Mechanical Properties and Durability of Advanced Environmental Barrier Coatings in Calcium-Magnesium-Alumino-Silicate Environments

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Abstract

Environmental barrier coatings are being developed and tested for use with SiC/SiC ceramic matrix composite (CMC) hot turbine engine components. Several oxide and silicate based compositions are being studied for use as top-coat and intermediate layers in a three or more layer environmental barrier coating system. Specifically, the room temperature Vickers-indentation-facture-toughness testing and high temperature reaction study reactions with Calcium Magnesium Alumino-Silicate (CMAS) or “sand”) are being conducted using advanced testing techniques such as high pressure burner rig tests as well as high heat flux laser tests.

Introduction

Advanced SiC/SiC ceramic matrix composites (CMCs) developed for gas turbine engine hot section component applications are susceptible to environmental attack from harsh combustion and general operation. This is why it is necessary to apply layers of environmental barrier coatings (EBCs) to protect SiC/SiC CMCs. EBC materials have to withstand the extremely high temperature and corrosive environment, and integrate well with the CMCs to ensure excellent thermal cyclic durability. Advanced multi-component oxide and silicate composites are being developed to improve the coating mechanical integrity and environmental stability for CMCs.

SiC/SiC CMC gas turbine components generally require a layered environmental barrier coating system for improved performance, stability, and durability. EBCs are doped with rare earths and other metal oxides to improve their thermal mechanical and physical properties at high temperature. EBC top coats and intermediate coatings are typically made of rareearth doped oxides and silicates. The coatings stability with calcium magnesium alumino-silicates (CMAS), which is sand and a common air born pollutant, is critical. The objective of this study is to determine the mechanical performance of several candidate EBC systems. The stability of candidate EBC material and coating systems in the presence of CMAS is also investigated.

Experimental Procedure

Sample preparation
- Sintering
- Polishing
- Indentation
- SEM/EDS
- Reaction and chemical change
- Pressure and void generation

CMAS Reaction and Behavior

CMAS Reaction

- Oxides
  - SiO2
  - TiO2
  - Al2O3
- Silicate
  - Barium Strontium Alumino-Silicate (BSAS)
  - Al6Si2O13 (Mullite)
- EBC Reaction
  - Oxides
    - SiO2
    - TiO2
  - Silicate
    - Al6Si2O13 (Mullite)
  - BSAS
    - Al6Si2O13 + 20wt% BSAS
  - HfO2
    - HfO2 + 50wt% Al2O3
  - Y2Si2O7
    - Y2Si2O7 + 20%BSAS

Sample Configurations

- For a diameter 3.18 mm thick disc specimens
- Hybrid Air EB-PVD coating system consists of mixture of ZrO2, SiC, and BSAS silicate system
- Laser high heat flux testing

Results

Fracture Toughness

Hardness Vickers

Laser Heat Flux Testing

Figure 2: The initial vickers indentation results of non-CMAS-reacted coatings. (a) the mean value of each samples Kc was measured from the crack lengths. ZrO2 311 was the toughest material. (b) the samples HV as measured using the load of the diagonals. Hardness data was easily taken from the fracture toughness tests so (b) shows the hardest material as the HfO2 + 5wt%Y2O3.

Figure 4: (above) Laser-high-heat flux tests were conducted on three structurally identical samples. With surface concentration increasing from left to right it is evident that the CMAS is causing damage and melting of the coatings. (Left) the increase in conductivity is due to the continued etching from the high temperatures.

Figure 6: (right) Shows the increasing thickness of various layers of mullite. Each layer represents a different effect CMAS had. Time in hours is on the x axis. Depths is on the y axis.

Concluding Remarks

Initial fracture toughness testing using the Vickers indentation approach has shown that the ZrO2 and HfO2 coating materials are the most fracture resistant. Further testing is being considered to determine the structure and fracture toughness of materials reacted with CMAS.

Seven mechanisms of CMAS interactions with the coating materials have been identified. While the oxides were more stable than the silicates, they were still affected by penetration and void generations from CMAS especially when initial high pressure is present. Silicates reacted strongly with the CMCs generally decreasing the melting point and causing the coating to change phases as evidenced from x-ray diffraction such as in Y2Si2O7 case. Some coating materials experienced combinations of all of the effects. The laser high heat flux tests showed the damage and potentially reduced temperature capability caused by the CMAS on a multilayer hybrid EB-PVD Plasmaspray oxide-silicate EBC. This can be fatal to the coating structure as the operating temperature approaches the melt point of these materials after reacting with CMAS. The HIPBR tests showed that the CMAS-reacted Er2SiO5 seemed to be damaged (dilacination and disintegration) and had higher recession rates compared to the non-reacted Er2SiO5.

While these studies are not complete, the current results easily showed that CMAS can cause serious damage to the coating or coating materials. Coating that have improved resistance to CMAS must be designed and tested for advanced EBC systems.

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Figure 5: (above) Shows the recession of TA SiC Composite as well as the recession of the Er2SiO5 and TA SiC Composite No.11, No.12 and TA SiC Composite No. 8 - early study. The high pressure burner rig (HPBR) tests showed that the CMAS-reacted Er2SiO5 seemed to be damaged (dilacination and disintegration) and had higher recession rates compared to the non-reacted Er2SiO5. This photo illustrates the combined effects of penetration, gas, void generation, reaction/chemical change, and melting.

Figure 7 (left) SEM backscatter electron image with three images stitched together. Y2Si2O5 exposed to CMAS twice for a total of 100 hours. This photo illustrates the combined effects of penetration, gas, void generation, reaction/chemical change, and melting.

Figure 8: (above) Shows the recession of TA SiC Composite as well as the recession of the Er2SiO5 with a higher recession rate.

CMAS Reaction Depths

Time (hr)

Thermal conductivity, W/m-K

Figure 9: (right) Shows the increasing thickness of various layers of mullite. Each layer represents a different effect CMAS had. Time in hours is on the x axis. Depths is on the y axis.

CMAS-Reaction Depths

Figure 10: (above) Hybrid EB-PVD coating system consisting of mixture of ZrO2 and silicate system

High Pressure Burner Rig Test – Tyrannohex SA and Er2SiO5

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