Coatings for Use at High Temperatures
Room Pacific Salon 2 - Session A2-1-ThM

Thermal and Environmental Barrier Coatings I

Moderators: Sabine Faulhaber, University of California, San Diego, USA, **Kang N. Lee**, NASA Glenn Research Center, USA, **Pantcho Stoyanov**, Pratt & Whitney, USA

8:00am **A2-1-ThM-1 Mechanical Characterization and Modelling Issues for Thermal Barrier Coating Lifetime Assessment***, **Vincent Maurel**, V Guipont,* Mines-ParisTech, France **INVITED**

One of the major challenges for protective coatings is to determine the time to failure of ceramic layer during ageing for both TBC and EBC. For TBC, scenarii of damage have been well established from decades, based on microstructure to damage analysis with an increase use of 3D measurement tools (synchrotron tomography, FIB). The aim of this paper is to review some experiments to modeling issues.

Firstly, the characterization of adhesion is a key factor in the evaluation of time to failure. The measurement of adhesion should be addressed including the analysis of scatter induced by both the methodology of measurement and the "natural" scatter associated to TBC process. Recently, the use of LAser Shock Adhesion Test (LASAT) has shown its capability for both ranking different coating solutions and evaluating the evolution of a given coating as a function of aging [1-2], limiting the scatter associated to measurement. Besides, the laser shock could be used to introduce a defect, an interfacial delaminated area, known in size and location. Thus, local adhesion properties could be determined [2].

Secondly, dealing with modeling of lifetime, different strategies have been discussed in the literature taking into consideration a typical multi-scaled problem. Local analysis of failure has shown its efficiency to model the link to microstructure and aging to local failure. However, for the time being, only macroscopic analysis enables to derive lifetime at the scale-length of a typical component (eg turbine blade). We develop macroscopic lifetime model based on adhesion testing [3,5]. Finally, the robustness of this kind of models has been analyzed through sensitivity analysis based on large numerical sampling. As a conclusion, the propagation of scatter from measurement to life modeling is evaluated and guidelines for experimental focus points have been derived.

References

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8:40am **A2-1-ThM-3 The Effect of Bond Coat Asperity Removal on the Lifetime of Atmospheric Plasma Sprayed Thermal Barrier Coatings***, **Kenneth Kane**,* Oak Ridge National Laboratory, USA*; M Sweet,* Praxair, USA*; M Lance, B Pint,* Oak Ridge National Laboratory, USA

Atmospheric plasma sprayed (APS) MCrAlY (M = Co, Ni) bond coats are inherently rough, typically being comprised of a mixture of convex and concave regions. Initially the roughness provides a high surface area platform for mechanical interlocking of a yttria stabilized zirconia (YSZ) top coat however after high temperature oxidation the convex asperities of the bond coat are prone to form multiphasic, nonhomogeneous thermally grown oxide (TGO). Non-uniform TGO growth is generally thought to have a deleterious effect on top coat adhesion and the removal of these regions should impact coating performance. In the presented work, CoNiCrAlY APS bond coats deposited onto Hastelloy-X substrates were modified to varying degrees (unmodified, lightly modified, and heavily modified) prior to YSZ deposition. The modifications resulted in large asperities being replaced with flat regions, leaving intact concavities and smaller asperities. Samples were isothermally exposed at 1100°C for 100 h to evaluate the effect modification has on TGO formation. Furnace cycle testing (FCT) at 1100°C/1-h was used to gauge the effect modification has on coating lifetime. BS-SEM and EDS analysis of TGO formation and cracking behavior was used to elucidate the changes in FCT lifetime due to modification.

9:00am **A2-1-ThM-4 Effect of Superalloy Substrate on the Lifetime of Electron Beam Physical Vapour Deposited Thermal Barrier Coatings***, **Chen Liu**, Y Chen, P Xiao,* University of Manchester, UK

Previous studies have reported that the cyclic oxidation lifetime of thermal barrier coatings (TBCs) is affected by the composition of superalloy substrates [1-3]. The presence of titanium (Ti) in CMSX-4 has been reported to be detrimental to TBC lifetime because the Ti-rich oxides can degrade the thermally grown oxide (TGO)/bond coat interface adherence [4]. However, the mechanism of how the chemical composition of the substrate affect the lifetime of TBCs is still not fully understood. To further elucidate the effect of substrates on TBCs, the CMSX-4 and René N5 single crystal superalloys have been used as substrates for TBCs with Pt-diffused γ/γ' bond coats and electron beam-physical vapour deposited (EBPVD) yttria-stabilized zirconia (YSZ) top coats. The cyclic oxidation (1 h holding time at 1200°C) test has been carried out on TBCs with different substrates. It was found that TBC deposited on the CMSX-4 substrate exhibited an average lifetime 20% higher than that deposited on the René N5 substrate. Specifically, spallation of TBC occurred mainly along the bond coat/TGO interface for TBC with the René N5 substrate whereas, for TBC with the CMSX-4 substrate, failure occurred mostly along the TGO/YSZ interface and sometimes within the TGO. This suggests that the bond coat/TGO interface for TBC with the René N5 substrate might be degrade by the chemical composition diffused from the substrate into the coating. To confirm this, transmission electron microscope (TEM) with STEM (scanning transmission electron microscope)/EDX (energy-dispersive X-ray) detector was used to examine the TGO/coating interface of TBCs. Segregation of sulfur has been found at the bond coat/TGO interface of TBC with the René N5 substrate, while no impurity segregation was observed at the bond coat/TGO interface of TBC with CMSX-4 substrate. In addition, no Ti-rich oxides was found in the TGO on the CMSX-4 substrate, indicating that the lifetime of this TBC system is not affected by the presence of Ti in the substrate.

Reference

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[2] Bouhanek K, Adesanya OA, Stott FH, Skeldon P, Lees DG, Wood GC. High Temperature Corrosion and Protection of Materials 5, Pts 1 and 2 2001;369-3:615-22.

[3] Tawancy HM, Al-Hadhrami LM. J Eng Gas Turb Power 2011;133.

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9:20am **A2-1-ThM-5 Self-Healing Thermal Barrier Coatings Produced by Laser Processing***, **Bowen Wei**, J Gu, S Joshi, T Huang, N Dahotre, S Aouadi,* University of North Texas, USA

Thermal barrier coatings (TBCs) are widely applied to protect superalloy blades in gas turbines and jet engines that are subjected to high temperatures and corrosive environments. However, the dissimilarities between the coefficients of thermal expansion of the ceramic coatings and metallic substrates will cause thermal stresses and lead to the generation and growth of cracks. This will facilitate oxygen diffusion through the TBC, and a thermally grown oxide (TGO) will be generated between the TBC and the bond coat, which will ultimately lead to failure. A potential effective solution to overcoming this challenge is to grow a self-healing layer on the TBC. In this work, YSZ/Al2O3/SiC and YSZ/Al2O3/TiC self-healing model systems were produced by laser processing with the premise that the healing process occurs as a result of the oxidation of the carbide phase. The formation of the healing oxide phase was observed using X-Ray diffraction and its formation in the crack site was confirmed using cross-sectional scanning electron microscopy. The optimum process parameters to create a self-healing composite were determined. Finally, the impact of the self-healing overlayer on deformation and failure resistance as well as corrosion resistance at elevated temperatures was investigated.

9:40am **A2-1-ThM-6 Influence of Heat Treatment on Thermal Cyclic Fatigue Lifetime of TBC System***, **Jianhong He**, T Sharobem,* Oerlikon Metco, USA

Heat treatment of a component with TBC coating in vacuum is a common industrial practice. However, there is no systematic investigation on its cause. This paper tested thermal cyclic fatigue lifetime of TBC systems heat treated in different levels of vacuum (as sprayed, heat treated in atmosphere, 0.5 mbar and 6.67 x 10 -4 mbar) and found there are significant difference in thermal cyclic fatigue lifetime. Detailed TGO examinations on cross section and EDS analysis indicate that TGO configurations in samples heat treated in different levels of vacuum is rationale of the differences in thermal cyclic fatigue lifetime.

10:20am **A2-1-ThM-8 Effects of Chemical Modification on Bond Coat Oxidation and Internal Stresses in $Yb_2Si_2O_7$ Environmental Barrier Coatings**, ***Benjamin Herren,*** California Institute of Technology, USA; *J Almer,* Argonne National Laboratory, USA; *K Lee,* NASA Glenn Research Center, USA; *K Faber,* California Institute of Technology, USA

A key failure mode of environmental barrier coatings in steam environments is spallation, often caused by a thermally grown oxide (TGO) resulting from oxidation of the bond coat. Safeguarding against this failure mode can increase the usable lifespan of EBCs, with one approach focused on limiting oxide growth rate. This study examines the effects of topcoat compositional modification on oxide growth rate and internal stresses, by addition of Al_2O_3 or Al_2O_3-containing compounds, e.g., mullite and yttrium-aluminum-garnet, of a current state-of-the-art EBC ($Si/Yb_2Si_2O_7$). Cyclic steam oxidation tests of these EBC systems and post-exposure analyses were used to study the effects of oxide additions on TGO growth rate and microstructure; after 1000-hour exposures to high-temperature steam conditions, some modified EBC compositions showed significant reductions to TGO growth – in certain cases, larger than 80 percent. (K. N. Lee, J. Am. Ceram. Soc., doi: 10.1111/jace.15978). X-ray scattering of these same EBC systems at the Advanced Photon Source at Argonne National Laboratory was used to evaluate strain in the multilayer systems as steam oxidation progressed. Strain and the associated internal stresses for modified EBCs were evaluated with respect to TGO thickness and chemistry and compared to the baseline EBC composition for the same exposure conditions.

10:40am **A2-1-ThM-9 Thermal Shock and CMAS Resistant Tunable Self-Healing Thermal Barrier Coatings**, ***Jingjing Gu,*** *B Wei, T Huang, S Bakkar, D Berman, R Reidy, S Aouadi,* University of North Texas, USA

Thermal barrier coatings (TBCs) are used to protect gas turbine blades from oxidation and corrosion. Commercial TBCs often exposed to sand, dust, ash, and other particulates in addition to elevated temperatures. Found in desert sands and volcanic ash, calcia-magnesia-alumina-silicate(CMAS) particles can degrade TBCs through chemical attack, and coating delamination and spallation, thus, limiting the durability of gas turbines in these environments. In this work, laser cladding was used to create a self-healing protective overlayer on TBC coatings to improve chemical and thermal resistance. Self-healing coatings were applied onto traditional yttria-stabilized zirconia (YSZ) layers. $YSZ/Al_2O_3/SiC$ and $YSZ/Al_2O_3/TiC$ overlayer coatings were deposited using a Nd:YAG laser. Within the overlayer, the carbide phase oxidizes and seals the porosity in the TBCs. After thermal cycling and CMAS tests, resulting phases were identified X-Ray diffraction. In addition, cross-sectional scanning electron microscopy was used to investigate the subsurface and interlayer damage and CMAS penetration occurring resulting from thermal cycling. The performance of these overlayered TBC was compared to the traditional TBCs.

11:00am **A2-1-ThM-10 Variables Affecting Steam Oxidation Kinetics of Environmental Barrier Coatings**, ***Kang N. Lee,*** NASA Glenn Research Center, USA

Increased fuel efficiency is obtained through increased thermal efficiency of turbine engines by increasing the overall pressure ratio (OPR). Increased OPR requires increased turbine inlet temperature, which is paced by advances in turbine hot section materials. SiC/SiC Ceramic Matrix Composites (CMCs) are the most promising materials to enable a quantum leap in temperature capability. Environmental Barrier Coatings (EBCs) are an enabling technology for CMCs by protecting them from water vapor-induced recession. Spallation of EBC induced by thermally grown oxide (TGO) resulting from steam oxidation is a key EBC failure mode. A logical approach to improve EBC life, therefore, is to reduce TGO growth rates. A study was undertaken to investigate the effect of two variables, EBC chemistry and CMC substrate, on TGO growth rates. Using Si/Yb2Si2O7 as the baseline, various oxides were added in Yb2Si2O7 to investigate the former, while various CMC substrates were used to investigate the latter. EBC was processed using air plasma spraying. Oxidation kinetics was determined using steam cycling test in 90% H2O + 10% O2. Correlations between oxidation kinetics, chemistry, phase, and microstructure are used to explain the effect of EBC chemistry and CMC substrate on TGO growth rates.

11:20am **A2-1-ThM-11 High Temperature Investigations of Thermochemistry and Phase Stability in the ZrO_2-Y_2O_3-Ta_2O_5 System**, ***Maren Lepple,*** DECHEMA Forschungsinstitut, Technische Universität Darmstadt, Germany; *S Ushakov, K Lilova,* University of California, Davis, USA; *C Macauley, C Levi,* University of California, Santa Barbara, USA; *A Navrotsky,* University of California, Davis, USA

Compositions in the ZrO_2-Y_2O_3-Ta_2O_5 system are of interest for new high performance thermal barrier coating applications due to their promising high-temperature properties. Alongside an extended tetragonal phase field stable to temperatures at least up to 1500 °C obtained by equimolar co-doping of Y^{3+} and Ta^{5+}, the $YTaO_4$ phase field recently attracted attention. Both phase fields of interest lie on the ZrO_2-$YTaO_4$ quasibinary investigated in this work.

For high temperature applications, it is essential to understand phase stabilities and relations as well as energies and driving forces of the stable and metastable phases. Experimental and computational thermodynamics using the method CALPHAD (Computer Coupling of Phase Diagrams and Thermochemistry) gives a self-consistent description of the materials system, facilitating materials development. In this work, the energetics and phase stabilities of several compounds in the ZrO_2-Y_2O_3-Ta_2O_5 system were investigated experimentally. The enthalpies of formation of different phases as a function of composition were determined using high-temperature oxide melt solution calorimetry. Transition temperatures and enthalpies and phase stabilities were explored by differential thermal analysis (DTA) up to 2400 °C and in-situ high temperature synchrotron X-ray diffraction. The very high melting temperatures of the refractory oxides were investigated by measurement of cooling traces using laser melting. The enthalpy of fusion of $YTaO_4$ was determined using drop calorimetry on a laser heated aerodynamically levitated samples. The results will be used for CALPHAD modeling to obtain a comprehensive understanding of the thermochemistry of the quasibinary.

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