Thermochemistry of Calcium-Magnesium-Aluminum-Silicate (CMAS) and Components of Advanced Thermal and Environmental Barrier Coating Systems

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Summary

There is increasing interest in the degradation mechanism studies of thermal and environmental barrier coatings (TEBCs) of gas turbines by molten calcium-magnesium-aluminum-silicate (CaO-MgO-Al2O3-SiO2, CMAS). CMAS minerals are usually referred to as silicon-containing sand dust and volcano ash materials that are carried by the intake air into gas turbines (e.g., in aircraft engines), and their deposits often react at high temperatures (>1200 °C) with the engine turbine coating systems and components. The high-temperature reactions cause degradation and accelerated failure of the static and rotating components of the turbine engines. Some results of the reactions between the CMAS and rare-earth (RE = Y, Yb, Dy, Gd, Nd, and Sm)-oxide-stabilized ZrO2 or HfO2 systems are discussed as well as the stability of the resulting oxides and silicates. Plasma-sprayed hollow-tube samples (outside diameter \( \varnothing = 4.7 \) mm, wall thickness = 0.76 mm, and height = 26 mm) were half filled with CMAS powder, wrapped and sealed with platinum foil, and heat treated at 1310 °C for 5 h. Samples were characterized by differential scanning calorimetry, X-ray diffraction, electron microscopy analysis of cross sections, and energy dispersive X-ray spectroscopy. It was found that CMAS penetrated the samples at the grain boundaries and dissolved the TEBC materials to form silicate phases containing the RE elements. Furthermore, it was found that apatite crystalline phases were formed in the samples with total RE content higher than 12 mol% in the reaction zone for the ZrO2 system. In general, samples with the nominal compositions 30% yttria-stabilized zirconia (30YSZ), HfO2-7Dy2O3, and ZrO2-9.5Y2O3-2.25Gd2O3-2.25Yb2O3 exhibited lower reactivity or more resistance to CMAS than the other coating compositions of this work.

Introduction

Thermal and environmental barrier coatings (TEBCs) are critical for next-generation turbine engines because of their ability to allow the implementation of lightweight and high-temperature SiC/SiC engine ceramic matrix composite (CMC) components (Refs. 1 and 2). The incorporation of SiC/SiC CMC hot-section components in high-pressure turbine engine systems will enable engine designs with higher
inlet temperatures, higher thrust-to-weight ratio, and reduced cooling, thus helping to significantly improve engine efficiency and performance. However, a prime-reliant coating system design approach is particularly important to implement the CMC technology in the turbine engine systems to fully protect the ceramic components in combustion and harsh operation environments. In particular, in order to meet the environmental barrier coating (EBC) protection requirements to prevent the SiC/SiC CMC from water vapor attack for in-turbine-engine combustion environments (Refs. 1, 3, and 4), advanced ZrO₂, HfO₂, and rare earth (RE) silicate EBC systems have also been proposed as candidate coating materials to improve temperature capability and environmental protection of SiC/SiC CMCs because of their exceptional stabilities in the turbine combustion environments (Refs. 1, 5, and 6).

The significantly higher operating temperatures envisioned for next-generation turbine engine hot-section CMC components impose significant material design challenges and also raise serious component environmental durability issues. During engine operation, entrained road-sand calcium-magnesium-aluminum-silicate (CaO·MgO·Al₂O₃·SiO₂, CMAS) deposits on the turbine TEBCs and components form glassy melts, which can significantly reduce the TEBC and silicon-based ceramic component temperature capability. It is critical to understand the high-temperature interactions between the coating materials and CMAS in order to develop advanced CMAS-resistant coatings. Some more recent work has been done to determine the mechanisms by which CMAS can cause failure and performance degradations in yttria-stabilized zirconia (YSZ) thermal barrier coatings (TBCs) and RE silicate TEBCs (Refs. 7 to 13).

The objective of this report is to investigate the thermochemistry reactions and stability of advanced plasma-spray-processed ZrO₂ and HfO₂ TEBCs in contact with CMAS at high temperature. Although the ZrO₂ and HfO₂ systems have been used and classified as a TBC material, this report explores the possibility of improving these ceramic systems containing RE elements in an EBC system. Thus, these advanced coating systems are named here “thermal and environmental barrier coatings,” or TEBCs. A particular emphasis has been placed on the effect of yttria and RE dopants on the CMAS resistance in the advanced ZrO₂ and HfO₂ systems, and on correlating with the dopant oxides. The information will also help in understanding the reaction mechanisms of ZrO₂ and HfO₂, which may help in developing a more CMAS-resistant coating system for CMC components in next-generation turbine engines.

**Experimental Materials and Methods**

**Materials**

Ceramic powders based on rare-earth- (RE = Y, Yb, Dy, Gd, Nd, and Sm) oxide-stabilized ZrO₂ or HfO₂ systems were air plasma sprayed onto 1/8-in. Ø graphite bar substrates to form 0.030-in.-thick coatings. These materials were selected because they have been developed as low-conductivity TBCs for turbine engine applications (Ref. 14). The air-plasma-sprayed specimens were sintered at 1500 °C for 5 h, resulting in hollow-tube samples (outside diameter Ø = 4.7 mm, wall thickness = 0.76 mm, and height = 26 mm). Following sintering, the samples were half filled with NASA-composition CMAS powder (Ref. 15) synthesized by Washington Mills Ceramics Corporation (Sun Prairie, WI) using NASA specifications, wrapped and sealed with platinum foil, and heat treated at 1310 °C for 5 h. All the samples, including the hollow tubes and NASA CMAS, were characterized before and after reaction by differential scanning calorimetry (DSC), X-ray diffraction (XRD), and electron microscopy analysis of cross sections (details of the characterization techniques are given in the Sample Characterization section).

**Sample Characterization**

The sintered hollow-tube specimens were analyzed by helium picnometry and by nitrogen adsorption in a surface characterization analyzer (3Flex, Micrometics Instrument Corporation, Norcross, GA). The pristine NASA composition CMAS and the reacted hollow-tube samples with CMAS were ground in an agate mortar and analyzed by XRD on a Bruker D8 Discover diffractometer (Bruker-AXS GmbH, Karlsruhe, Germany). The NASA pristine powder was also characterized by nitrogen adsorption;
inductively coupled plasma optical emission spectroscopy (ICP–OES) at NSL Labs, Cleveland, OH; field emission scanning electron microscopy (FE–SEM) Hitachi S–4700–II (Hitachi High Technologies, Gaithersburg, MD) equipped with energy dispersive X-ray spectroscopy (EDS) (EDAX, Mahwah, NJ), secondary electron (SE), and backscatter electron (BSE) detectors; and differential scanning calorimetry (DSC) thermal analysis using a Netzsch Model F1 Pegasus® calorimeter (Netzsch GmbH, Selb, Germany). The evolution of the reaction between NASA composition CMAS and ZrO2-30Y2O3 powder samples (1:2 mass ratio) was also characterized by DSC thermal analysis. The lower and upper section of the reacted hollow-tube samples were cut at approximately 3 mm from their end and mounted in a PolyFast® resin (Struers), polished using a nonaqueous solution. The mounted samples were carbon coated and analyzed by FE–SEM coupled with EDS.

Results

The composition of the sintered hollow-tube samples (Table I) analyzed by EDS are similar to the nominal compositions. The EDS analysis of the samples was performed at 30 kV, and the amount of zirconium and yttrium was obtained from their Kα lines since they do not overlap. Instead of coating the samples, a charge compensator probe was used to dissipate charging at their surface.

Table II shows the initial parameters of the hollow-tube samples (Brunauer-Emmet-Teller (BET) specific surface area, density, surface area and total volume of pores, and CMAS surface concentration) measured by N2 gas adsorption, He picnometry, and geometric and gravimetric methods. The samples are well sintered, and their relative density (ρgeometric·100/ρhelium) ranges from 90 to 100 percent. The specific surface area of the hollow tubes are also very low (<0.01 to 0.3 m²/g), indicating that the samples are well sintered. The samples also exhibit very small pore volume (3 ×10⁻⁵ to 30 ×10⁻⁵ cm³/g) and surface area (0.001 to 0.16 m²/g).

Table III shows a comparison of the composition of NASA CMAS measured by EDS and ICP–OES analyses. The NASA CMAS compositions measured by EDS and ICP-OES are the same—within the experimental error—with the exception of Al₂O₃, which is slightly different: the Al₂O₃ content measured by EDS is 1.9±0.8 mol% higher than that measured by ICP–OES.

Figure 1 shows the XRD pattern of the as-received CMAS powder. The as-received CMAS sample analyzed by powder XRD followed by quantitative phase analysis using a whole-pattern-fitting procedure (Rietveld refinement) was determined to be 66.4±0.9 percent amorphous, 23.5±0.7 percent Ca₂Mg₉₀.₆₆Al₉₀.₃₆Si₁₅.₂₂O₇ (PDF card 98-000-9495), 6.6±0.4 percent CaSiO₄ (PDF card 04-016-5334), and 3.5±0.1 percent SiO₂ (PDF card 00-046-1045).

### Table I. Chemical Composition of Sintered Hollow-Tube Samples Measured by Energy Dispersive X-Ray Spectroscopy

<table>
<thead>
<tr>
<th>Sample (nominal composition)</th>
<th>Content, a,b mol%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HfO₂</td>
</tr>
<tr>
<td>I: ZrO₂-12Y₂O₃</td>
<td>-----</td>
</tr>
<tr>
<td>II: ZrO₂-30Y₂O₃</td>
<td>-----</td>
</tr>
<tr>
<td>III: HfO₂-7Dy₂O₃</td>
<td>93(3)</td>
</tr>
<tr>
<td>IV: ZrO₂-9.5Y₂O₃-4.5Gd₂O₃-4.5Yb₂O₃</td>
<td>84(3)</td>
</tr>
<tr>
<td>V: ZrO₂-9.5Y₂O₃-2.25Gd₂O₃-2.25Yb₂O₃</td>
<td>77(2)</td>
</tr>
<tr>
<td>VI: ZrO₂-3Y₂O₃-5Sm₂O₃-1.5Yb₂O₃</td>
<td>94(3)</td>
</tr>
<tr>
<td>VII: ZrO₂-3Y₂O₃-1.5Nd₂O₃-1.5Yb₂O₃-0.3Sc₂O₃</td>
<td>92(3)</td>
</tr>
</tbody>
</table>

a Derived formulas from measured contents of oxides are
I: Zr₀.₇₇±₀.₀₃Y₀.₂₂±₀.₀₀9O₂.₀₀±₀.₀₆
II: Zr₀.₅₃±₀.₀₂Y₀.₄₇±₀.₀₀₇O₂.₀₀±₀.₀₅
III: Hf₀.₈₈±₀.₀₄Dy₀.₁₂₅±₀.₀₀₉O₂.₀₀±₀.₀₇
IV: Zr₀.₇₃±₀.₀₃Y₀.₇₅±₀.₀₀₅Gd₀.₀₅₆±₀.₀₀₁Yb₀.₀₄₅±₀.₀₀₁O₂.₀₀±₀.₀₆
V: Zr₀.₇₃±₀.₀₃Y₀.₇₅±₀.₀₀₅Gd₀.₀₅₆±₀.₀₀₁Yb₀.₀₄₅±₀.₀₀₁O₂.₀₀±₀.₀₆
VI: Zr₀.₇₃±₀.₀₃Y₀.₇₅±₀.₀₀₅Gd₀.₀₅₆±₀.₀₀₁Yb₀.₀₄₅±₀.₀₀₁O₂.₀₀±₀.₀₆
VII: Zr₀.₇₃±₀.₀₃Y₀.₇₅±₀.₀₀₅Gd₀.₀₅₆±₀.₀₀₁Yb₀.₀₄₅±₀.₀₀₁O₂.₀₀±₀.₀₆

b Uncertainties calculated as two standard deviations of the mean are given in parentheses.
**TABLE II.—INITIAL PARAMETERS OF SINTERED HOLLOW-TUBE SAMPLES**

<table>
<thead>
<tr>
<th>Sample</th>
<th>CMAS surface concentration, b g/cm²</th>
<th>BET specific surface area, c m²/g</th>
<th>Surface area of pores, d m²/g</th>
<th>Total pore volume ×10⁻⁵, cm³/g</th>
<th>Density, g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: ZrO₂-12Y₂O₃</td>
<td>147±4</td>
<td>0.038±0.004</td>
<td>0.024±0.002</td>
<td>3.6±0.4</td>
<td>5.13±0.003</td>
</tr>
<tr>
<td>II: ZrO₂-30Y₂O₃</td>
<td>69±2</td>
<td>0.307±0.03</td>
<td>0.11±0.01</td>
<td>28±3</td>
<td>5.13±0.03</td>
</tr>
<tr>
<td>III: HfO₂-7Dy₂O₃</td>
<td>135±4</td>
<td>&lt;0.01</td>
<td>0.07±0.01</td>
<td>14±1</td>
<td>8.23±0.02</td>
</tr>
<tr>
<td>IV: ZrO₂-9.0Y₂O₃-4.5Gd₂O₃-4.5Yb₂O₃</td>
<td>142±4</td>
<td>0.12±0.01</td>
<td>0.036±0.004</td>
<td>12±1</td>
<td>6.18±0.003</td>
</tr>
<tr>
<td>V: ZrO₂-9.5Y₂O₃-2.25Gd₂O₃-2.25Yb₂O₃</td>
<td>104±3</td>
<td>0.12±0.01</td>
<td>0.013±0.001</td>
<td>13±1</td>
<td>6.07±0.003</td>
</tr>
<tr>
<td>VI: ZrO₂-3Y₂O₃-1.5Sm₂O₃-1.5Yb₂O₃</td>
<td>89±3</td>
<td>&lt;0.01</td>
<td>0.16±0.02</td>
<td>30±3</td>
<td>5.8±0.2</td>
</tr>
<tr>
<td>VII: ZrO₂-3Y₂O₃-1.5Nd₂O₃-1.5Yb₂O₃-0.3Sc₂O₃</td>
<td>91±3</td>
<td>&lt;0.01</td>
<td>0.0010±0.0001</td>
<td>3.0±0.3</td>
<td>5.3±0.2</td>
</tr>
</tbody>
</table>

*aComposition of the samples given in mol%.
*bCalcium-magnesium-aluminum-silicate (CMAS).
*cBrunauer-Emmett-Teller (BET).
*dCumulative measured by BJH (Barrett-Joyner-Halenda) method for pores between 8.5 Å and 150 μm.
*eMeasured in optical microscope.

**TABLE III.—COMPARISON OF TARGETED NASA CALCIUM-MAGNESIUM-ALUMINUM-SILICATE (CMAS) COMPOSITIONS MEASURED BY INDUCTIVELY COUPLED PLASMA OPTICAL EMISSION SPECTROSCOPY (ICP–OES) AND ENERGY DISPERSIVE X-RAY SPECTROSCOPY (EDS)**

<table>
<thead>
<tr>
<th>Method</th>
<th>CaO</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>Fe₂O₃</th>
<th>NiO</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP–OES</td>
<td>30±2</td>
<td>5.3±0.3</td>
<td>11.9±0.6</td>
<td>42±2</td>
<td>8.7±0.4</td>
<td>1.5±0.1</td>
</tr>
<tr>
<td>EDS</td>
<td>29.8±0.2</td>
<td>5.9±0.4</td>
<td>13.8±0.5</td>
<td>41.5±0.9</td>
<td>8.0±0.5</td>
<td>1.0±0.4</td>
</tr>
</tbody>
</table>

Figure 1.—X-ray diffraction patterns of as-received calcium-magnesium-aluminum-silicate (CMAS) sample.
Figure 2.—Differential scanning calorimetry (DSC) traces of calcium-magnesium-aluminum-silicate (CMAS) during heating (solid line) up to 1500 °C at 5 °C/min and then cooling (dashed line).

Figure 2 shows the DSC traces of the NASA CMAS during heating up to 1500 °C (at 5 °C/min) and cooling to room temperature. Four heat effects were observed on heating of the sample to 1500 °C. The first weak endothermic peak, with onset temperature at 692 °C, corresponds to glass transition (Tg) of the sample. The weak Tg endothermic peak is followed by two exothermic peaks, with onset temperatures at 856 and 965 °C, that are related to crystallization of the glass phase. The strongest endothermic peak, related to melting of the NASA CMAS sample, is observed at 1195 °C (onset temperature). During cooling from 1500 °C to room temperature, only an exothermic peak with onset temperature at 1144 °C is observed in the DSC trace. This exothermic peak during cooling corresponds to crystallization of the melted sample. The four heat effects observed in this thermal study corroborates well with those from a previous study (Ref. 16) detected in a differential thermal analysis (DTA) instrument up to 1500 °C at a heating rate of 5 °C/min for a CMAS sample having a different composition (34 wt% SiO2, 30 wt% CaSO4·2H2O, 17 wt% SiO2+KAlSi3O8, 14 wt% dolomite CaMg(CO3)2, and 5 wt% NaCl).

Figure 3 shows the DSC traces of the NASA CMAS mixed with the 30% YSZ powder coating during heating up to 1500 °C. In addition to the four heat effects related to the NASA CMAS sample (Fig. 2), an endothermic peak with onset temperature at 1258 °C is observed in the DSC trace. This endothermic peak corresponds to the reaction between the NASA CMAS and 30YSZ samples.

SEM images at lower magnification (30× to 80×) of cross sections of the lower cut sections of the hollow-tube samples reacted with CMAS at 1310 °C for 5 h are shown in Figure 4. Note that because of the magnification limits of the SEM instrument, only part of the cross-sectional areas of the hollow tubes were imaged. CMAS reacted and penetrated the inner and outer walls of the platinum-foil-wrapped hollow-tube material, causing an expansion of their volume. Voids or pockets formed after the reaction of the samples and CMAS. The HfO2-7Dy2O3 (7DySH) sample III exhibited the lowest CMAS penetration, or highest resistance to CMAS, followed by samples V (ZrO2-9.5Y2O3-2.25Gd2O3-2.25Yb2O3) and II (30YSZ). The 25-μm layer observed on the outer wall of the hollow tube is the platinum foil used to wrap and seal the hollow tubes containing CMAS.
Figure 3.—Differential scanning calorimetry (DSC) traces of calcium-magnesium-aluminum-silicate (CMAS) mixed with sample II ZrO$_2$-30Y$_2$O$_3$ (1:2 weight ratio) during heating up to 1500 °C at 5 °C/min.

Figure 4.—Scanning electron microscopy images at low magnification of lower section of cross sections of ceramic hollow-tube samples reacted with calcium-magnesium-aluminum-silicate (CMAS) at 1310 °C for 5 h. (a) I: ZrO$_2$-12Y$_2$O$_3$. (b) II: ZrO$_2$-30Y$_2$O$_3$. (c) III: HfO$_2$-7Dy$_2$O$_3$. (d) IV: ZrO$_2$-9.0Y$_2$O$_3$-4.5Gd$_2$O$_3$-4.5Yb$_2$O$_3$. (e) V: ZrO$_2$-9.5Y$_2$O$_3$-2.25Gd$_2$O$_3$-2.25Yb$_2$O$_3$. (f) VI: ZrO$_2$-3.0Y$_2$O$_3$-1.5Sm$_2$O$_3$-1.5Yb$_2$O$_3$. (g) VII: ZrO$_2$-3.0Y$_2$O$_3$-1.5Nd$_2$O$_3$-1.5Yb$_2$O$_3$-0.3Sc$_2$O$_3$. 
SEM images at higher magnification (3000×) of the hollow-tube sample cross sections reacted with NASA CMAS at 1310 °C for 5 h are shown in Figure 5. The areas imaged are near to the inner edge of the hollow-tube walls and are referred to here as “reacted regions.” CMAS melted, reacted, or penetrated the coating material through the grain boundaries as seen in the dark areas of the electron micrographs. Sample V ZrO₂-9.5Y₂O₃-2.25Gd₂O₃-2.25Yb₂O₃ is the only one that the (dark area) grain boundary is not evident from the image at 3000× magnification. The grains in the samples with total rare earth (RE₂O₃) content up to 12 mol% are approximately of the same shape and have their boundaries rounded, with possible exception of the HfO₂ coating. Samples with total RE₂O₃ content higher than 12 mol% exhibited rectangular-shaped grains in addition to the rounded grains in their microstructure.

Chemical composition of the samples measured by EDS analysis are given in Table IV. The grain boundaries of the reacted samples I to IV, VI, and VII are rich in SiO₂ (33 to 51 mol%) and CaO (25 to 48 mol%) with minor amounts of ZrO₂ (2 to 20 mol%) for the zirconia-based samples I and IV to VII; HfO₂ (0.8 mol%) for the hafnia sample; RE oxides (0.9 to 4 mol%, total); MgO (6 to 11 mol%); and Al₂O₃ (2 to 9 mol%). In addition to the major components of CMAS detected by EDS in the grain boundary of the reacted samples, 2 to 5 mol% Fe₂O₃ was detected in samples I, III, IV, VI, and VII, and 1 mol% NiO was detected in samples I and IV. EDS analysis detected high contents of SiO₂ (43 mol%), CaO (16 mol%), and Y₂O₃ (22 mol%) in grains 2 and 4 of sample V (Fig. 5). Note the grain boundary is not observed in the SEM image of this sample (Fig. 5). In addition to the CMAS-rich components detected in the grain boundaries of samples II and IV, EDS analysis also detected high contents of CaO...
(21 mol%), SiO₂ (43 mol%), and Y₂O₃ (31 mol%) in grain 2 of sample II as well as high contents of CaO (11 mol%) and SiO₂ (43 mol%) and a low content of Y₂O₃ (2 mol%) in grains 1 to 3 of sample IV. In general, the grains of the reacted samples that retained most of their initial composition still exhibited minor amounts of SiO₂ (2 to 4 mol%), CaO (3 to 6 mol%), MgO (0 to 1 mol%), Al₂O₃ (0.2 to 0.5 mol%), and Fe₂O₃ (0.5 to 2 mol%).

The XRD pattern of the lower section of hollow-tube samples reacted with CMAS are presented in Figures 6 to 12. Fluorite or cubic symmetry (PDF card 01-077-2115) was detected by XRD analysis as the main crystalline phase in the zirconia-based samples with initial RE content higher than 12 mol%. Beyond the cubic phase, hexagonal or oxyapatite silicate secondary phases Ca₄Y₆O(SiO₄)₆ (PDF card 00-027-0093) and Ca₄Y₆(SiO₄)₃O (PDF card 04-007-9210) were detected by XRD in samples IV ZrO₂-9Y₂O₃-4.5Gd₂O₃-4.5Yb₂O₃ and V ZrO₂-9.5Y₂O₃-2.25Gd₂O₃-2.25Yb₂O₃, respectively. Hexagonal Zr₃Yb₄O₁₂ (PDF card 04-002-0210) secondary phase was also detected in sample V ZrO₂-9.5Y₂O₃-2.25Gd₂O₃-2.25Yb₂O₃. There were three different secondary phases (hexagonal Ca₄Y₆O(SiO₄)₆, PDF card 00-027-0093; hexagonal Ca₄Y₆(SiO₄)₃O, PDF card 04-007-9210; and cubic Mg₅Y₆Si₅O₂₄, PDF card 00-020-0696) detected by XRD in sample II 30YSZ. XRD only detected tetragonal crystalline phases in zirconia-based samples VI ZrO₂-3Y₂O₃-1.5Sm₂O₃-1.5Yb₂O₃ and VII ZrO₂-3Y₂O₃-1.5Nd₂O₃-1.5Yb₂O₃-0.3Sc₂O₃. Cubic (PDF card 04-005-6040) and monoclinic (PDF card 98-001-7637) phases were detected in the reacted hafnia-based sample HfO₂-7Dy₂O₃.
<table>
<thead>
<tr>
<th>Sample a</th>
<th>Content, b mol%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HfO₂</td>
</tr>
<tr>
<td>I G 1, 2, 3, 4</td>
<td>81(1)</td>
</tr>
<tr>
<td>II G 1</td>
<td>75(2)</td>
</tr>
<tr>
<td>G 2</td>
<td>33(2)</td>
</tr>
<tr>
<td>GB 3</td>
<td>4.8(2)</td>
</tr>
<tr>
<td>III G 2</td>
<td>85(5)</td>
</tr>
<tr>
<td>GB 1</td>
<td>0.8(5)</td>
</tr>
<tr>
<td>IV G 1, 2, 3</td>
<td>52(1)</td>
</tr>
<tr>
<td>G 4, 5</td>
<td>77(6)(9)</td>
</tr>
<tr>
<td>GB 6</td>
<td>7.7(4)</td>
</tr>
<tr>
<td>V G 1, 3</td>
<td>79(1)</td>
</tr>
<tr>
<td>G 2, 4</td>
<td>5.4(3)</td>
</tr>
<tr>
<td>VI G 1, 2, 3</td>
<td>86.4(8)</td>
</tr>
<tr>
<td>G 4, 5</td>
<td>9.4(5)</td>
</tr>
<tr>
<td>VII G 1, 3</td>
<td>87(2)</td>
</tr>
<tr>
<td>GB 2</td>
<td>2.2(3)</td>
</tr>
</tbody>
</table>

aI: ZrO₂-12Y₂O₃ (see Fig. 5(a))  
II: ZrO₂-30Y₂O₃ (see Fig. 5(b))  
III: HfO₂-12Dy₂O₃ (see Fig. 5(c))  
IV: ZrO₂-9Y₂O₃-4.5Gd₂O₃-4.5Yb₂O₃ (see Fig. 5(d))  
V: ZrO₂-9.5Y₂O₃-2.25Gd₂O₃-2.25Yb₂O₃ (see Fig. 5(e))  
VI: ZrO₂-3Y₂O₃-1.5Sm₂O₃-1.5Yb₂O₃ (see Fig. 5(f))  
VII: ZrO₂-3Y₂O₃-1.5Nd₂O₃-1.5Yb₂O₃-0.3Sc₂O₃ (see Fig. 5(g))  
G is grain, and GB is grain boundary.  
bUncertainties calculated as two standard deviations of the mean are given in parentheses.
Figure 6.—X-ray diffraction pattern of ground lower section of 12% yttria-stabilized zirconia (YSZ) hollow-tube sample I reacted with calcium-magnesium-aluminum-silicate (CMAS).

Figure 7.—X-ray diffraction pattern of ground lower section of 30% yttria-stabilized zirconia (YSZ) hollow-tube sample II reacted with calcium-magnesium-aluminum-silicate (CMAS).
Figure 8.—X-ray diffraction pattern of ground lower section of HfO$_2$-7Dy$_2$O$_3$ (7DySH) hollow-tube sample III reacted with calcium-magnesium-aluminum-silicate (CMAS).

Figure 9.—X-ray diffraction pattern of ground lower section of ZrO$_2$-9.0Y$_2$O$_3$-4.5Gd$_2$O$_3$-4.5Yb$_2$O$_3$ hollow-tube sample IV reacted with calcium-magnesium-aluminum-silicate (CMAS).

Figure 10.—X-ray diffraction pattern of ground lower section of ZrO$_2$-9.5Y$_2$O$_3$-2.25Gd$_2$O$_3$-2.25Yb$_2$O$_3$ hollow-tube sample V reacted with calcium-magnesium-aluminum-silicate (CMAS).
Discussion

CMAS first melted before it penetrated or reacted with the samples at the grain boundaries via melt/solid-state diffusion, forming a CMAS compound containing the REs, zirconium, or hafnium. The products of the reaction or phases detected in this work and the penetration mechanisms of CMAS corroborates well with those found by Ahlborg and Zhu (Ref. 17) in the HfO₂-23.9 mol% (Gd, Yb, Y)₂O₃ and ZrO₂-4.4 mol% (Y, Gd, Yb)₂O₃-2.6 mol% (TiO₂ + Ta₂O₅) compositions reacted with CMAS (35 mol% CaO-10 mol% MgO-7 mol% Al₂O₃-48 mol% SiO₂ with minor amounts of Fe₂O₃ and NiO, provided by General Electric) at 1500 °C for 100 h. In this work, EDS analysis detected high contents of silicon and oxygen in the grain boundaries of the samples with a total amount of REs up to 12 mol%. Note that no silicate phase was detected by XRD in these samples implying that its content was below the detection limit of the XRD instrument or that the silicate phase is amorphous. Above 12 mol% REs, this silicate compound or phase may have crystallized into oxyapatite phases (Ca₄Y₆O(SiO₄)₆ and CaY₄(SiO₄)₃O as evident from the XRD, depending on the sample), which were formed only in the samples with a total amount of REs higher than 12 mol%. Note that some elemental substitutions are possible in the structural sites of the phases; for example, calcium can be replaced by magnesium, and yttrium can be replaced by...
aluminum, iron, or other REs. These substitutions are evident in the grains 1, 2, and 3 of sample IV since elements other than calcium, yttrium, and silicon are detected by EDS in this sample.

The fact that the CMAS did not completely penetrate sample V (ZrO$_2$-9.5Y$_2$O$_3$-2.25Gd$_2$O$_3$-2.25Yb$_2$O$_3$) when compared with sample IV (ZrO$_2$-9.0Y$_2$O$_3$-4.5Gd$_2$O$_3$-4.5Yb$_2$O$_3$) containing the same elements, but with higher RE content, may be due to possible actual higher Y$_2$O$_3$ content in the sample, thus leading to higher Y$_2$O$_3$ in the CMAS melt and helping the complete conversion of CMAS and the sample material to the final products of the reaction or crystalline phases oxyapatite (CaY$_4$(SiO$_4$)$_3$O) and Zr$_3$Yb$_4$O$_{12}$.

Note that sample IV (ZrO$_2$-9.0Y$_2$O$_3$-4.5Gd$_2$O$_3$-4.5Yb$_2$O$_3$) contained the same elements, but with lower Y$_2$O$_3$ and higher RE content, and exhibited amorphous and crystalline phases, indicating that reaction reached an equilibrium where the most stable phases formed were cubic zirconia, oxyapatite, and amorphous silicate phases. The higher RE contents of this sample might have led to a RE–CMAS melt composition that does not favor a stability field for the crystalline oxyapatite phases. In contrast, the 30YSZ sample with higher content of Y$_2$O$_3$ was more resistant (less penetration) to the CMAS melt than the 12YSZ sample with lower yttrium content. For this system containing only zirconia and yttria, the lower Y$_2$O$_3$ content of the 12YSZ was not enough to react with the CMAS melt to form stable oxyapatite crystalline phases at the temperature of the reaction. From these observations, we conclude that the most resistant samples to CMAS penetration are those in which potentially higher melting glass CMAS forms, or only samples that favor the formation of crystalline phases between the reaction of a vast amount of CMAS material and a minimum amount of RE. Although the relation between the stability field of the competing phases in the system involving the sample and CMAS melt works well to explain our initial findings, further work exploring other parameters as kinetics and the effect of the RE oxide clusters of reduced coating solid diffusivity still need to be done. Based on the current results, the combination of high stability composition cluster oxide coating materials and dopant elements stabilize the CMAS melts and are likely to contribute to a more CMAS-resistant coating system.

The relative stability of zirconia-based samples can be assessed and discussed regarding their resistance to the CMAS melt reaction using the concept of optical basicity of zirconium or the RE oxides (Refs. 12 and 18 to 20). Optical basicity, which is another measure of the basicity of a metal oxide, is a measure of the electron donation capability of the oxygen anion to a particular cation (here, Zr$^{4+}$, Y$^{3+}$, Gd$^{3+}$, Nd$^{3+}$, Sm$^{3+}$, Sc$^{3+}$, or Yb$^{3+}$) (Refs. 18 to 20). Optical basicity generally uses data from X-ray photoelectron (Ref. 21) and ultraviolet (UV) (Ref. 18) spectroscopy data as input parameters. Here the optical basicity of zirconia-based samples is calculated through the following equation (Ref. 18):

$$\Lambda_{ab} = \frac{ax\Lambda_{ZrO_2} + \left(by\Lambda_{(RE_2O_4)} + cz\Lambda_{(RE_2O_3)} + \cdots \right)}{2n}$$

for Zr$^{4+}$,$(RE^{3+})_1(RE^{3+})_2\cdots$O$_{2-}^n$ (1)

where $a^+$, $b^+$, and $c^+$ are the valences, and $x$, $y$, $z$, and $n$ are the stoichiometric coefficients for Zr$^{4+}$, RE$^{3+}$, and O$^{2-}$. The stoichiometric coefficients used in these calculations are given in the footnote of Table I. The known optical basicities of zirconia or of the REs are given in Table V.

**TABLE V.—OPTICAL BASICITY OF ZIRCONIA AND RARE EARTH OXIDES**

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Optical basicity, $\Lambda_{ab}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y$_2$O$_3$</td>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>Yb$_2$O$_3$</td>
<td>0.94</td>
<td>22</td>
</tr>
<tr>
<td>Nd$_2$O$_3$</td>
<td>1.19</td>
<td>22</td>
</tr>
<tr>
<td>Sm$_2$O$_3$</td>
<td>1.14</td>
<td>22</td>
</tr>
<tr>
<td>Gd$_2$O$_3$</td>
<td>1.18</td>
<td>22</td>
</tr>
<tr>
<td>Dy$_2$O$_3$</td>
<td>1.08</td>
<td>22</td>
</tr>
<tr>
<td>Sc$_2$O$_3$</td>
<td>0.89</td>
<td>18</td>
</tr>
<tr>
<td>ZrO$_2$</td>
<td>0.86</td>
<td>23</td>
</tr>
</tbody>
</table>
TABLE VI.—THEORETICAL OPTICAL BASICITY
OF ZIRCONIA-BASED SAMPLESa

<table>
<thead>
<tr>
<th>Sample# (nominal composition)</th>
<th>Optical basicity, ( \Delta_{ob} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: ZrO2-12Y2O3</td>
<td>0.83</td>
</tr>
<tr>
<td>II: ZrO2-30Y2O3</td>
<td>0.81</td>
</tr>
<tr>
<td>IV: ZrO2-9Y2O3-4.5Gd2O3-4.5Yb2O3</td>
<td>0.84</td>
</tr>
<tr>
<td>V: ZrO2-9.5Y2O3-2.25Gd2O3-2.25Yb2O3</td>
<td>0.83</td>
</tr>
<tr>
<td>VI: ZrO2-3Y2O3-1.5Sm2O3-1.5Yb2O3</td>
<td>0.85</td>
</tr>
<tr>
<td>VII: ZrO2-3Y2O3-1.5Nd2O3-1.5Yb2O3-0.3Sc2O3</td>
<td>0.84</td>
</tr>
</tbody>
</table>

aCalculated with Equation (1) and data of Table V.

The optical basicity obtained by Equation (1) is the mean value of the constituents’ metal oxides, accounting for charge neutralization of each cation, and it does not take into account structural parameters. This method is used since there are no data available for the optical basicity of RE3+ that considers structural parameters (e.g., coordination number and spin state of the cation) and since it has been successfully applied to explain the trend in properties of silicate glasses (Ref. 18), silicate-based coatings (Ref. 24), and framework titanates (Ref. 25). The calculated theoretical optical basicities of the zirconia-based samples are given in Table VI. The optical basicity of the hafnia-based sample was not calculated since the optical basicity of hafnium or hafnium oxide is still not available in the literature.

It is noticed here that the zirconia-based samples II ZrO2-30Y2O3 and V ZrO2-9.6Y2O3-2.25Gd2O3-2.25Yb2O3 with the lowest optical basicity seemed more resistant to CMAS or showed less depth of CMAS melt penetration. It has been proposed by Navrotsky (Refs. 26 and 27) that the acid-base character of oxide melts (e.g., CMAS) is governed by its acid-base equilibrium:

\[
\text{Si}_2\text{O}_7^{6-} \text{(acid)} + \text{O}^{2-} \text{(oxide)} = 2\text{Si}_2\text{O}_4^{4+} \text{(base)}
\]

Acid-base interactions, network substitution of silicon and aluminum, and mixing of nonnetwork cations are the main processes occurring when an oxide sample reacts with the silicate (CMAS) melt (Ref. 28). It is likely that the zirconia-based samples having the lowest optical basicity, or being the weakest bases, are less reactive to the silicate oxide melt (CMAS), which have a component with acid character. The better CMAS resistance of ZrO2-9.6Y2O3-2.25Gd2O3-2.25Yb2O3 than 12YSZ, considering that both have an optical basicity of 0.83, may be related to the higher optical basicity of RE oxides Gd2O3 and Yb2O3, which would drive Equation (2) more to the right, resulting in a melt with more base character at the grain boundaries of the samples, which ideally diminishes their reactivity with CMAS melt. However, the results are not convincing because of the complexity of the coating systems and the coating-CMAS interactions, particularly when in contact with a large amount of CMAS melts. In general, one can expect that the most CMAS-resistant coating system will be the one with sufficient contents of RE oxides of high optical basicity while also containing highly stable and low-optical-basicity base and RE oxides, effectively stabilizing CMAS and minimizing coating loss to the CMAS melts at high temperatures.

Conclusions

The thermochemistry reactions and stability of advanced plasma-sprayed ZrO2- and HfO2-based components of thermal and environmental barrier coatings systems in contact with CMAS have been investigated at 1310 °C. The effects of yttria and rare earth dopants on the coating CMAS resistance have been particularly studied. It has been found that HfO2-7Dy2O3, ZrO2-9.6Y2O3-2.25Gd2O3-2.25Yb2O3, and ZrO2-30Y2O3 coatings had the highest CMAS stability. The CMAS resistance has been attributed to the incorporation of high optical basicity oxide dopants and also the intrinsic high-stability base and dopant material systems that have low optical basicity, particularly as illustrated in the HfO2 and multicomponent ZrO2 cluster coating cases. The multicomponent dopant oxide cluster coatings may have a significant benefit in achieving the overall coating CMAS resistance.