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High-temperature oxidation behavior and analysis of impedance spectroscopy of 7YSZ thermal barrier coating prepared by plasma spray-physical vapor deposition

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Abstract Quasi-columnar structure 7YSZ (yttria stabilized zirconia) thermal barrier coatings (TBCs) are prepared by plasma spray-physical vapor deposition (PS-PVD) onto pretreated and un-pretreated bond coating, respectively. An isothermal oxidation experiment of 7YSZ TBCs is carried out in the atmosphere of 950 °C in order to simulate the high-temperature oxidation process of engine blades. The isothermal oxidation process of 7YSZ thermal barrier coatings is investigated systematically by impedance spectroscopy. The electrochemical physical model and equivalent circuit of columnar 7YSZ coatings are established. Results show that the isothermal oxidation kinetic curve of columnar 7YSZ thermal barrier coatings appears to follow the parabolic law. A pretreatment of bond coating can reduce the growth rate of the thermally grown oxide (TGO) layer, restraining the initiation and propagation of microcracks between YSZ and TGO layers. The oxidation rate constants of 7YSZ coatings with pretreated and un-pretreated bond coating are 0.101×10^{-12} $cm^2 \cdot s^{-1}$ and 0.115×10^{-13} $cm^2 \cdot s^{-1}$, respectively. Impedance analysis shows that the content of oxygen vacancies decreases and the density increases after the TGO layer is oxidized for 150 h. In addition, shrinkage microcracks formed by sintering during the oxidation process is the main reason for an increase of the capacitance and a decrease of the resistance in the grain boundary of YSZ.

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1. Introduction

Thermal barrier coatings (TBCs) are widely applied to hot-components of turbine engines to increase the operation temperature and to protect components like blades, which have

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a complex structure with a metallic bond coat (MCrAlY, M = Ni or Co) on a superalloy substrate for oxidation/corrosion resistance and a ceramic topcoat of yttria stabilized zirconia (YSZ) attached on the bond coating for heat protection.[1,2] At present, there are mainly two methods to fabricate YSZ topcoats, which are air plasma spraying (APS) and electron beam-physical vapor deposition (EB-PVD). However, these two methods also have some disadvantages. Conventional layered structured APS TBCs show high deposition rates and good thermal insulation but poor thermal shock resistance. On the contrary, columnar structured EB-PVD TBCs exhibit higher strain tolerance and better thermal shock resistance but higher thermal conductivity and lower deposition rates compared with APS TBCs.[3]

Recently, a new hopeful technique called plasma spray-physical vapor deposition (PS-PVD) has been developed based on the low pressure plasma spray process (LPPS) and combines the advantages of thermal spraying (high deposition rates) and physical vapor deposition (high strain tolerance). The plasma plume of PS-PVD can expand to over 2 m long and nearly 400 mm in diameter under parameters of high power input (about 180 kW) and low work pressure (about 100 Pa).[4] At a high power level, the temperature of the plasma plume can exceed 6000 K.[5] Therefore, fine grain sized powders are enough to be evaporated and achieve an EB-PVD-like columnar coating.

High-temperature oxidation is inevitable for TBCs. A layer of thermally grown oxide (TGO) forms at service, which can inhibit the diffusion of oxygen elements into the bond coating and protect the substrate. Moreover, a thermal mismatch due to great differences of the thermal expansion coefficients between bond coating and ceramic coatings makes ceramic layer premature failure easy. Much of related literature has studied the high-temperature oxidation behaviors of TBCs, TGO growth evolution, and micro-cracks propagation within a ceramic layer. For example, Doleker and Karaoglanli[6] have compared the oxidation behaviors of YSZ and $Gd_2Zr_2O_7$ TBCs, which indicate that the $Gd_2Zr_2O_7$ TBCs have lower thermal conductivity, lower oxygen permeability, and higher structural stability at higher temperatures. These advantages render the $Gd_2Zr_2O_7$ a good alternative top coating material for TBCs. Ahmadian and Jordan[7] have studied the effect of rapid cycling on oxidation, microcracks, and lifetime of APS TBCs. Their results have shown that there must be very significant inelasticity presenting in crack formation and crack growth in TBCs. Chen et al.[8] have investigated the oxidation and crack nucleation/growth in an APS TBCs with a NiCrAlY bond coat. Their results have shown that mixed oxides form at the beginning of the thermal exposure in air, along with the formation of the Al_2O_3 layer and cracks initiated mostly in association with the formation of $(Cr,Al)_2O_3\cdot Ni(Cr,Al)_2O_4\cdot NiO$.

Impedance spectroscopy (IS) is a cheap, sensitive, and non-destructive testing method, which has been used extensively to measure the electrical properties of ceramic materials.[9–11] In the past decade, impedance spectroscopy has been used to reflect the growth of TGO during oxidation and the effect of cracks propagation of the YSZ layer on YSZ electrical properties. For example, Zhang et al.[12] have used impedance spectroscopy to measure the relationship between the microstructure of a top coat and its electrical properties, as well as thickness and compositional changes of the TGO in environments with different oxygen partial pressures at 1050 °C for TBCs produced by EB-PVD. Wang et al.[13] have studied the TGO growth in APS TBCs after oxidation in air at 1100 °C. Ali et al.[14] have also adopted impedance spectroscopy to investigate the relevance between the microstructure and electrical properties of TGO in APS TBCs oxidation in air at 1150 °C.

At present, all of the studies are aimed at APS TBCs and EB-PVD TBCs and the great mass of oxidation temperatures of TBCs above 950 °C. The present work is the first to evaluate the oxidation behaviors of PS-PVD TBCs in air at 950 °C using impedance spectroscopy. The electrochemical physical model and equivalent circuit of PS-PVD TBCs are established in the work. IS analysis of PS-PVD TBCs has shown four relaxation processes, where three of them correspond to YSZ grains, YSZ grain boundaries, the TGO, and the metal electrode effect. Furthermore, the oxidation kinetics and behaviors of pretreated and un-pretreated PS-PVD TBCs are compared.

2. Experimental

2.1. Sample preparation

Nickel-based super-alloy K417 was cut into columnar specimens with a dimension of ∅25.3 mm × 6 mm as substrates, which were grit-blasted before PS-PVD. The composition of K417 is given in Table 1. A NiCoCrAlYTa bond coating (about 100 μm) was deposited by low-pressure plasma spray (LPPS) (Guangdong Institute of New Materials, Guangzhou, China) on the surface of superalloy. The preparation of all 7YSZ coatings (about 300 μm) was carried out on a PS-PVD system (Sulzer-Metco Multicoat™, Switzerland) onto pretreated and un-pretreated bond coatings, respectively. The process of surface pretreatment for bond coating is based on the following procedures. Firstly, the surface of bond coating was polished using a polishing machine (Tegramin-25, Struers). Subsequently, the surface of bond coating was heated to 1000 °C through the plasma plume of PS-PVD for 10 minutes in a vacuum chamber with addition of a certain amount of oxygen. The surface temperature of the substrate was maintained at 850 °C to 1000 °C in the process of fabricating 7YSZ coatings. The powder information and spraying parameters of PS-PVD are given in Tables 2 and 3, respectively.

2.2. High-temperature oxidation testing

All specimens were heated in air to 950 °C with a rate of 10 $K\cdot min^{1}$ and isothermally oxidized for 10, 50, 100, 150, and 250 h, respectively. Three specimens were used for impedance measurements and two for microstructure analysis for each oxidation condition.

2.3. Characterization

Impedance measurements were implemented at 400 °C using an Ametek Parstat 4000 electrochemical impedance spectroscopy (EIS) analyzer (Parstat4000, AMETEK Inc, USA), which was controlled by a computer. Spectra analysis was performed with the help of Zview impedance analysis software to obtain the electrical properties of TBCs. In this measurement,

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