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Hot corrosion resistance of air plasma sprayed ceramic $Sm_2SrAl_2O_7$ (SSA) thermal barrier coatings in simulated gas turbine environments

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ABSTRACT

Samarium strontium aluminate ($Sm_2SrAl_2O_7$-SSA) and Yttria-stabilized zirconia (YSZ) thermal barrier coatings (TBCs) were developed on NiCrAlY bond coated Inconel 718 superalloy substrate using air plasma spray process. The hot corrosion study was conducted in simulated gas turbine environments (molten mixtures of 50 wt% Na_2SO_4 + 50 wt% V_2O_5 and 90 wt% Na_2SO_4 + 5 wt% V_2O_5 + 5 wt% NaCl) for two different temperatures of 700 and 900 °C. A developed SSA TBCs showed about 8% and 22% lower lifetime at 700 and 900 °C, respectively than YSZ TBCs in 50 wt% Na_2SO_4 + 50 wt% V_2O_5 (vanadate). The hot corrosion life of SSA TBCs being found about 13% and 39% lower than YSZ TBCs in 90 wt% Na_2SO_4 + 5 wt% V_2O_5 + 5 wt% NaCl (chloride) at 700 and 900 °C, respectively. X-ray diffraction results showed the formation of $SmVO_4$, SrV_2O_6, and $SrSO_4$ as a major hot corrosion product in 50 wt% Na_2SO_4 + 50 wt% V_2O_5 and 90 wt% Na_2SO_4 + 5 wt% V_2O_5 + 5 wt% NaCl environments respectively for SSA TBCs. Similarly, YSZ TBCs also showed YVO_4 as hot corrosion product in vanadate and chloride environments. Both the TBCs suffer a more severe hot corrosion attack in chloride environment at 900 °C. The leaching of Sr^{2+} and Y^{3+} ions from SSA and YSZ respectively play a vital role in the destabilization of coating in vanadate and chloride environments at 700 and 900 °C. In both SSA and YSZ TBCs, the leaching of ion has significantly low influence as compared to attack by chloride ions at the bond coat-top coat interface in the presence of chloride environment. The hot corrosion resistance of SSA TBCs was improved three times higher in the presence of MgO and NiO inhibitor in vanadate environment at 900 °C mainly due to the formation of a stable $Ni_3V_2O_8$ phase at the surface.

1. Introduction

Hot corrosion is one of the high-temperature material degradations in TBCs through the chemical reactions of molten salts and ceramic top coat, especially with Na, S, and V from fuel impurities and chlorine in the form of salt from sea or from runway de-icing treatment or marine environments [1]. These impurities can form Na_2SO_4 and V_2O_5 at elevated temperatures (600–1000 °C) and deposited on the surface of gas turbine blades. In general, hot corrosion attack is classified into two forms: Type I and Type II mainly observed within the temperature ranges of 850–950 °C (high-temperature hot corrosion) and 650–800 °C (low-temperature hot corrosion) respectively [2]. The severe degradation of ceramic top coat caused molten salt directly reacted with the metallic bond coat in TBCs. Consequently, molten salt led to form non-protective oxide scales (Cr_2O_3, NiO, $NiCr_2O_4$ and $NiAl_2O_4$) at the bond coat and ceramic top coat interface and this significantly affected delamination life of TBCs (It is the life of TBCs until the disbondment of ceramic top coat from the bond coat surface through hot corrosion process) [3]. The conventionally used YSZ ceramic TBC was found to undergo a phase transformation from tetragonal (t′) to monoclinic (m′) ZrO_2 due to the reactions of molten salts with yttria (Y_2O_3) stabilizer at the temperatures of 600–1000 °C [4].

Yttrium ions leached out from YSZ and react with $NaVO_3$ (due to the combined reaction of Na_2SO_4 + V_2O_5) to form YVO_4. The detailed reaction mechanism of YSZ and Scandia stabilized zirconia (SSZ) with V_2O_5 was reported by Jones. It was found that the YSZ easily prone to hot corrosion than SSZ in vanadium-containing engine environments. Scandia (Sc_2O_3) has been identified as more hot corrosion resistance stabilizer than Y_2O_3 in ZrO_2. In addition, Sc_2O_3 is a less basic oxide than Y_2O_3 and therefore less likely to react with acidic vanadate salts [5]. Though YSZ TBCs easily prone to hot corrosion than other ceramic still YSZ has been used as a standard material for gas turbines was mainly due to low thermal conductivity and the high melting point which are most important characteristics for TBC applications. Along with that YSZ is commercially available and more economical as compared to other rare earth-based zirconate ceramics.

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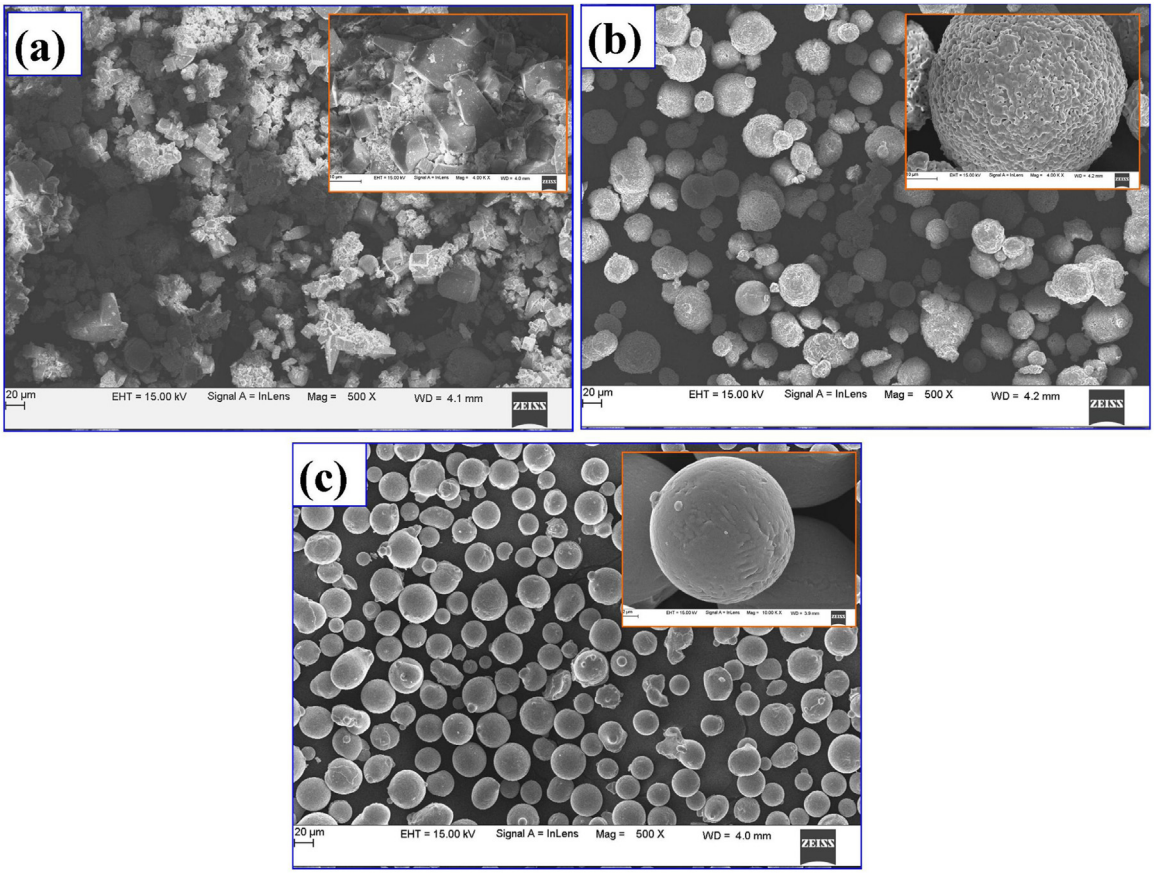

Fig. 1. Morphology of (a) as-synthesized SSA; (b) YSZ; and (c) NiCrAlY powder (Note: Higher magnification of respective images is also shown here).

In order to improve the hot corrosion performance of conventional zirconia-based TBCs several alternate ceramics have been developed and tested at elevated temperatures (It is the range of temperatures (600–1000 °C) for the changes in hot corrosion reaction between the ceramic top coat and corrosive salts). Xu et al. have studied hot corrosion behavior of rare earth zirconates ($La_2Zr_2O_7$ and $La_2Ce_2O_7$) and YSZ in the presence of Na_2SO_4 + V_2O_5 at 900 °C for 100 h. The CeO_2 containing TBCs exhibited better resistance against hot corrosion than YSZ due to its lower basicity [6]. Hot corrosion of $LaTi_2Al_9O_{19}$ ceramic after exposure to the V_2O_5 environment at 700–950 °C in the air was studied by Zhou et al. At 700 °C for 10 h, $AlVO_4$, $LaVO_4$, and TiO_2 phases were identified as major corrosion products. However, at 800 °C it was partially degraded into α-Al_2O_3 and θ-Al_2O_3 due to the thermal instability of $AlVO_4$. Final corrosion products were composed of α-Al_2O_3, $LaVO_4$ and TiO_2 at 950 °C. From the X-ray diffraction study, it was clear that the characteristic peak of original $LaTi_2Al_9O_{19}$ was absent at 950 °C and all the diffraction peaks corresponded to α-Al_2O_3, $LaVO_4$ and TiO_2 phases which indicated $LaTi_2Al_9O_{19}$ ceramic suffered more degradation at 950 °C than 700 and 800 °C. Hence, these results convey that degradation of ceramic top coat was significantly affected at the temperature of 950 °C [7]. Vakiliford et al. have reported the hot corrosion behavior of functionally graded TBCs (NiCrAlY + YSZ) in the presence of sodium and vanadium atmosphere at 800 °C for 120 h. The results showed that an improved hot corrosion performance of functionally graded TBC was observed than duplex TBCs (NiCrAlY / YSZ) due to the formation of $CrVO_4$ which postponed the phase transformation of t′-ZrO_2 to m′-ZrO_2 [8]. Hot corrosion behaviors of Al_2O_3-clad YSZ coatings in vanadium-sulfate containing environments also studied by Zhong et al. [9]. The significant improvement in hot corrosion resistance of Al_2O_3 clad YSZ was observed than that of as-deposited YSZ coatings mainly due to chemical inertness and restrained molten salts by the dense clad layers.

Amongst several ceramic TBC candidate materials, most recently $Sm_2SrAl_2O_7$ (SSA) was also found to be an alternate ceramic due to its matching thermo-physical properties with the NiCrAlY bond coat, high thermal stability, and high melting point. The coefficient of thermal expansion (CTE) value of the SSA material is found about 13.5 × 10^{-6} K^{-1} [10,11] which is equivalent to NiCrAlY bond coat (14 × 10^{-6} K^{-1}) at 1000 °C [12]. In addition, the published study is also proved that oxidation resistance of pre-oxidized SSA based TBCs found to be superior over conventional YSZ TBCs at 1100 °C in the presence of air [13,14]. However, the hot corrosion behavior of plasma sprayed SSA TBCs in the presence of 50 wt% Na_2SO_4 + 50 wt% V_2O_5 (vanadate) and 90 wt% Na_2SO_4 + 5 wt% V_2O_5 + 5 wt% NaCl (chloride) environments are not studied by many researchers. Hence, further studies are required to evaluate the hot corrosion performance of SSA TBCs vis-à-vis conventional YSZ TBCs in the presence of vanadate and chloride environments at high-temperature.

To minimize the attack of vanadate and sulfate on TBCs coatings, available oxides such as CaO or MgO or Cr_2O_3, and NiO can be used as inhibitors at high-temperature [15]. Literature survey said that the molten CaO-MgO-Al_2O_3-SiO_2 (CMAS) which can easily penetrate YSZ ceramic top coat, deplete the yttria content, and shorten the lifetime of TBCs. But mostly CMAS problem encountered in the presence of airborne ash or volcano ash (CaO, MgO, Al_2O_3, SiO_2 and Fe_2O_3) at the higher temperature (> 1000 °C). The literature survey also indicated that the presence of individual oxides such as MgO or Al_2O_3 did not show any CMAS effect on TBCs [16]. May et al. have reported the formation of abundant and hard refractory compounds using Ca based inhibitors [17]. Some researchers have also studied the synergetic effect of Cr-Si on sodium-induced hot corrosion process [18]. The main principle of hot corrosion inhibition is to trap corrosive elements from