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Microstructure and thermo-physical properties of yttria stabilized zirconia coatings with CMAS deposits

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Abstract

Yttria stabilized zirconia (YSZ) thermal barrier coatings (TBCs) are used to protect hot-components in aero-engines from hot gases. In this paper, the microstructure and thermo-physical and mechanical properties of plasma sprayed YSZ coatings under the condition of calcium–magnesium–alumina–silicate (CMAS) deposits were investigated. Si and Ca in the CMAS rapidly penetrated the coating at 1250 °C and accelerated sintering of the coating. At the interface between the CMAS and YSZ coating, the YSZ coating was partially dissolved in the CMAS, inducing the phase transformation from tetragonal phase to monoclinic phase. Also, the porosity of the coating was reduced from ~25% to 5%. As a result, the thermal diffusivity at 1200 °C increased from 0.3 mm^2/s to 0.7 mm^2/s, suggesting a significant degradation in the thermal barrier effect. Also, the coating showed a ~40% increase in the microhardness. The degradation mechanism of TBC induced by CMAS was discussed.

Keywords: Thermal barrier coatings (TBCs); Calcium–magnesium–alumina–silicate (CMAS); Microstructure; Thermal diffusivity; Microhardness

1. Introduction

Thermal barrier coatings (TBCs) have been widely employed to improve the durability of hot section components in gas turbine engines.[1–4] Because of the demanding extreme operating conditions, TBCs possess one of the most complex structures among the widely available coatings which are used to protect structural materials from various environments. TBCs are multilayered systems consisting of a ceramic topcoat for thermal insulation, a thermally grown oxide (TGO) scale, predominantly Al_2O_3, a metallic bond coat that provides oxidation/hot corrosion resistance, and a superalloy substrate that is the load-bearing component. The ceramic topcoat of TBCs is typically made of zirconia partially stabilized with yttria (YSZ) for its low thermal conductivity and high thermal expansion coefficient.[5]

With the ever increasing demand to increase the turbine inlet temperature (TIT) for improved engine efficiency, a prime reliability TBCs system to effectively protect the hot section turbine components has been a critical requirement for gas turbine engines. Extensive efforts have been made to identify the failure mechanisms of the TBCs to increase the durability and reliability of TBCs.[6–9] Among the various life-limiting factors, one key durability issue of TBCs is their resistance to environmental degradation due to molten deposits arising from the aggressive combustion environment as well as from air-ingested foreign particles, commonly known as calcium–magnesium–alumina–silicate (CMAS, $CaO–MgO–Al_2O_3–SiO_2$) which refers to the main chemical components of Ca, Mg, Al, and Si.[10–13] The CMAS melts are produced when siliceous minerals (dust, sand, volcanic ash, and runway debris) are ingested with the intake air and deposited on the hot surface of the components. Below the melting point, these deposits cause erosive wear, blockage of cooling holes and local spallation. When operated at high temperature, these deposits melt and adhere to the coating surface. They rapidly penetrate into the whole coating through the open pores of the coating, and during cooling stage, these deposits crystallize and cause spallation of the coating because of the thermal expansion mismatch between the CMAS and the coating. CMAS damage to TBCs has been investigated in detail by Mercer et al.,[14] Krämer et al.,[15] Li et al.,[16] Chen,[17] and Aygun et al.[18] Some efforts have been made to improve the resistance of TBCs to high-temperature attack by glassy deposits.[19,20]

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Table 1
Processing parameters for plasma spraying of YSZ coatings (*D*: spray distance; *F*: feed rate; *V*: transverse speed of plasma gun).

Power (kW)	*D* (mm)	Ar (slpm)	H_2 (slpm)	*F* (g/min)	*V* (mm/s)
37.5	120	80	16	40	500

The objective of this study is to investigate the microstructure evolution of plasma sprayed YSZ coatings under the simulate CMAS condition and understand the effect of CMAS deposits on the thermo-physical and mechanical properties of the coatings. Also, the CMAS degradation mechanism of the YSZ TBC is also discussed.

2. Experimental procedures

2.1. Preparation of the simulated CMAS coating

Ni-based superalloy K3 was used as the substrate materials for TBCs. YSZ coatings were prepared by Metco 7M atmospheric plasma spray facility with 9 MB spray pistol and Metco 4MP-dual type feedstock system. The 7.8 wt.% Y_2O_3 and 2.6 wt.% HfO_2 stabilized zirconia powder feedstock was used for spraying the YSZ coatings, which mostly comprised tetragonal phase with the content of more than 94%. Free-standing YSZ coating specimens were produced by removing the coatings from the substrates using hydrochloric acid. The processing parameters for spraying the YSZ coating are listed in Table 1. The choice of spray parameters were based on the first author's previous work.[21]

A laboratory synthesized CMAS with chemical composition of 22CaO–19MgO–14$AlO_{1.5}$–45SiO_2 in mole percent was used in this study. The chemical composition of CMAS was determined based on the chemical composition of the deposits on vane blades in aircraft engines after hundreds times of flight service. The CMAS was prepared by mechanically milling the mixtures of CaO, MgO, Al_2O_3 and SiO_2 at room temperature for 24 h. The CMAS powders were deposited onto the YSZ coating specimens by plasma spraying at a concentration of 20 mg/cm^2. The feedstock morphology of the simulated CMAS was shown in Fig. 1. The average size of the powder was ~150 μm. The simulated CMAS particles were agglomerated to enhance the powder flow ability. After agglomeration, the composition of the CMAS deposits showed a little variation. The content of Si decreased, while the contents of Ca and Al increased, as shown in Table 2, possibly due to the loss of SiO_2 during ball milling.

Table 2
Chemical composition of CMAS deposits on the YSZ free-standing coating samples (mol%).

SiO_2	CaO	MgO	$AlO_{1.5}$
30.44	28.15	18.85	22.56

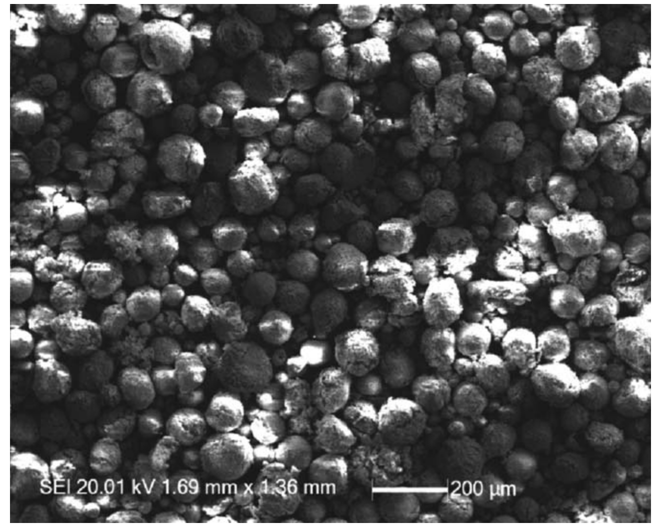

Fig. 1. Morphology of the simulated CMAS powders for spraying.

2.2. Heat treatment

Heat treatment of free-standing coating specimens with CMAS deposits was performed in a muffle furnace. The specimens were heated in the furnace to 1250 °C and held at this temperature for 4 h, 8 h, 16 h, 24 h and 48 h, respectively. Both the heating and cooling rates were kept at 6 °C/min. The temperature for heat-treatment was chosen based on the CMAS deposits melting temperature reported in literature.[15]

2.3. Microstructure characterization

The microstructure of the YSZ coating was characterized by a QUANTA 144 600 scanning electron microscopy (SEM). The porosity of the free-standing coating was determined by a mercury porosimetry (Micromeritics Autopore II, Shimadzu, Kyoto, 149 Japan). Before the porosity measurement, all the surfaces of the specimens were finely polished in order to eliminate the effect of surface roughness on the porosity measurements. As Raman spectroscopy is particularly sensitive to zirconia polymorphs,[22] Raman spectra were measured on RM2000 Raman spectroscopy (Renishaw Company, UK) to identify the phase change of YSZ coatings caused by CMAS attack at high temperature. The crucial parameters were used as follows: laser wavelength: 632.8 nm; Raman shift scope: 100–4000 cm^{-1}; microscope: ≥1 μm; wave resolution of spectrum: 1 cm^{-1}. Raman spectroscopy was used to analyze the phases of YSZ coating adjacent to the CMAS deposit. Along the white line, every 5 μm distance, the phase of YSZ was characterized.

2.4. Thermo-physical properties

Free-standing YSZ coating specimens were produced by removing the coatings from the substrates using hydrochloric acid. The diffusivity of the free-standing YSZ coatings was determined by laser flash technique. Thermal diffusivity