Coatings for Use at High Temperatures
Room Royal Palm 1-3 - Session A2

Thermal and Environmental Barrier Coatings

Moderators: Kang Lee, NASA Glenn Research Center, USA, Lars-Gunnar Johansson, Chalmers University of Technology, Sweden, Pantcho Stoyanov, Pratt & Whitney, USA

8:00am **A2-1 Corrosion Degradation of High Temperature Coatings: Similarities and Differences for Marine and Aero-Turbine Applications***, **Daniel Mumm**,* University of California, Irvine, USA **INVITED**

Gas turbine engines are utilized throughout the world, as aircraft and ship propulsion systems and as stationary power generation systems. The materials utilized in the hot-section of marine gas turbines are subject to a wide range of high temperature oxidation/corrosion degradation processes, dependent upon the fuels used and the site-specific environments. Operation in marine environments leads to salt-laden intake air, whereas additional constituents in the intake air (pollutants, atmospheric particulate matter, etc.) have unique influences on the oxidation/corrosion degradation mechanisms of thermal and environmental barrier coating utilized with hot-section components. Ongoing research has also illustrated that the performance and lifetime of such materials is also highly dependent upon the exposure temperatures and the specific thermal cycling history associated with operational service demands. This talk will discuss ongoing efforts to explore high temperature oxidation and corrosion processes, and the resulting materials degradation, under more complex exposure conditions – with a focus on the synergistic role of mixed-mode (Type II, Type I and oxidation condition) exposures and complex corrosive deposit chemistries including sulfate mixtures and oxides. The research findings are discussed in relation to the performance of marine propulsion, aero-propulsion and power-generation turbines operating in marine environments. Implications for understanding of the observed degradation mechanisms is essential for enabling the design of materials capable of being utilized in increasingly hostile gas turbine operational scenarios.

8:40am **A2-3 Evolution of Microstructures and Interfaces in Doped, Layered, and Composite Coatings Exposed to Sand Laden Flows in a Gas Turbine Engine***, **Andy Nieto**, M Walock, A Ghoshal, M Murugan,* US Army Research Laboratory, USA*; D Zhu,* NASA Glenn Research Center, USA*; W Gamble, J Swab, B Barnett, M Pepi,* US Army Research Laboratory, USA*; R Pegg, C Rowe,* US Navy Naval Air Systems Command, USA

Calcia-magnesia-alumina-silicate (CMAS) attack on thermal barrier coatings (TBCs) have led to a need for new TBC coating designs that incorporate mechanisms for mitigating CMAS deposition and infiltration, while maintaining or enhancing the critical properties of TBCs, namely durability and strain tolerance under high temperature and velocity in cycling engine operating conditions. Several approaches have been investigated here, including the use of dopant elements and phases, multi-layered coatings, and blended composite coatings. These included doped ZrO_2 based coatings, layered Y_2O_3 stabilized ZrO_2 (YSZ), HfO_2, and Gd_2O_3 coatings, as well as composite YSZ/Gd_2O_3 coatings. The coatings were deposited on turbine nozzle vanes and tested inside of a full scale engine with air flow temperatures at ~1400 °C and several sand ingestion cycles. SEM, EDS, and TEM were utilized to compare the microstructures before and after exposure to the sand laden combustion flows within the gas turbine engine. Emphasis was placed on the interfaces formed between the coatings and the formed CMAS deposits. Interfaces within the coatings, such as those in between phases or between layers, were also evaluated in order to understand which microstructural designs were most effective at mitigating CMAS infiltration/attack and particulate adhesion, whilst maintaining structural stability and integrity.

9:00am **A2-4 The Effect of HVOF Bond Coating with APS Flash Coating on TBC Performance***, **Michael Lance**, J Haynes, B Pint,* Oak Ridge National Laboratory, USA

Previous work reported the benefit of a ~50 µm thick air plasma sprayed (APS) "flash" coating to improve the performance of high-velocity oxygen fuel (HVOF) bond coatings. In this study, NiCoCrAlYHfSi HVOF bond coatings were deposited on directionally-solidified (DS) 247 disk substrates with APS yttria-stabilized zirconia (YSZ) top coatings. The HVOF-only bond coatings were compared to APS flash coatings of NiCoCrAlYHfSi and NiCoCrAlY using 1-h cycles at 1100 °C in air with 10% H_2O. Photo-stimulated luminescence spectroscopy was used to map residual stresses in the thermally-grown Al_2O_3 scale as a function of exposure time. Five specimens of each coating type were cycled to determine an average coating lifetime under these conditions and, after failure, oxide thickness and morphology were compared on various bond coatings to better understand the influence of the flash coating presence and composition.

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9:20am **A2-5 Influence of Process Conditions and Ceramic Doping on the Performances of Advanced TBCs Based on Al Slurry***, **Germain Boissonnet**, B Grégoire, J Balamain, G Bonnet, F Pedraza,* University of La Rochelle, France

Current processes of fabrication of thermal barrier coatings (TBCs) for the hottest sections of aeronautical engines are very complex and quite expensive. Therefore, they cannot be applied to other sections that require thermal insulation due to the increase of the turbine inlet temperatures. Among the alternative coating techniques, slurries from Al microspheres that result in the formation of hollow alumina top foam appear particularly attractive [1-3]. Their insulation properties are indeed equivalent to those of conventional APS YSZ coatings [4]. However, the current process of fabrication leads to poor mechanical resistance of this light foam [5].

Therefore, the effects of the annealing atmosphere and of the introduction of Al_2O_3 and YSZ ceramic particles on the strengthening and on the thermal insulation potential of the ceramic foam will be presented. Alumina was chosen due to its good chemical compatibility with the Al slurry to harden the top coat while binding with the hollow oxide spheres. Concurrently, YSZ is expected to lower the overall thermal conductivity of the top coat while simultaneously increasing its stress compliance *because of the high thermal expansion coefficient of this material*. Low water vapor pressures will also be shown to thicken the shells of the hollow particles compared to Ar and oxygen [5]. Also, the reaction mechanisms of YSZ particles with molten Al to result in the formation of $Al_3Zr/\alpha\text{-}Al_2O_3$ composites [6] that leads to remarkable changes in thermal and mechanical properties of the top coat will be described in light of the results from DSC, XRD, Raman micro-spectrometry and thermal diffusivity.

References

1. F. Pedraza et al., Materials Chemistry and Physics 134 (2012) 700-705.

2. X. Montero et al., Surface & Coatings Technology 206 (2011) 1586-1594.

3. V. Kolarik et al., Materials at High Temperatures 29, *2* (2012) 89-94.

4. F. Pedraza et al., Journal of Materials Science and Chemical Engineering 3 (2015) 17-22.

5. F. Pedraza, R. Podor, Material Characterization 113 (2016) 198-206.

6. H. Zhu et al., Composites Science and Technology 70 (2010) 2183-2189.

9:40am **A2-6 Synthesis and Characterization of Combined Oxides and Ni Superalloy Coatings by Cathodic Arc Evaporation for Bond Coat Application***, X Maeder, J Ast,* Empa, Swiss Federal Laboratories for Materials Science and Technology, Switzerland*; M Döbeli,* ETH Zurich, Switzerland*; K von Allmen, A Neels, A Dommann,* Empa, Swiss Federal Laboratories for Materials Science and Technology, Switzerland*; H Rudigier,* Oerlikon Balzers, Oerlikon Surface Solutions AG, Liechtenstein, Switzerland*; B Widrig, **Jürgen Ramm**,* Oerlikon Balzers, Oerlikon Surface Solutions AG, Liechtenstein

Typical coating systems in gas turbines are made of several layers, generally consisting of (1) a bond coat, which guarantee the mechanical stability over a wide range of temperature, (2) a thermally grown oxide, acting as an oxygen diffusion barrier and (3) a top porous ceramic, acting as a temperature barrier. Such a stack presents many interfaces where internal stresses and failure can occur. We will show here the capability of creating a complete layer stack for a bond coat by cathodic arc evaporation in an in-situ process sequence, i.e. without interruption of vacuum. Superalloy targets were produced from Ni-(Al-C-Co-Cr-Mo-Ta-Ti-W) and Ni-(Al-B-C-Co-Cr-Hf-Mo-Ta-Ti-W-Zr) powders by spark plasma sintering and processed in subsequent non-reactive and reactive modes. The phases, microstructure and composition of the powder, target and synthesized coatings are characterized by TEM, transmission EBSD, X-ray diffraction and RBS analyses and discussed. An epitaxial growth of the pure metallic coating can be observed on both multi and single crystalline superalloy substrates, which guaranty an enhanced mechanical stability of the first coating interface. The thin transition layer between the reactive and non-reactive depositions is composed of nano-crystalline partially oxidized Ni superalloy. Fully oxidized Ni superalloy and Al-Cr-O layers can be deposited on top. The thermal stability of the stack has been tested by in-situ high temperature XRD analyses as well as post mortem TEM, transmission EBSD and RBS analyses.

10:00am **A2-7 Steam Oxidation Behavior of $Yb_2Si_2O_7$-Based Environmental Barrier Coatings***, **Kang Lee**,* NASA Glenn Research Center, USA

Increased fuel efficiency is a game changer for gas turbines as fuel is the single most important cost, accounting for up to about 40% of the overall operation cost of commercial aircrafts. Increased fuel efficiency is obtained through increasing the thermal efficiency of the engine by increasing the overall pressure ratio (OPR). Increased OPR requires increased turbine inlet temperature, which is paced by advances in turbine hot section materials temperature capability. High turbine inlet temperature also contributes to environmentally friendly engines by reducing NOx. SiC/SiC Ceramic Matrix Composites (CMCs) are the most promising materials to revolutionize the temperature capability of turbine hot section materials because of their high temperature mechanical properties and light weight. Environmental barrier coatings (EBCs) is an enabling technology for CMCs by protecting CMCs from environmental degradation, especially from water vapor. One of the most likely EBC failure modes is oxidation by water vapor generated by combustion reactions (steam oxidation). The current state-of-the-art EBC is based on $Yb_2Si_2O_7$ and Si bond coat. In gas turbines water vapor migrates through $Yb_2Si_2O_7$ and oxidizes Si bond coat, forming a layer of silica (SiO_2), known as TGO, at the Si/$Yb_2Si_2O_7$ interface. As TGO grows in thickness with time the strain energy increases, ultimately leading to an EBC failure. This paper will discuss steam oxidation behavior of $Yb_2Si_2O_7$-based EBCs.

10:20am **A2-8 The Fatigue Behavior of TiCrAlTaSiN Coated and Uncoated Titanium Alloys***, B Lerch, **Dongming Zhu**, S Kalluri,* NASA Glenn Research Center, USA

Advanced multi-component TiCrAlTaSiN-based multilayered coatings were processed onto Ti-6Al-4V (Ti-6-4) and GammaMet PX (GMPX or TiAl) alloys by magnetron-enhanced physical vapor deposition technique. The coatings have been in developments aiming for improving advanced Ti alloy turbine engine component durability and oxidation-erosion resistance. In this work, the performance of the multi-component titanium nitride based coating systems (including the outer layer nitride based coating and inner TiCrAlSi barrier bond coat) was studied, and the coating influence on the fatigue behavior of the titanium-based alloys were compared. Although the multi-component coating was initially optimized to improve the coating high temperature oxidation and erosion resistance, the lower ductility nitride based coatings need further microstructure or composition optimizations to improve the mechanical stress resistance and stain tolerances for the highly loaded and high cycle fatigue turbine blade operating conditions, in particular for GMPX and other gamma TiAl alloys because the intermetallic Titanium alloys have limited ductility and are sensitive to defects. The preliminary results showed that the inner layer TiCrAlSi coatings had better adhesion and ductility, may help improve the oxidation resistance for the Ti alloys.

10:40am **A2-9 Crack Propagation Behavior of Thermal Barrier Coatings with Cyclic Thermal Fatigue Tests***, **Dowon Song**, T Song,* Hanyang University, Republic of Korea*; H Park, Y Jung,* Changwon National University, Republic of Korea*; J Zhang,* Indiana University Purdue University Indianapolis, USA

Crack formation and propagation behavior in thermal barrier coatings (TBCs) was observed through cyclic thermal fatigue (CTF) test for further understanding of TBC failure mechanisms. An analytical model was employed to predict residual stress distribution in the TBC samples to explain the experimentally observed crack-growth behavior. Initial cracks were formed on the surface and cross-section of TBCs prepared by air–plasma spray using Vickers indentation, and then CTF tests were performed for both cracked TBCs. Surface-cracked top coats were partially delaminated depending on their initial crack lengths that were formed with each loading level, suggesting a threshold surface crack length and showing a parabolic growth behavior. In the cross-sectional cracked TBC, cracks were strongly dependent on the direction, showing longer crack lengths in the direction parallel/horizontal to the interface between the top and bond coats than the direction perpendicular/vertical to the interface. The horizontal cracks grew in the similar manner as those on the surface, but the cracks in the vertical direction did not grow too much with CTF tests. All fatigue crack-growth rates show a negative dependence on stress intensity range in the Paris law due to the competing interaction of the residual stresses from indentation and thermal cycling. This study and analysis can be helpful for the further understanding of TBC failure in the design of reliable TBC systems.

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