Wednesday Morning, May 25, 2022

Coatings for Use at High Temperatures
Room Pacific E - Session A2-2-WeM

Thermal and Environmental Barrier Coatings II

Moderators: Sabine Faulhaber, University of California, San Diego, USA, **Kang Lee**, NASA Glenn Research Center, USA

8:00am **A2-2-WeM-1 Design of Multi-Component Rare Earth Silicate EBCs for Property Optimization**, *M. Ridley, C. Miller, R. Webster, H. Olson, A. Salanova, K. Tomko, J. Tomko, J. Ihlefeld,* University of Virginia, USA*; C. Toher,* Duke University, USA*; P. Hopkins,* ***Elizabeth Opila (ejo4n@virginia.edu)***, University of Virginia, USA **INVITED**

Environmental barrier coatings (EBCs) are required for application of SiC-based ceramic matrix composites in hot section turbine engine applications. State of the art EBCs are composed of ytterbium silicates. Multicomponent rare earth (RE) silicates offer the opportunity to simultaneously optimize a multitude of coating properties, including thermal conductivity, steam resistance, calcium magnesium aluminosilicate (CMAS) resistance, and thermal expansion coefficient. Design criteria for RE cation selection in multicomponent RE silicates can be formulated. Thermal conductivity of the EBCs can be reduced via phonon scattering mechanisms attributed to a wide range of RE mass and size. Large RE cations favor formation of an apatite barrier layer limiting further CMAS reactions. Small RE cations favor the beta-phase disilicate and X2 monosilicate with more favorable steam resistance and thermal expansion coefficients. Preliminary results for multicomponent rare earth silicate EBC thermal and thermochemical property optimization will be presented.

8:40am **A2-2-WeM-3 Cyclic Steam Oxidation of Single Layer Ytterbium Disilicate-Based Environmental Barrier Coatings Deposited onto Enhanced Roughness Silicon Carbide**, *K. Kane,* Oak Ridge National Laboratory, USA*; E. Garcia,* Center for Thermal Spray Research, Stony Brook University, USA*; C. Parker, M. Lance, B. Pint,* ***Mackenzie Ridley (ridleymj@ornl.gov)***, Oak Ridge National Laboratory, USA **INVITED**

Environmental barrier coatings (EBCs) are used to protect SiC-based structural components from water vapor induced recession in gas-turbine environments. The current generation of EBCs are typically comprised of a ytterbium disilicate (YbDS) top coat deposited onto a Si bond coat with atmospheric plasma spray. While having already achieved commercial success in the aviation sector, these EBCs are inherently temperature limited by the melting temperature of Si, 1414°C. Increasing EBC application temperatures therefore necessitates the removal of the Si bond coat. In this study, single layer ytterbium disilicate/monosilicate EBCs were deposited directly onto SiC manufactured with enhanced roughness to increase single layer adhesion. 1-h cyclic steam testing was conducted at 1350° and 1425°C, and several variations of ytterbium disilicate based EBCs were tested on several variations of enhanced roughness to investigate the relationship between EBC composition and underlying SiC geometry on both thermally grown oxide formation and coating spallation. This research was funded by the Advanced Turbine Program, Office of Fossil Energy, Department of Energy.

9:20am **A2-2-WeM-5 Raman Spectroscopic Identification of Ytterbium Silicate and Thermally Grown Oxide Silica Phases in Environmental Barrier Coatings**, ***Michael Lance (lancem@ornl.gov)***, *K. Kance, B. Pint,* Oak Ridge National Laboratory, USA

To accurately model the long-term durability of multilayered (bond coat/ top coat) environmental barrier coatings (EBCs), a more complete understanding of the phase composition and transformations of the silica thermally grown oxide (TGO) is desired.For the top coating, mixed Y/Yb silicate EBCs have been proposed as a dual-function thermal/environmental barrier coating that may also offer several other advantages over solely Yb-silicate EBCs. For the TGO formed during thermal cycling in steam, cristobalite formation and subsequent ß- to α-cristobalite transformation has been identified as a potentially life limiting parameter. In this study, Raman micro-spectroscopy was used to both compare top coating phase evolution of mixed Y/Yb- and Yb-silicate EBCs, and to quantify cristobalite formation on a thermally sprayed Si bond coating. This research was funded by the Advanced Turbine Program, Office of Fossil Energy, Department of Energy.

9:40am **A2-2-WeM-6 The Behavior Of Suspension Plasma Sprayed 8YSZ Thermal Barrier Coating With Laser Microtextured Bond Coat Under High Temperature Testing**, ***Pawel Sokolowski (pawel.sokolowski@pwr.edu.pl)***, *T. Kielczawa, M. Nowakowska,* Wroclaw University of Science and Technology, Poland*; R. Musalek, T. Tesar,* Institute of Plasma Physics of the Czech Academy of Sciences, Czechia

Despite intensive development, the Thermal Barrier Coating technology still relies on the idea of oxidation resistant metallic bond coat and thermally insulating ceramic top coat. The interface between these two layers plays a crucial role in how the structure of the TBC system behaves during high-temperature operation. In this work, laser microtexturing is proposed as a method for controlling that interface.

The 80 to 100 µm thick NiCrAlY layer was deposited by Atmospheric Plasma Spraying over the nickel-based super alloy substrate. Then, the infrared fiber nanosecond laser was used for shaping the topography of the bond coat prior to the top coat deposition. The surface geometry was controlled by the laser set-up operational conditions, mainly: (i) laser power, (ii) frequency, (iii) scanning velocity, and (iv) inter-pass spacing. The two groove-based patterns were finally selected for further work together with one as-sprayed bond coat, as a reference. The 8 wt.% yttria stabilized zirconia (8YSZ) was deposited by means of Suspension Plasma Spraying over all three types of bond coats. The samples were then subjected to isothermal oxidation and thermal cyclic fatigue testing to study the influence of bond coat topography on the overall behavior of coatings under high-temperature conditions. Microstructural studies revealed that the tailored bond coat topography may promote the obtaining of a homogeneous, columnar-like top coat. On the other hand, the grooves seem to promote locally the oxidation of the bond coat and the substrate. This means that the microtexture depth plays a crucial role and should be very precisely controlled in order to prolong the TBC lifetime.

11:00am **A2-2-WeM-10 Oxidation and Failure in Environmental Barrier Coatings**, ***Bryan Harder (bryan.harder@nasa.gov)***, *K. Lee, M. Presby,* NASA Glenn Research Center, USA*; J. Setlock,* University of Toledo, USA **INVITED**

The use of silicon carbide (SiC) ceramic matrix composites (CMCs) in turbine engines enables increased operating temperatures and reduced cooling demands, which can reduce cost, increase efficiency, and lower emissions.However, due to reactions with the turbine environment that can cause rapid oxidation and recession of components, SiC/SiC CMCs require a protective barrier called an environmental barrier coating (EBC).Although the EBC provides protection from recession via the gas stream, oxidation of the bond coat or substrate occurs with prolonged exposure during operation.The thermally grown oxide (TGO) layer that forms between the EBC and the bond coat or the substrate is a weak interface that can cause failure of the coating system.In this work, we evaluate the influence of the TGO on coating failure in state-of-the-art and advanced EBC systems.The change in the bond strength with a growing TGO layer is discussed as well as the effect of calcium-magnesium-aluminosilicate (CMAS) glass exposure on TGO kinetics and coating adhesion.

11:40am **A2-2-WeM-12 Impact of Surface Degradation on the Radiative Heat Transfer in Thermal Barrier Coatings**, ***Francis Blanchard (francis.blanchard@polymtl.ca)***, *B. Baloukas, M. Azzi, M. Kadi, J. Sapieha, L. Martinu,* Polytechnique Montreal, Canada

As aircraft engine operating temperatures increase, so must the thermal insulation capabilities of the thermal barrier coatings (TBCs) used to shield metallic components in the combustion chamber and high-temperature turbine areas. Heat transfer from the hot gases to the engine components occurs through two main mechanisms: conduction and radiation. Considerable efforts have been deployed over the years to ensure TBCs have low thermal conductivity, thanks to a porous microstructure generally achieved by thermal spray or EB-PVD techniques. The radiative component of heat transfer, however, has been comparatively largely ignored in TBC design. This issue is compounded by the exponential increase in radiative heat for higher gas temperature.While TBCs are naturally reflective to radiative heat due to scattering, this property is vulnerable to degradation, even more so than their low thermal conductivity.

The two main degradation phenomena threatening TBCs over their lifetime are (1) morphological changes due to high heat exposure (sintering, phase transition, etc…) and (2) chemical attack by CMAS (Calcium-Magnesium-Alumino-Silicate). Fundamental understanding of these two mechanisms is an important aspect in the design and development of high performance TBCs. In this work, the effects of high temperature cycling and CMAS infiltration on the optical performance of Yttria-stabilized zirconia (YSZ) coatings prepared by APS were systematically investigated. Absorption and scattering coefficients have been extracted from spectrophotometry measurements in a novel way via the inverse adding-doubling (IAD) method. The microstructure was analysed using scanning electron microscopy (SEM) and mercury infiltration porosimetry (MIP) in an attempt to establish a relationship between the evolving microstructure and the optical properties. Both were found to have a significant impact on performance, with CMAS infiltration having the biggest impact. A finite-difference time-domain (FDTD) model was developed in order to predict the optical performance of TBCs before and after degradation with good agreement with experimental data. This model could be used to investigate ways to mitigate the effect of this degradation.

12:00pm **A2-2-WeM-13 Development and Characterization of an Environmental Barrier Coating System for Novel Mo-Si-Ti Alloys Using Magnetron Sputtering***, **Ronja Anton (ronja.anton@dlr.de)**, N. Laska, U. Schulz,* German Aerospace Center (DLR), Germany

Mo-Si-Ti-based alloys are promising candidates for future high temperature applications beyond-Ni-based superalloys in turbine engines. Mo-Si-Ti-based alloys have a density of about 7.7 g/cm^3 to 7.0 g/cm^3 depending on the Ti content, which makes them lighter than Ni-based superalloys. Moreover, a better creep resistance at high temperature favors the application. Unfortunately, due to their insufficient oxidation and corrosion behavior especially at intermediate (pest oxidation) and partially at high temperature, the necessity of a protective coating becomes inevitable to perform in an oxidizing and water vapor containing atmosphere. In the present work, a multisource sputter coater was used for the deposition of a four-layer EBC system. The oxidation protection was provided by a dual layer coating system, containing a graded Mo-Si interlayer in order to compensate differences in the coefficient of thermal expansion (CTE) and a top layer of pure Si for the development of the desired thermally grown oxide layer of SiO_2. Coatings were applied by DC magnetron sputtering using pure elemental targets of Mo and Si. Regarding a sufficient water vapor resistance, ytterbium monosilicate (YbMS) is well-known and provides a CTE close to the Mo-based substrate alloys. Consequently, to reinsure the thermodynamic equilibrium between the oxidation protective Si layer and the YbMS, a further intermediate layer of ytterbium disilicate (YbDS) was deposited. The manufacturing of the Yb-based silicate coatings was done by reactive magnetron sputtering using oxygen and pure elemental targets of Yb and Si. Since the Yb target is highly reactive and leans towards poisoning, a parameter study with varying pressures, O_2 flows and target currents was performed to find the optimal operating point and the most stable process window to ensure the required coating composition. Finally, the entire EBC system consists of four different layers.

In this study, the multilayer coating system has been applied by magnetron sputtering on two novel Mo-Si-Ti alloys with a chemical composition of Mo21Si34Ti0.5B and Mo12.5Si8.5B27.5Ti2Fe (in at.%). The produced EBC system on the different alloys was tested at 800 °C and 1200 °C in laboratory air as well as in a streaming water vapor test rig. The emphasis was put on the chemical reactions and diffusion processes within the interfaces of the coating system and that were analyzed by scanning and transmission electron microscopy equipped with EDS respectively. In addition, the phase formation was evaluated using high temperature X-ray diffraction techniques.

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