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Microstructural characterization of modified YSZ thermal barrier coatings by high-current pulsed electron beam

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ABSTRACT

Thermal sprayed YSZ coatings subjected to high-current pulsed electron beam (HCPEB) with different pulses were investigated. The microstructure evolution, surface roughness and phase transformation of the coatings were characterized by means of a scanning electron microscope (SEM), a three-dimensional laser scanning microscope (LSM) and X-ray diffraction (XRD), respectively. Under HCPEB irradiation, the coarse surface was melted and a flat and compact surface with a continuous micro-crack network was formed. At the same time, rapid thermal cycles during HCPEB irradiation led to the very fine grains formed on the surface and the fully dense columnar grains in the fracture cross-section. When using 10 or 20 pulses, wavy morphology and vapor deposition were induced due to the evaporation effect. The phase composition in irradiated coatings mainly consisted of a non-equilibrium t′-phase, the same as the as-sprayed phase composition. After HCPEB irradiation with 10 or 20 pulses, the residual m-phase was mostly eliminated owing to the homogenization of composition during the HCPEB irradiated process. High temperature oxidation test indicates that the irradiated coating with 10 pulses has a much higher oxidation resistance.

1. Introduction

The preparation of thermal barrier coatings (TBCs), which exhibit an increasing potential in improving the efficiency and durability of hot section components in gas-turbine engines, is one of the most active research topics in the field of high-temperature alloys in recent years [1–3]. Commercial TBCs are typically two layered structures, consisting of a thermally insulating ceramic top coat (TC) and an oxidation resistant metallic bond coat (BC) [4,5]. At present, yttria stabilized zirconia (YSZ) is an appropriate choice for the ceramic top coat due to its high coefficient of thermal expansion (CTE) and a significant low thermal conductivity [6–8]. It can be deposited by electron beam physical vapor deposition (EB-PVD) [9] or more frequently by air plasma spraying (APS) due to its comparatively cost-effective deposition conditions and high deposition efficiency [10,11]. However, there still exist some inherent shortcomings associated with the interconnected porosities, horizontal micro-cracks, and coarse surface generally fabricated by the APS technique [1,12,13]. Although these features give a better thermal protection, they can also affect the mechanical properties and deteriorate the oxidation and corrosion resistance, which are considered to be the path for molten salts and corrosive gases to attack the TBCs. Furthermore, the infiltration of oxygen through the top coat by diffusion through the connected porosities results in an increase in thickness of the thermally grown oxide (TGO), and eventually contributes to the spallation of top coat when the critical level is reached [11–14]. Therefore, the ideal top coating engineered to be impermeable and resistant to corrosion and oxidation in the coatings provides a very significant improvement to the expected durability of the TBCs.

The pulsed energetic beams, including laser, pulsed ion beams and electron beams, have been proved as powerful tools to modify the surface microstructure and performance of materials [15–17]. Numerous studies have focused on sealing the porosity in plasma-sprayed ZrO_2-based ceramic top coat by laser surface treatment, including laser glazing [11,18–20] and laser cladding [21]. Studies indicated that laser melting and solidification can produce a columnar structure replacing the initial lamellar structures, less surface roughness, free from porosity and the formation of crack networks perpendicular to the surface. They have proved that laser surface modification is an available approach to improve the hot corrosion resistance, oxidation resistance and durability of TBCs [18–22]. Currently, high intensity pulsed ion beam (HIPIB) irradiation has been used for overcoming the deficiencies of the ceramic coating prepared by the EB-PVD method to achieve a sealing effect for the columnar grains, showing that the oxidation resistance of the irradiated coatings was significantly improved [23,24].

Compared with the role of laser or ion beam techniques, high-current pulsed electron beam (HCPEB) irradiation is characterized by a pure energy transport process, which not only overcomes the problem of the impact of ionic impurities by ion beam irradiation, but also has a much higher energy efficiency than a laser beam [25–27]. During the

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transient bombardment process, the beam energy (10^8–10^9 W/cm^2) transfers into the surface layer of a material within a short time of microsecond scale; the thermal and mechanical processes including rapid melting, evaporation, thermal stress and solidification occur simultaneously. Therefore, a significant enhancement of mechanical properties and substantial modification of surface characteristics can be achieved [17,26–29]. Actually, the HCPEB technique has already been used to improve the surface properties of various coatings. Some of the associated microstructure modifications, such as grain refinement, melt homogenization and "sealing" effect, have been demonstrated on a number of systems [30–32]. However, full attention has not been paid to the research on the microstructural characterization of YSZ top coat deposited by the APS method. Therefore, an investigation on microstructural modification of YSZ top coat by HCPEB irradiation was necessary.

In this paper, plasma-sprayed ZrO_2–8 wt.% Y_2O_3 TBCs were subjected to a HCPEB treatment process. The modified microstructure, surface roughness and phase transformation of the APS YSZ coatings were characterized thoroughly with an attempt to comprehend the modification mechanism of HCPEB irradiation and their influence on the surface properties of TBCs.

2. Experimental

2.1. TBC preparations

Disk-shaped specimens (ϕ 25.4 mm × 6 mm) made of Ni-based superalloy GH4169 (Cr 19.62, Fe 17.75, Nb + Ta 5.08, Mo 3.03, Ti 1.08, Al 0.58, Si 0.17, Ni balance, wt.%) were used as substrates. The sprayed powders were commercial Co–23Cr–13Al–0.5Y powder and 8% Y_2O_3 partially stabilized ZrO_2 ceramic powder. Before deposition, all the samples were blasted by corundum with a grain size of 60 mesh to eliminate surface oxides and to obtain the required roughness for coating adhesion. Then the APS equipment of type Praxair 3710 was used for the deposition of CoCrAlY bond coat with 160 μm and YSZ top coat with 240 μm. The corresponding spraying parameters are given in Table 1.

2.2. HCPEB treatment

YSZ coatings were irradiated at room temperature with 1, 10 and 20 pulses using a Nadezhda-2 type HCPEB source. The HCPEB bombardments were carried out under the following parameters: the electron energy 27 kV, the current pulse duration 1.5 μs, the energy density 4 J/cm^2, the beam diameter 50 cm, and the vacuum 10^{-5} Torr. More details about the principle of HCPEB system are in Reference [29].

2.3. Oxidation test

As-sprayed coating and 10-pulsed irradiated coating were selected for the oxidation test, which was conducted in a muffle furnace at 1050 °C in air for 100 and 200 h. After oxidation for a certain time, the oxidized specimens were removed from the furnace and air-cooled to room temperature, and then taken out to characterize the TGO morphology.

Table 1
Plasma spraying parameters.

Parameter	Bond coat	Top coat
Voltage (V)	38	39
Current (A)	750	860
Powder feed rate (rpm)	2.5	3.5
Spray distance (mm)	85	72
Spray rate (mm/s)	450	250

2.4. Characterization

Microstructural characterization of the initial and irradiated samples was comprehensively performed by using a scanning electron microscope (SEM) of type JEOL JSM-7100F. With the purpose of examining the phase transformations of zirconia before and after HCPEB irradiation, X-ray diffraction (XRD) with CuKα radiation in a Rigaku D/max-2500/pc X-ray diffractometer was carried out. Additionally, a three-dimensional laser scanning microscope (LSM) of type VK-X100/X200 was employed to evaluate the characteristic features and surface roughness of these coatings.

3. Results

3.1. Surface and cross-sectional morphology

Typical SEM surface morphologies of the plasma-sprayed surface of the YSZ coating are shown in Fig. 1. It can be observed that the surface is apparently rough and consists of accumulating large number of splash-type splats with many incomplete melted particles. The surface view, shown in Fig. 1(b), depicts that the structural defects like large cavities and micro-cracks are observed everywhere, mainly due to the thermal stress arising from rapid solidification of flattening particles during the plasma sprayed process. In gas-turbine application, the rough surface and structural weaknesses inherent in the as-sprayed top coating allow greater penetration of molten salts or corrosive gases to attack the bond coating, which leads to the spalling or failure of the entire coating system.

Fig. 2 shows the micrographs of YSZ coatings after HCPEB treatment with different pulses, which is featured by the wavy aspect of the surface. After a single pulse of irradiation, as shown in Fig. 2(a), the coarse surface of the as-sprayed YSZ coating was melted apparently. The inhomogeneous distribution of craters was formed in the melt region and micro-cracks were observed extending on the surface to form a continuous micro-crack network (Fig. 2(b)). It is worth noting that most craters located on the surface were accompanied by the micro-cracks, implying that the evolution of surface craters has an inherent relation with the formation of surface cracking. After 10 pulses of irradiation, the wavy aspect due to the "hills and valleys" at the remelted surface was slightly more pronounced, as shown in Fig. 2(c) and (d). The coating surface was remelted completely accompanied by removal of all the principal characteristics in the as-sprayed coatings such as porosities, splats, protrusions, and non-melted or partially melted particles. Besides, surface craters were sealed mostly and the formation of micro-crack network became more severe. As the number of pulses increased up to 20, as shown in Fig. 2(e) and (f), the general aspect of the surface was rather similar to that of the 10-pulsed coating. The surface became more smooth and compact, and the cracks developed in a much broader way.

High magnification micrographs of the irradiated surface are shown in Fig. 3(a)–(c) with different HCPEB pulses. Fig. 3(d)–(f) depicts the corresponding mean size of these ultrafine grains in Fig. 3(a)–(c), accordingly. After a single pulse of irradiation, as shown in Fig. 3(a), highly refined grains with a mean size of 0.178 ± 0.0022 μm were formed. After 10 pulses of irradiation, the number of these fine grains significantly decreased, and correspondingly, the size increased to 0.756 ± 0.020 μm (Fig. 3(b) and (e)). It is interesting that as the number of pulses increased up to 20, these fine grains tended to grow in smaller size, from which the mean size is shown to be 0.574 ± 0.033 μm (Fig. 3(c) and (f)). Another important aspect is about the vapor deposition attached to these very fine grains after 10 and 20 pulses, as shown in Fig. 3(b) and (c). The vapor adsorption has a negligible effect on the surface roughness value in the following measurements because they were loosely adherent to the grain surface.

The surface roughness (Ra) measurement was performed by LSM analysis where Ra is the arithmetical mean deviation from the solid