the nickel boride layers such as hardness, Young's modulus, plastic deformation resistance, and the distribution of residual stresses were estimated using Berkovich nanoidentation tests applying a constant load (50 mN) across the diffusion layers. The scratch tests were performed over the surface of the nickel boride layer-substrate systems using a Rockwell-C diamond indenter with a continuously increasing normal force from 1 to 80 N, whereas the behavior of the coefficient of friction and the residual depth as a function of the scratch length were monitored during the tests. For the determination of the critical loads, the combination of acoustic emission signal with microscopic observations of the worn tracks were used; the critical loads were estimated at which the layer cracks (cohesive failure) or is detached (adhesive failure) and they explained according to the mechanical properties of the nickel boride layer-substrate system. For all the set of experimental conditions, the presence of different failure mechanisms over the worn tracks was detected, while the results showed that the critical loads increase with increasing nickel boride layer thickness.

9:40am **E1-3-6 Comparison of Surface Treatments for Adhesive Force Measurements Between Magnetron Sputtered TiW Thin Films and Alumina Substrates***, B Atabay, **Elif Apaydin**,* Aselsan Inc., Turkey

This work evaluates the adhesion characteristics of magnetron sputtered Titanium Tungsten (TiW) thin films to surface treated polycrystalline alumina (Al_2O_3) substrates. The experimental relationship has been established in the same region of substrates between four different sets of surface treatments of alumina (Al_2O_3) and TiW thin film adhesion. A progressive load scratch test for adhesion was performed between two surfaces by applying a gradually incremented vertical load and measuring the opposing horizontal force. The 132 N of adhesive force can be obtained by suitable surface pre-treatment of alumina. Results were evaluated by optical microscopy, SEM and surface scratch measurement techniques.

10:00am **E1-3-7 Influence Of Microstructure on Wear of Boroaluminized-Hot-Work Tool Steels***, **Undrakh Mishigdorzhiyn**, N Ulakhanov,* East Siberia State University of Technology and Management, Russian Federation*; Y Chen, H Liang,* Texas A&M University, USA

This research investigates a possibility in improving wear resistance in hot-worked toolsteels by means of high-temperature boroaluminizing in treatment pastes. Boroaluminizing was conducted in sodium fluoride (as an activator), boron carbide and aluminum (BC:Al=4:1) in a furnace. The treatment was administered for 4 hours at 1100°. The microstructure, microhardness, and phase compositions of the boroaluminized layers were evaluated and their effects on wear were studied. Results indicated that high-temperature boroaluminizing improves wear resistance of hot worked tool steels.

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