Protective and High-temperature Coatings
Room Palm 3-4 - Session MA1-1-MoM

Coatings for High Temperatures and Harsh Environment Applications I

Moderators: Sabine Faulhaber, University of California, San Diego, USA, **Francisco Javier Perez Trujillo**, Universidad Complutense de Madrid, Spain

10:00am **MA1-1-MoM-1 Improving the Lifetime and Efficiency of Next Gen Aircraft Turbine Engines with PVD***, **Thibault Maerten [thibault.maerten@oerlikon.com]**,* Oerlikon Balzers Coating AG, France

Aircraft engine operating conditions continue to push the limits of material capabilities, which requires robust, multifunctional, and durable coating solutions for turbine hot-sectioncomponents. These turbines are mainly made from metallic components that are protected by thermal barrier coatings (TBCs). A TBC system is usually formed by a top ceramic layer deposited onto a bond layer over the substrate. MCrAlY (where M = Ni, Co, Fe or combinations of these metals) coatings are widely used as bond-coat material on blades and vanes due to their good resistance against oxidation and corrosion at high temperature. MCrAlY coatings are typically applied through thermal spray, electroplating and CVD methods. However, with ever-increasing turbine combustion temperatures, rotation speed for the sake of increased efficiency, the classic deposition methods are approaching their functional limits.

Significant developments over the last decade have made Physical Vapor Deposition (PVD) technologies increasingly compelling for MCrAlY coating deposition. PVD MCrAlY coatings exhibit high deposition rate, excellent surface adhesion, high density, and exceptional uniformity on complex geometries such as airfoils. Additionally, PVD MCrAlY coatings show a significantly lower surface roughness (Ra = 3-4 µm), which can be further smoothed by post-treatment, benefiting the application of EB-PVD TBCs.

With these significant advantages, PVD MCrAlY coatings produced by cathodic arc offer new opportunities for next gen aircraft engines development. In this talk, we aim to present several case studies involving replacement by PVD of traditional methods to produce MCrAlY. The coating properties (microstructure, composition, thickness distribution) and resulted performances (fatigue debit, oxidation and corrosion resistance) will be presented and compared.

10:20am **MA1-1-MoM-2 Mechanisms of Solid Particle Erosion in Aerospace Materials and Protective Coatings***, **Stephen Brown [stephen.brown@polymtl.ca]**[1], Etienne Bousser, Benjamin Milan-Ramos,* Polytechnique Montréal, Canada*; Juan Manuel Mendez,* MDS Coating Technologies, Canada*; Marjorie Cavarroc-Weimer,* Safran Tech, France*; Ludvik Martinu, Jolanta Ewa Klemberg-Sapieha,* Polytechnique Montréal, Canada

Solid particle erosion (SPE) is a tribological process involving material removal by repeated impacts of high-velocity particles. Despite years of research, fundamental mechanisms governing SPE remain poorly understood, particularly those concerning the erosion of metals at 90° impingement and the deformation of protective coatings in the elasto-plastic erosion regime. This work presents a detailed erosion study of bare Ti-6Al-4V and protective TiAlN-based coatings under varied particle velocity (50-120 m/s), impingement angle (15°-90°), and particle type/size (Al_2O_3, crushed glass 50-140 µm). Beyond standard metrics such as scar depth and volume loss rates, the eroded surfaces were extensively characterized by Plasma Focused Ion Beam cross-sectioning (PFIB), Electron Backscatter Diffraction (EBSD), Transmission Electron Microscopy (TEM) of eroded lamellae with Selected Area Diffraction, Transmission Kikuchi Diffraction (TKD), and nanoindentation mapping.

For Ti-6Al-4V, full erosion tests were compared to single particle impacts; both approaches showed cloudy microstructures indicative of severe local strain near impact sites, confirmed by TEM to be nanocrystalline. The affected depth did not exceed 7 µm, and nanoindentation revealed an 11% hardness increase. Extensive particle embedment occurred during multi-impact tests, yet damage morphology and affected depth were near-identical to single impacts, challenging cumulative wear models and suggesting that the 90° erosion of Ti-6Al-4V can be represented as the sum of individual impacts.

TiAlN coatings deposited via cylindrical magnetron sputtering exhibited architecture-dependent failure. Monolithic TiAlN initially degraded by nano-chipping, along with plastic deformation of the columnar structures 100-200 nm into the subsurface. This was followed by catastrophic adhesive failure after the coating thins beyond a certain threshold. A multilayer TiAlN/TiAl system exhibit a similar but distinct failure mode: cracks propagated along TiAl interlayers, promoting local delamination of the overlying TiAlN. In essence the same threshold-type failure occurs, however, the TiAl interlayers decrease the TiAlN layer thickness and thus the distance to the nearest interface. The result is progressive layer-by-layer material removal rather than bulk spallation, offering insight into how architecture governs erosion resistance.

10:40am **MA1-1-MoM-3 Microstructure and Oxidation of PVD Coatings on TiAl and Ni Superalloys for High-Temperature Applications***, **Radosław Swadźba [radoslaw.swadzba@git.lukasiewicz.gov.pl]**,* Łukasiewicz Research Network - Uppersilesian Institute of Technology, Poland **INVITED**

Modern aircraft engines operate at increasingly higher temperatures to improve thermal efficiency and reduce fuel consumption. These extreme conditions place severe oxidation and corrosion demands on structural materials such as TiAl intermetallics and Ni-based superalloys. Although these alloys combine excellent strength-to-weight ratios with good high-temperature mechanical properties, their long-term performance depends strongly on effective surface protection. The development of advanced oxidation-resistant coatings is therefore essential for enabling higher operating temperatures and extending the lifetime of next-generation aeroengine components.

This talk presents recent work on the development, microstructural design, and oxidation behaviour of protective coatings produced by the Closed Hollow Cathode Physical Vapor Deposition (CHC-PVD) method on TiAl and Ni-based substrates. The CHC-PVD process offers high plasma ionization, allowing deposition of thick, adherent, and compositionally complex coatings with tailored architectures.

The coating systems investigated include Ti–Al–Cr alloys modified with Si and Y, MAX phase coatings (Ti_2AlC and Cr_2AlC) on γ-TiAl, and MCrAl-type coatings on Ni-based superalloys. Detailed characterization was performed using High-Resolution Transmission Electron Microscopy (HRTEM), Scanning Transmission Electron Microscopy (STEM), and high-temperature X-ray diffraction (HT-XRD) to study both as-deposited coatings and their phase evolution during heat treatment. These advanced techniques made it possible to reveal nanolaminate microstructures, analyze interfaces, and examine thermally grown oxides in detail.

High-temperature oxidation studies under isothermal and cyclic conditions revealed clear differences in performance among the investigated coatings. The degradation modes, along with the formation and evolution of protective alumina scales, were examined in detail using HRTEM and STEM to establish correlations between microstructure, composition, and oxidation behavior.

The results highlight the potential of the CHC-PVD technique for producing advanced high-temperature coatings with optimized microstructures and oxidation behavior, contributing to the development of durable, lightweight materials for future aircraft engines.

11:20am **MA1-1-MoM-5 Predictive Analytics of Aluminide Diffusion Coatings Using Machine Learning to Forecast Their Aging and Service Life***, **Vladislav Kolarik [vladislav.kolarik@ict.fraunhofer.de]**, Maria del Mar Juez Lorenzo,* Fraunhofer Institute for Chemical Technology ICT, Germany*; Pavel Praks, Renata Praksová,* IT4Innovations National Supercomputing Center, VSB - Technical University of Ostrava, Czechia

Aluminide diffusion coatings offer a reliable and economical way to protect steel from high-temperature corrosion in harsh environments. These coatings can be applied as aluminum slurries using various deposition methods, including spraying or brushing, and are subsequently heat-treated to form the diffusion layer. Predictive analytics using machine learning offers great potential to forecast the aging behavior and lifetime of the coating under operating conditions. Machine learning predictions rely solely on historic data and do not require physical models to describe dependencies. This is especially advantageous for systems influenced by multiple parameters, as machine learning can identify patterns and relationships that humans cannot. Regression-based predictive models, such as Symbolic Regression or decision-tree algorithms like CatBoost and XGBoost, have proven to be suitable.

Two key variables were identified for describing the service life of an aluminum diffusion coating: (1) the ratio of the inner Fe_3Al layer to the total

[1] **Graduate Student Award Finalist**

coating thickness, and (2) the aluminum concentration in the Fe_3Al layer. The first variable indicates a milestone in the coating's service life, occurring when the ratio equals 1. At this point the diffusion coating evolves into a single aluminum-poor layer. The aluminum concentration in this single layer reflects the amount of aluminum remaining in the coating, which is essential for forming a protective alumina layer. The input parameters, time, temperature, atmosphere, overall coating thickness, thicknesses of the partial layers, number of the partial layers, type of slurry etc., were collected from our previous research as well as from literature. The transition to a single-layer coating was forecasted to occur after 28,000 hours at 650°C in air, following a time law close to parabolic, indicating that diffusion dominates the process. The aluminum content remains in the range of 25 at% over 100,000 hours, indicating that Fe_3Al will still be present.

The research shows that machine learning is very effective in analyzing complex material systems affected by multiple parameters, where understanding the relationships and importance of these parameters is difficult using conventional physical modeling approaches.

11:40am **MA1-1-MoM-6 Tailored Formation of Intermetallic Phases in Nanolayered Metallic Systems***, **Vincent Ott [vincent.ott@kit.edu]**, Sven Ulrich, Michael Stüber,* Karlsruhe Institute of Technology (KIT), Institute for Applied Materials (IAM), Germany

The temperature induced formation and stability of phases in nanoscale multilayer thin films are strongly affected by confinement effects and interface-controlled kinetics. As the characteristic dimensions of the layers are reduced, the thermodynamic driving forces and atomic mobility change, leading to distinct size-dependent phase formation behavior during heat treatment. In metallic multilayers, this often results in a modified or entirely suppressed sequence of equilibrium phase transformations. Using the Ru/Al model system and its ternary extensions with Hf, Cr, and Cu, we demonstrate that decreasing the individual layer thicknesses can kinetically inhibit the formation of equilibrium phases while promoting the preferential stabilization of the crystallographically simple cubic B2 structure. This enables the controlled synthesis of metastable intermetallic alloys beyond the thermodynamic equilibrium regime. The phase evolution was monitored in-situ by high-temperature X-ray diffraction (HT-XRD), while complementary electron microscopy and atom probe tomography (APT) provided insight into the resulting nanoscale structure and chemical distribution. The general validity of this kinetic stabilization concept is further illustrated by the Fe–Ti system, in which the B2 FeTi phase can be selectively formed at comparable nanometer-scale periodicities. These findings highlight the potential of nanoscale layering to engineer novel metastable phases with tailored structural and functional properties.

12:00pm **MA1-1-MoM-7 The Evaluation of Oxidation Resistance on Pack Aluminized CoCrFeNi2 and Al0.5CoCrFeNi2 High Entropy Alloys***, **Thanawat Santawee [thanawat.sant@ku.th]**, Pongpak Chiyasak,* Kasetsart University, Thailand*; Chia-Lin Li, Jyh-Wei Lee,* Thin Film Technologies, Ming Chi University of Technology, Taiwan*; Wei-Chun Cheng,* National Taiwan University of Science and Technology, Taiwan*; Aphichart Rodchanarowan,* Kasetsart University, Thailand

Aluminization is a crucial surface engineering process widely employed to improve the oxidation and corrosion resistance of metals and alloys exposed to high-temperature environments. This technique plays an essential role in industrial applications such as gas turbines, aerospace engines, and heat exchangers, where long-term material stability is critical. In this study, $FeCoCrNi_2$ and $Al_{0.5}FeCoCrNi_2$ high entropy alloys (HEAs) were fabricated by casting and subjected to pack aluminizing at 950 °C for 6 hours to develop protective aluminide surface layers. The cross-sectional morphology analysis using scanning electron microscopy revealed the formation of uniform aluminide coating on the surface with an average thickness of approximately 50 μm and a distinguishable interlayer at the coating–substrate interface. X-ray diffraction analysis identified the presence of (CoCrFeNi)Al-based aluminide phase, indicating successful aluminum diffusion and phase transformation resulting from interactions with the base alloy elements. Thermogravimetric analysis demonstrated a clear reduction in mass gain after aluminizing compared with the uncoated alloys, indicating a significant improvement in oxidation resistance. After oxidation testing, the formation of protective Al_2O_3 and Cr_2O_3 phases was detected on the coating surface, contributing to enhanced stability at elevated temperatures. Additionally, nanoindentation testingshowed that the hardness of surface aluminide layer increased nearly threefold after aluminizing, reaching 12.2 GPa for $FeCoCrNi_2$ and 13.3 GPa for $Al_{0.5}FeCoCrNi_2$. Thiswork suggests that the pack aluminization process significantly enhances the surface structure and oxidation resistance of both HEA systems.

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