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Thermal cyclic life and failure mechanism of nanostructured 13 wt%Al_2O_3 doped YSZ coating prepared by atmospheric plasma spraying

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Abstract

Nanostructured 13 wt%Al_2O_3 doped nanostructured 8 wt% yttria stabilized zirconia (nano-13AlYSZ) coatings were deposited by atmospheric plasma spray (APS). The isothermal oxidation and thermal cyclic life of the nano-13AlYSZ coating at 1100 °C were investigated. The isothermal oxidation test results indicate that the oxidation kinetics of nano-13AlYSZ follows a parabolic law. The parabolic rate constant at 1100 °C is calculated 0.04365 $mg^2\,cm^{-4}\,h^{-1}$. The thermal cyclic life of nano-13AlYSZ coating is about 953 times at 1100 °C. The failure of the nano-13AlYSZ coating occurs at the interface between the nano-13AlYSZ coating and the thermal growth oxide (TGO). A finite element method is employed to analyze the stress distribution in the nano-13AlYSZ coating. The results show that maximum stresses occur at the top coat/TGO interface.

Keywords: Atmospheric plasma spraying; Nanostructured Al_2O_3–Y_2O_3–ZrO_2; Thermal cyclic life; Finite element method

1. Introduction

Nanostructured yttria stabilized zirconia coatings (nano-YSZ) have received wide interest because of their low thermal conductivity, high coefficient of thermal expansion, excellent thermodynamic and mechanical properties in the turbine environment [1–7]. However, the grain growth and the phase instability during annealing [8–11], and consequently the disappearance of the nanostructure during sintering process, severely weaken the thermal and mechanical properties of the coatings. In order to improve the thermal and mechanical properties, nanostructured coatings have been modified by doping with several additives, such as Al_2O_3 [12,13], La_2O_3 and HfO_2 [14–16]. In our previous work, the microstructure and thermal physical properties of nanostructured Al_2O_3-YSZ coatings have been studied. It is shown that the addition of nano-sized Al_2O_3 effectively inhibits the grain growth of the ZrO_2 phase leading to the high thermal stability at high temperature [17]. Meanwhile, the addition of Al_2O_3 has a great influence on decreasing the thermal conductivity of nano-YSZ [18]. During the high temperature service, a thermally grown oxide (TGO) forms at the bond coat/top coat interface. The TGO plays an important role in the failure of thermal barrier coatings due to the grain growth, cracks always occurs between the interface of top coat/TGO or bond coat/TGO when the stresses is large enough. The stresses produced during the thermal cyclic process result in the spallation of the top coating when it is large enough. Therefore, the stress is the main reason for the thermal barrier coating failure. A transient thermal structural finite element solution was employed to analyze the stress distribution in the nano-YSZ and traditional YSZ coatings. However, the failure mechanism of the nanostructured Al_2O_3 doped YSZ coating during the thermal cycling process is rarely reported.

With the above background, the objective is to study the isothermal oxidation behavior and thermal cycling life of the nano-Al_2O_3 doped nano-YSZ coating. For the purpose of quantitative determination of the stress states in the nano-Al_2O_3 doped YSZ coating as it cools in air, finite element method is employed to model the coating. In addition, the failure mechanism of the nanostructured Al_2O_3-YSZ coating has been explored.

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2. Experimental procedure

2.1. Preparation of TBCs

Commercially available nano-YSZ (8 wt% yttria stabilized zirconia) and nano-Al_2O_3 powders (Nanjing High Technology Nano Company of China) were used as starting materials. The average sizes of nano-YSZ and nano-Al_2O_3 particles were 30 nm and 20 nm, respectively. Mixtures of 13 wt%Al_2O_3–87 wt%YSZ (13AlYSZ) were mixed and reconstituted into spherical micrometer-sized granules (typical size range in 30–100 μm) by spray-drying process. For comparison, the nano-13AlYSZ and conventional YSZ coating with the same thicknesses of bond coat and ceramic layer were produced under the same plasma spraying parameters. The parameters for plasma spraying bond coat and top coat are shown in Table 1.

2.2. Cyclic oxidation

For thermal cycling test, the substrates were cut into coupons with a dimension of 15 mm × 10 mm × 3 mm from a wrought sheet of nickel-based superalloy with nominal composition (wt%) of Ni–5Co–10Cr–4Mo–5W–3.5Al–2Ti–2Nb (K3). In order to improve the adherence of the coating, these coupons were grit-blasted, using 250-μm alumina grit, to obtain a sharp-peaked surface contour with a roughness average of 4–5 μm. The coupons were coated with a NiCrAlY bond coat to a thickness of about 100 μm. A top coat of nano-13AlYSZ was deposited on the substrate to a thickness of about 200 μm using APS process.

Furnace cycle tests were performed under atmospheric pressure using a tube type furnace. The average heating rate was 10 °C/min from room temperature to 1100 °C. The samples were firstly heated at 1100 °C for 50 min, and then force cooled by an air fan for 10 min to ambient temperature. The lifetime of the coatings were defined by the cycle numbers at which 5% of total coating surface area was spalled or delaminated.

2.3. Isothermal oxidation

For isothermal oxidation test, the samples were coated on all sides and the isothermal oxidation tests were carried out at 1100 °C for 147 h in static air. The specimens were placed in alumina crucibles, oxidized at 1100 °C and then cooled to room temperature at regular intervals for mass measurements. The sensitivity of the balance used was 0.1 mg. Three measurements of weight gain at each time were taken and averaged. The oxidation behavior was evaluated by the weight gain of the samples.

Table 1
Plasma-sprayed parameters for bond coating and nano-13AlYSZ coating.

	NiCrAlY bond coating	13AlYSZ coating
Primary gas Ar (L/min)	60	60
Secondary gas H_2 (L/min)	20	15
Carrier gas Ar (L/min)	3.5	4.5
Gun current (A)	580	600
Gun voltage (V)	60	63
Spray distance (mm)	290	80
Powder feed rate (g/min)	45	25

2.4. Microstructure analysis

The nano-13AlYSZ coating before and after thermal cycling was characterized using a D/max 2200pc X-ray diffractometer (Cu Ka radiation; Rigaku, Tokyo, Japan). The microstructure of the nano-13AlYSZ coating was determined by an S-3500 scanning electron microscope (SEM, Hitachi, Tokyo, Japan) with energy dispersive X-ray spectroscopy (EDS).

2.5. Finite element analysis of TBCs

The FE analysis was calculated to determine detailed stress states in the test specimens coated with the TBCs as cooling to 20 °C from a stress-free state at 1100 °C using finite element code ANSYS 9.0 developed by ANSYS Inc., Canonsburgh, PA, USA.

2.5.1. Specimen geometry

The model consisted of four layers: substrate (3 mm), bond coat (0.1 mm), TGO and top coat (0.25 mm). The thickness of the TGO was set to 10 μm. The TBC/bond coat interface was modeled by a sinusoidal wavy interface with a wavelength of 200 μm and amplitude of 20 μm. The 2D four-node thermal-structure coupled-field solid element PLANE13 was selected. The specimen geometry is shown in Fig. 1. Path A is along the interface between the top coat and TGO. Path B is perpendicular surface of the top coating, from the top coating to the substrate at the edge of the coating.

2.5.2. Material properties

All layers were assumed to be homogeneous, isotropic and pure elastic. Creep and plastic deformation of each layer were assumed negligible. In addition, material properties used for substrate, bond coat, alumina and top coat were temperature

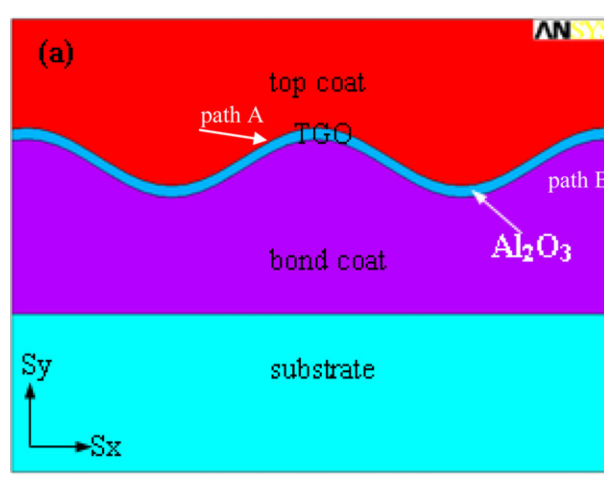

Fig. 1. The geometry model.