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Adhesion strength and thermal shock properties of nanostructured 5La3TiYSZ, 8LaYSZ and 8CeYSZ coatings prepared by atmospheric plasma spraying

Lei Jin[a,*], Guifang Liu[b], Peizhong Li[c], Haibin Zhou[a], Chun Wang[a], Guodong Zhou[a]

[a]Science and Technology on Power Beam Process Laboratory Beijing Aeronautical Manufacturing Technology Research Institute, Chaoyang District, Beijing 100024, China
[b]Changzhou LanXiang machinery Co., Ltd., Changzhou 213022, China
[c]Inner Mongolia Baotou Steel Rare-earth (Group) Hi-Tech Co., Ltd., Baotou 014030, China

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Abstract

The effects of ceramic dopant species and amount on adhesive strength and thermal shock resistance behavior of nanostructured thermal barrier coatings (TBCs) were investigated in detail. Firstly, nanostructured 5 wt% La_2O_3+3 wt% TiO_2+92 wt% YSZ(5La3TiYSZ), 8 wt% La_2O_3+92 wt% YSZ (8LaYSZ) and 8 wt% CeO_2+92 wt% YSZ(8CeYSZ) coatings were prepared using atmospheric plasma spraying (APS) technology under the same technic parameters. Secondly, microstructure, adhesion strength and thermal shock behavior of three kinds of coatings were discussed. The results show that 5La3TiYSZ has the highest adhesion strength and the best thermal shock resistance in three kinds of coatings. The adhesion strength and thermal shock life for nanostructured TBCs heavily depend on ceramic materials. Among dopants nanostructured TiO_2, La_2O_3 and CeO_2 oxides, TiO_2 can take relatively good effects in YSZ and the reason are also discussed using first principles.
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1. Introduction

Thermal barrier coatings (TBCs) are applied on aeronautical engine components in order to improve superalloy's oxidation resistance. Lots of studies prove that TBCs can extend lifespan of superalloy in high temperature. TBC systems are made up of a metallic MCrAlY (M stands for either Co, Ni or Fe or a combination of these elements) bond coat and yttria-partially stabilized zirconia (YSZ) ceramic top coat. Nanostructured YSZ TBCs (nano-YSZ) have lower thermal conductivity, higher coefficient of thermal expansion, excellent thermal cycling lifetime and better mechanical properties [1–5] than those of conventional YSZ. Therefore, nano-YSZ coatings have aroused wide interest in recent years. However, they ultimately fail or detach from high temperature alloy substrate because nano-grains grow at 1100 °C or higher temperature [6,7]. Based on some disadvantages of nano-YSZ coatings, many researchers dope nanostructured CeO_2, TiO_2, La_2O_3 or other oxides into nanostructured YSZ and find that these oxides do improve YSZ's properties under brutal challenge [8–10].

Spallation of the ceramic top coat from bond coat is the most critical issue for limiting durability of TBCs. Once this type of damage occurred, hot components made of superalloy substrate will be overheated, resulting in oxidation and complete failure. Adhesion strength is a major parameter

*Corresponding author. Tel.: +86 010 85701575.
E-mail address: yugongyishanjin@126.com (L. Jin).

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characterizing the resistance of the ceramic top coat against spallation. Besides, thermal shock performance is also a very important indicator to evaluate TBCs. In recent years, thermal shock performance of nanostructured YSZ coatings has been also reported [11]. The test result indicates that thermal shock performance of nanostructured TBC is enhanced because it has high porosity, uniform pore distribution without penetrating and parallel cracks and less phase transformation than conventional YSZ. The thermal stress and internal stress are main reasons for explaining different service life between nanostructured and conventional TBCs, and the detail report can consult reference [12]. Some investigations and reports also discuss the effects of different CeO_2 dopant amount on thermal shock resistance [13].

Previous studies of nanostructured TBCs mainly focus on ceramic powder composition, size, morphology, coating design, manufacturing method, residual stress formation and control, and so on [14–17]. Up to now, the studies about the adhesion strength and thermal shock performances are unsystematic, especially for different kinds of nanostructured ceramic coats.

With the above background, nanostructured 5La3TiYSZ, 8LaYSZ and 8CeYSZ coatings are treated as investigation objects in the present work. The purpose is to better understand the effect of dopants and doping amount on adhesion strength and water-quenching failure. Ultimate aim is to provide experimental and theoretical basis for further improving properties of TBCs.

2. Experimental procedures

2.1. Preparation of nanostructured CeYSZ coatings

The size of La_2O_3, CeO_2, TiO_2 and YSZ particle is between 20 nm and 50 nm. Three kinds of 5La3TiYSZ, 8LaYSZ and 8CeYSZ nanostructured powders are composed of 5 wt% La_2O_3 + 3 wt% TiO_2 + 92 wt% YSZ, 8 wt% La_2O_3 + 92 wt% YSZ, and 8 wt% CeO_2 + 92 wt% YSZ, respectively. Due to light quality, small inertia and non-flowing of nano powder, they cannot be directly used for air plasma spraying. Therefore, spray drying technology is taken to produce micron-sized agglomerates composed of nanostructured granules. The optimized agglomerate parameters are listed in Table 1. Subsequently, powders were subjected to drying treatment at 100 °C for 0.5 h for air plasmas spray.

The substrates were cut into coupons with a dimension of 25mm in diameter and 6mm in thickness from a wrought sheet of nickel-based superalloy with nominal composition (wt%) of Ni–5Co–10Cr–4Mo–5W–3.5Al–2Ti–2Nb (K3). 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, in order to improve the adherence of coatings. The bond coatings with composition of commercial Ni–31Cr–11Al–0.1Y (−106+37 μm, Amdry 964) were deposited using an APS method. Afterwards, three kinds of nanostructured ceramic powders were deposited onto the surfaces of the Ni–31Cr–11Al–0.1Y bond coats using the same APS technic parameters. The thickness of bond coat and ceramic top coat were 80 μm and 200 μm, respectively. The air plasma spraying parameters are presented in Table 2.

Table 1
Parameters of powder agglomerated process.

Press (KPa)	Current (A)	Voltage (V)	Inlet temperature (°C)	Outlet temperature (°C)	Speed (r min^{-1})
0.12	4	380	60	120	7200

2.2. Adhesion strength

In this method, E-7 hot setting adhesive is applied and TBC is bonded to metal stainless steel cylinder. These specimens for the adhesive strength test were put in the oven at 100 °C for 3.5 h. The adhesive strength of each kind of TBC was measured at room temperature according to HB 5476-1991 standard. The bonding strength test described here is similar to the ASTMC633 method. The tensile strength is obtained from the ratio of the maximum load applied at rupture by the cross-section area [18,53]. To obtain more reliable values, 5 samples were tested and the average value are taken.

2.3. Thermal shock measurement

Under the actual service condition of the aircraft engine (such as temperature rise and fall violently), thermal shock is a quite important performance for thermal barrier coatings. Thermal shock tests were performed under atmospheric pressure at 1100 °C in static air. Each cycle is consisted of 30 min holding in high temperature furnace and 5 s cooling down to room temperature (using water quenching). The lifetime of the coatings is defined by the number of cycles at which 5% of total coatings surface area is peeled or delaminated. Each kind of coating take three samples to estimate lifetime.

3. Results and discussion

3.1. Phase compositions and microstructure of as-prepared TBCs

Through a large number of experiments and explorations for spray drying agglomerate process (Table 1). The nanosized

Table 2
Plasma-sprayed parameters for bond coating and nanostructured coating.

	NiCoAlY	Nanostructured coating
Primary gas Ar (L/min)	40	44
Secondary gas H_2(L/min)	7	10
Carrier gas Ar (L/min)	6	8
Gun current (A)	500	560
Gun voltage (V)	63	67
Spray distance (mm)	15	10
Powder feed rate (g/min)	40	48

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