Tribology and Mechanics of Coatings and Surfaces
Room Palm 1-2 - Session MC1-2-MoA

Friction, Wear, Lubrication Effects, and Modeling II

Moderators: Carsten Gachot, Vienna University of Technology, Austria, **Giovanni Ramirez**, Zeiss Industrial Quality Solutions, USA

1:40pm **MC1-2-MoA-1 Thermally Sprayed Hardmetal Coatings - Strategies for Replacement of WC-Co(Cr)***, **Lutz-Michael Berger (Lutz-Michael.Berger@ikts.fraunhofer.de)**, J. Pötschke, S. Conze,* Fraunhofer Institute for Ceramic Technologies and Systems IKTS, Germany **INVITED**

In 2023 the 100th anniversary of the invention of WC-Co was celebrated. It is one of the most successful composite materials ever and is applied as a sintered tool and wear protection, as well as a coating material. The reason for this success, are the extraordinary properties of WC, but also the nearly perfect interaction with Co as the binder metal. However, there are significant differences between sintered bodies and thermally sprayed WC-Co. These differences are the reason why nowadays WC-10Co4Cr is the standard material composition for highly wear-resistant coatings for service. As thermally sprayed coatings are serving more often at high temperatures and in corrosive environments, Cr_3C_2-NiCr is established as a second successful composite. The standard compositions have been developed on an empirical base, and have changed only little for decades, while there were significant changes in the feedstock powder production technologies.

However, there are currently several challenges which require to create alternatives with respect to environmental and health safety, supply, and of course technical performance. Reasons are the need to replace Co as the binder due to health and environmental issues but also the classification of both Co and W as critical raw materials.

Different possible strategies for partial (the binder only) and full WC-Co(Cr) replacement are currently investigated and will be discussed in detail. Thus, different complex binder alloys for WC-based thermal spray coatings are explored and compared with other alternative binder materials such as Ni or Fe-based alloys.

With respect to the full replacement of WC-Co(Cr) alternative hard materials are investigated:

1. Cr_3C_2 with additions of WC in order to improve the low-temperature wear properties of Cr_3C_2-NiCr
2. TiC/TiCN or NbC/NbCN as cubic hard materials with Ni- or Fe-based alloy binders
3. High-entropy carbides as the most recent development in this field.

One of the advantages of these alternative hard materials is their better compatibility with Co-free binder materials.

In order to develop effective coating material compositions, it is necessary to have a reliable approach for their selection. By using sintering bodies for this purpose, the interactions of the hard and the binder phase can be studied, and the potential of individual novel compositions can be evaluated.

2:20pm **MC1-2-MoA-3 Tribological Properties of Metallic Surfaces Obtained by 3D Additive Manufacturing (Laser Metal Deposition Process), for Repairing Applications***, T. ZURCHER, E. CHARKALUK,* Ecole Polytechnique, France*; **Vincent FRIDRICI (vincent.fridrici@ec-lyon.fr)**,* Ecole Centrale de Lyon - LTDS, France

The repair of worn metal parts represents a significant strategic challenge for industries. These repairs must be both economically and environmentally advantageous. Many ”conventional” repair processes are still used today to meet this need. However, most of these processes are not well-suited for performing fine repairs with complex geometries. An additive manufacturing (AM) process belonging to the Direct Energy Deposition family, called Laser Metal Deposition (LMD), addresses this specific need. This involves putting next to each other and stacking small weld joints called ”beads”, melting metal powder by projecting it under the focal point of a laser. The small diameter of the laser beam and the guidance of the nozzle’s movement by numerical control enable high-resolution repairs. The study of the mechanical properties of parts/repairs from this AM process has already been extensively addressed in the literature. However, very few studies have focused on their wear resistance property. This work thus focuses on the experimental study of the wear resistance of parts repaired by the LMD process, with the ultimate goal of providing methodological recommendations leading to repairs with good wear resistance. Inconel 718 and 316L stainless steel are studied in the case of a dry sliding flat-on-flat contact with reciprocating motion, under different conditions.

Through a detailed analysis of the wear of these repairs, a better understanding of their tribological behavior was acquired. Various wear modes based on tribological parameters, materials properties and LMD process parameters were highlighted. Furthermore, these studies have shown that the repair strategy and sliding direction do not significantly impact their wear resistance. Studies of residual stresses before and after wear tests have demonstrated that the inherent residual stresses of this process have a non-significant impact on wear. These studies have also shown that wear results are highly dependent on the repair material used and the tribological conditions applied on the repairs. Notably, it has been observed that 316L steel exhibits better wear resistance under similar tribological conditions. However, it has been demonstrated that IN718 repairs have a more competitive wear resistance compared to conventionally manufactured parts composed of the same alloy.

2:40pm **MC1-2-MoA-4 Improved Anti-Friction of Diamond-Like Carbon Incorporating Titanium***, **Jae-Il Kim (jaeil@kims.re.kr)**, Y. Jang, J. Kim,* Korea Institute of Materials Science (KIMS), Republic of Korea*; N. Umehara,* Nagoya University, Japan

Diamond-like carbon (DLC) is commonly introduced as a solid lubricant and anti-wear coating. On the other hand, the tribological performance of DLC is highly dependent on the intercontact with the mating material, which may result in high friction. The lubricity of DLCs is believed to be due to the carbonaceous transition layer formed on the mating materials. Industrially, steel- or copper-based alloys have been used as counterparts against DLCs to date, however, it is hard to achieve low friction in tribopairs with them due to the difficulty in forming a carbonaceous transfer layer.

We attempted to solve this problem by doping highly reactive titanium into DLC. Among many transition metals, titanium in particular has a large number of *d*-orbital vacancies, which can easily interact with the 2*p*-orbital of carbon. Therefore, we introduced the idea that this chemical property can promote the formation of a carbonaceous transfer layer, which we aimed to form a low-friction C/C contact interface to enhance the lubricity of the DLC/steel tribopair.

Ti-doped DLC was fabricated by co-depositing DLC with a filter cathode vacuum arc method and Ti with an unbalanced magnetron sputter. The tribological performance as a function of Ti concentration was investigated, and the tribofilms formed on the counterparts were chemically characterized. In conclusion, we report that the Ti-doped DLC exhibited enhanced long-term low-friction characteristic and superlubricity in various environments.

3:00pm **MC1-2-MoA-5 Tribological Study of Magnetron Spurrered W-S-(C) Thin Films Sliding Against Aluminium at High Temperatures***, **Todor Vuchkov (todor.vuchkov@ipn.pt)**, S. Jahan Sunny, A. Cavaleiro,* University of Coimbra, Portugal

Forming of Aluminium is often performed at elevated temperatures due to its poor formability and springback at room temperature. Forming of aluminium at elevated temperatures causes significant tribological issues like adhesive wear and galling, i.e. there can be significant material transfer from the workpiece to the tool/die. Due to the harsh conditions (temperatures up to 500°C), liquid lubricants cannot be utilized and solid lubricants can be an alternative. Self-lubricating thin films deposited by magnetron sputtering are good candidates for alleviating this issue, especially the ones containing transition metal dichalcogenides since they provide good lubrication in environments that lack humidity. In this study we deposited three types of films containing transition metal dichalcogenides (TMDs), of which one consisted only of WS_x and two films were alloyed with carbon (~27 and 35 at. % of carbon). We utilized various techniques for characterizing the physico-chemical properties of the deposited films like scanning electron microscopy, X-ray diffraction at elevated temperature and thermo-gravimetric analysis. The mechanical properties were assessed using scratch testing and nanoindenation. Tribological testing was performed against aluminium (1000 series) balls at room temperature, 200° and 400°C. The unalloyed WS coating had more porous columnar morphology while the carbon-alloyed ones showed increase compactness with reduced intercolumnar porosity. The thermal analysis indicated that the maximum operating temperature should be ~400-430 °C, for the pure WS coating, and a higher value of ~480-490°C for the carbon alloyed films. The thin films had good adherence to the tool steel substrates with an Lc2 critical load of 20-30 N and no gross delamination up to 70 N of load. The tribological results indicate that the unalloyed WS coating is the best solution for friction reduction against aluminium at the examined testing temperatures (up to 400°C). The carbon alloyed coatings also provided friction reduction but friction instabilities were observed and the film with the highest carbon content suffered excessive galling at 400°C. In terms of wear, the unalloyed WS coating generally suffered more wear compared to the other coatings. The results of the study present a high potential of the TMD-based sputtered coatings for applications involving sliding against aluminium at elevated temperatures.

4:00pm **MC1-2-MoA-8 Understanding the Tribological Mechanisms of TiO_2 Thin Layers: The Role of Composition and Structure of the Oxide Layer on Wear in Relation to Color Variation***, **Sarah Marion (sarah.marion@emse.fr)**, M. LENCI,* Mines Saint-Etienne, Université de Lyon, CNRS, France*; C. MINFRAY, V. FRIDRICI,* Laboratoire de Tribologie et Dynamique des Systèmes, Université de Lyon, Ecole Centrale de Lyon, France*; L. DUBOST,* IREIS, HEF group, France*; J. FAUCHEU, R. CHARRIERE,* Mines Saint-Etienne, Université de Lyon, CNRS, France

Although titanium is not a noble material, it is attracting more and more attention in the luxury industry (jewelry, watches, packaging) because of its lightness, hypoallergenic properties and, above all, the many colors it can produce when coated with a thin layer of TiO_2. However, its use in luxury goods is currently limited because its colors do not last very long. The wear resistance of thin colored layers of TiO_2, and especially the preservation of the original color, is an important issue for luxury jewelry.

The degradation of the color of anodized titanium is well studied in the field of architecture [1,2] and in this case, is mainly linked to a change of the thickness of the TiO_2 layer in the presence of acid rain. In addition, Diamanti et al [3] have shown that prolonged rubbing in an artificial sweat solution causes partial discoloration of the anodized titanium surface. However, the origin of the color degradation in this case has not been identified. The interferential origin of the color makes it particularly sensitive to a variation in thickness, but also to a variation in the chemical composition and internal structure of the oxide layer through a change of the refractive index.

The aim of this study is therefore to compare the wear resistance of thin TiO_2 layers produced by different processes. One is to anodize a Ti-6Al-4V substrate and the other is to deposit a TiO_2 layer by magnetron sputtering on a Ti-6Al-4V substrate. The influence of the chemical composition, crystallinity, internal morphology and thickness of the oxide layer on tribological behavior is studied and correlated with the change in color observed during dry rubbing and rubbing in the presence of artificial sweat.

[1] M. Kaneko, K. Takahashi, T. Hayashi, I. Muto, K. Tokuno, K. Kimura, Tetsu-to-Hagane. 89 (2003) 833-840.
[2] M. Kaneko, M. Kimura, K. Tokuno, Corros. Sci. 52 (2010) 1889-1896.
[3] M. V. Diamanti, P. Pozzi, F. Randone, B. Del Curto, Materials and Design 90 (2016) 1085-1091.

4:20pm **MC1-2-MoA-9 Tribocorrosion Behaviours of TiZrNbTaFeC High Entropy Carbide Coatings by Superimposed HiPIMS and MF System***, **Ismail Rahmadtulloh (ismailrahmadtulloh2@gmail.com)**, C. Wang,* National Taiwan University of Science and Technology, Taiwan*; B. Lou,* Chang Gung University, Taiwan*; J. Lee,* Ming Chi University of Technology, Taiwan

Recently, the tribocorrosion issue has become crucial in various industry applications due to its impact on the failure and degradation of materials. In this study, TiZrNbTaFeC high entropy alloy carbide coatings (HEACCs) were deposited on the surface of AISI 52100 using a superimposed high power impulse magnetron sputtering (HiPIMS) and medium-frequency (MF) sputtering system. We observed an amorphous-like phase in coatings containing carbon within the range of 0 to 16.53 at.%. However, a transition to an FCC structure occurred when the carbon content increased to 32.4 and 35.8 at.%. The highest average hardness of 22.1 GPa was observed for HEAC#14 with a carbon content of 32.4 at.%. The coatings were immersed in a 0.5 H2SO4 solution at room temperature. At static corrosion, the carbon-free TiZrNbTaFe coating has a higher polarization ratio of 6.53×10^4 Ωcm^2 followed by HEAC#18 (35.8 at.% C) of 3.71×10^4 Ωcm^2, indicating excellent corrosion resistance. For the tribocorrosion tests, the coatings were subjected to 1 N load using a pin-on-disk tribometer at a sliding speed of 50 rpm. The wear rate and details of tribocorrosion studies on TiZrNbTaFeC high entropy alloy carbide coatings will be explored.

4:40pm **MC1-2-MoA-10 Friction and Wear of a-C:H and a-C:H:Si Coatings Sliding Against Different Counterpart Materials Under Dry and Moist Environments***, **Francisco A. Delfin (delfinf@frcu.utn.edu.ar)**,* National University of Technology, Regional Faculty of Concepción del Uruguay (UTN – FRCU), Argentina*; J. Jeoffrey,* Universiti Teknologi Petronas, Malaysia*; M. Schachinger, C. Forsich,* University of Applied Sciences Upper Austria*; S. Brühl,* National University of Technology, Regional Faculty of Concepción del Uruguay (UTN – FRCU), Argentina*; D. Heim,* University of Applied Sciences Upper Austria

The self-lubricating effect of DLC coatings is a very well-known feature, although they have yet to occupy a substantially influential position in mainstream tribological applications. This objective is increasingly critical due to the escalating worldwide focus on achieving energy efficiency, lowering fuel consumption and cutting environmentally harmful emissions. To reach these milestones, a deeper understanding of DLC coatings is required, namely regarding the intricate relationship of friction and wear rates within diverse tribosystems, where parameters such as relative humidity and the material of the counter body show decisive influence. In this work, DLC coatings were deposited using a modified commercially available PA-CVD system on AISI 4140 steel. Two kind of coatings were produced, a-C:H and a-C:H:Si, at temperatures of 450 °C and 550 °C. Process gas consisted of a mixture of argon, acetylene, and HMDSO as silicon precursor. Characterization was carried out by means of nanoindentation, Raman spectroscopy, as well as GDOES and EDX. Tribological behavior was evaluated by means of Pin-on-Disk, using the coated sample as the disk, a 12 N normal load, a speed of 0.4 m/s and a total sliding distance of 2000 m. Counterparts were 6 mm balls, of which three different materials were used: AISI 52100 bearing steel, Al_2O_3 and Si_3N_4. Test chamber was conditioned using forced air recirculation and beakers containing either water or regenerated silica gel to create a humid or a dry environment, respectively. Friction coefficient was registered during the entire test. The wear track was evaluated with optical and confocal microscopy, as well as SEM/EDX and Raman spectroscopy. Hardness and elastic modulus increased with deposition temperature, and the values were doubled with silicon doping. However, a lower friction coefficient and wear volume loss were found in Si-free samples. In general, the coatings showed varied responses to the different environments and counterparts: a-C:H showed oxidation with higher humidity, whereas a-C:H:Si exhibited high wear in the drier ambient, producing several peaks in the friction coefficient during the test. The steel counterpart exhibited a lubricious oxide layer that helped reduce the friction coefficient, thus performing better in the humid environment. The Si_3N_4 counterpart showed the highest adhesion when sliding against a-C:H:Si, although a rather low friction coefficient and wear was shown when testing the Si-free samples.

5:00pm **MC1-2-MoA-11 Evaluation of the Sliding Wear Performance of Binary CrN and Nanocomposite CrSiCN Coatings in Arctic Environments***, N. D'Attilio, **Forest Thompson (forest.thompson@sdsmt.edu)**, N. Madden,* South Dakota School of Mines and Technology, USA*; E. Asenath-Smith,* US Army Corps of Engineers Cold Regions Research and Engineering Laboratory, USA*; G. Crawford,* South Dakota School of Mines and Technology, USA

The efficiency, service lifetime, and durability of engineering components operating in the severe cold and dry environments found in Earth's polar regions can potentially be improved using protective coatings based on transition metal nitrides. However, the tribochemical wear behavior of these ceramic materials is particularly sensitive to operating conditions. Thus, there is a need to understand the influence of arctic environments on the sliding wear performance of these coatings. In this work, binary CrN, columnar CrSiCN, and glassy CrSiCN coatings were produced using filament-assisted reactive magnetron sputter deposition. The coatings were characterized using energy dispersive X-ray spectroscopy, X-ray diffraction, transmission electron microscopy, and atomic force microscopy. The mechanical properties of the coatings were tested using nanoindentation and the wettability of the coatings was determined using tilting-base contact angle goniometry. A ball-on-flat tribometer equipped with an active cooling stage and dry air source was used to assess the tribological performance of the coatings under various combinations of coating surface temperatures and environmental dewpoints. Ultimately, the microstructure and amorphous phase content was found to play a major role in the performance of CrN-based coatings in these environments. The wear resistance of all coating types was found to suffer under a combination of low surface temperature (-20 °C) and low dewpoint (-33 °C), while their frictional behavior under frosting conditions (-20 °C surface temperature, -

10 °C dewpoint) was primarily controlled by the presence of ice at the contact zone.

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