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Thermal Shock Failure Mechanism of Nanostructured Zirconia Coating by Atmospheric Plasma Spraying

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Abstract: Nanostructured zirconia coatings has been prepared based on reasonable spraying technical parameters and the corresponding thermal shock property of the as-sprayed coating was examined at 1100 ºC. The structure and the surface/interface morphology of the coatings have been analyzed using X-ray diffraction (XRD), metallographic microscope, scanning electron microscopy (SEM), energy dispersive spectrum (EDS) and transmission electron microscopy (TEM). Based on the detailed analysis of the structure and phase composition, a rational mechanism has been proposed for thermal shock failure of the coating. Compared with other nanoparticles, those particles close to pores and pre-existing microcracks would preferentially grow up during the thermal shock process due to a better growth space. The growth of these nanoparticles is conducive to the formation of new microcracks which would lead to the growth of the other nanoparticles. With the growth of most or all of the nanoparticles, the nanostructured zirconia coating correspondingly changes into the quasi-microstructured coating. The thermal shock failure mode of the as-sprayed coating is similar to that of traditional zirconia thermal barrier coatings (TBCs).

Key words: thermal shock failure; zirconia coating; atmospheric plasma spraying

Plasma spraying zirconia thermal barrier coatings (TBCs) have been widely used in hot section components of gas turbine and diesel engines such as burners, transition ducts, shrouds, blades and vanes for their low thermal conductivity and thermal expansion coefficient which are close to that of the base metal[1,2], and the application of TBCs could reduce aero engine turbine blade surface temperature by about 200 ºC[3]. However, with the development of aviation gas turbines to high flow, high temperature and high thrust-weight ratio, the gas combustion temperature could get to more than 1650 ℃, or even be expected to reach 1930 ℃ in the future [3, 4]. The high temperature alloy and TBCs coatings widely used nowadays would be irresistible to the harsh working conditions. Therefore, it is urgent to find a new thermal barrier coating.

It has been reported that nanostructured thermal barrier coatings have lower thermal conductivity coefficient, higher thermal expansion coefficient and better mechanical performance in comparison with conventional zirconium oxide coatings[5], which make them a new generation of thermal barrier coating materials. As for the thermal performance process of nanostructured zirconia coating, current research is mainly focused on its thermal expansion coefficient and thermal diffusion coefficients[6, 7]. In the present study, we aim to investigate and test the thermal shock property of the nano-structured zirconia coating. According to the experimental results, a rational thermal shock failure mechanism of as-sprayed coating will be proposed.

1 Experiment

Feedstock powders with spherical shape and primary grain size of 25 nm (Fig.1), which are mainly composed of tetragonal phase zirconia, prepared via the coupling route of w/o emulsion with urea homogenous precipitation reported in previous works[8,9], were used to deposit the nanostructured zirconia coating. Plasma spraying process was carried out using a Sulzer-Metco F9-MB plasma gun mounted on an ABB
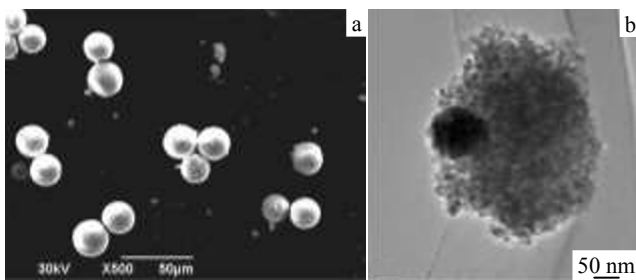
Fig. 1   SEM (a) and TEM (b) micrographs of zirconia powders

robot. 1Cr18Ni9Ti stainless steel plates with dimensions of 40 mm ×30 mm ×3 mm were used as substrates. Prior to the spraying, the substrates were cleaned with acetone and grit-blasted with alumina abrasive. In order to minimize the thermal expansion performance difference between substrate material and zirconia ceramic material, a 100 μm metal transition layer (bonding layer) was sprayed between the substrate material and the top ceramic material. The metal feedstock powders with a chemical composition of Ni-22Cr-10Al-1Y (wt%) and particle sizes ranging from 38 μm to 75 μm used for transition layer were the Amdry365-2 manufactured by the Sluzer Metco company. During the spraying process, the substrates were cooled by circulating water and the surfaces of coatings by compressed air. The process parameters of transition layer and surface ceramic layer are shown in Table 1.

According to aviation industry standard HB 7269-96, the thermal shock test was carried out in a muffle furnace. When the temperature of the furnace reached up to 1100 ℃, the samples were pushed into the furnace and held for about 10 min at 1100 ℃, and then they were directly quenched into water with room temperature for 2 min until the temperature of samples became the same as that of water according to thermometer measurement. After being taken out from water, the samples were dried and the surface and interface cracks of the samples were examined with the 10 times magnifying glass, then the samples were put into the 1100 ℃ furnace again to repeat the above-mentioned process. When a visible TBC failure area (spallation plus delamination) reaches about 5% of the total area, the thermal shock cycling was stopped, and the number of cycling was recorded and defined as the thermal shock failure lifetime of nanostructured zirconia coating.

Table 1   Spray process parameters of atmospheric plasma spraying

Powder	NiCrAlY	ZrO$_2$(3Y)
Power/kW	31.5	42
Current/A	450	610
Coating thickness/μm	100	250
Spray distance/mm	100	100
Powder quality/g·min^{-1}	55	20
Argon flow/L·min^{-1}	37	35

The surface and the cross-section morphology of the coating samples were determined by metallographic microscope and scanning electron microscopy (SEM), the particle sizes and morphologies of the feedstock powders and coatings by transmission electron microscopy (TEM), and the crystalline phases of ceramic layer by X-ray diffractometry (XRD). EDX-GENESIS60S energy dispersive spectrometer was employed to study the surface ingredients of the coatings.

2   Results and Discussion

2.1   Analysis of surface morphology

The surface and cross-section SEM micrograph of the failure sample is shown in Fig.2. Fig.2a reveals that the partial spallation exists inside the surface ceramic coating of the sample. In addition, it's obvious that a crack appears at the interface between bonding layer and surface ceramic layer, shown in Fig.2b, which indicates that the ceramic layer could also wholly spall from bonding layer surface. According to the fatigue theory[10], the layer interface of coating belongs to weak structural interface. During thermal shock process, when the coating samples were taken out from the high temperature furnace and quickly quenched in water at room temperature, very large stress is developed inside the coating due to the difference of thermal expansion coefficients between ceramic layer and bonding layer. At the same time, thermal grown oxide (TGO) could come into being in the coating. Under the action of cycling thermal stress and structure stress (oxidation stress), cracks would propagate along the layer interface and result in ceramic layer spallation from bonding layer.

Actually, according to the SEM micrograph of the failure sample surface (Fig.2a), the surface ceramic layer does not entirely spall along the interface between bonding layer and ceramic layer, but partly spalls from the inside of the zirconia ceramic coating. The causes of this phenomenon could be interpreted as follows: when the as-sprayed coating is heated and quenched, the ceramic layer is subjected to cycling thermal stress, which leads to the formation of microcracks. On the one hand, the microcracks could reduce concentration of stress resulted from the thermal expansion coefficient mismatch between the ceramic layer and the bonding layer by releasing stress inside the surface ceramic layer to prolong
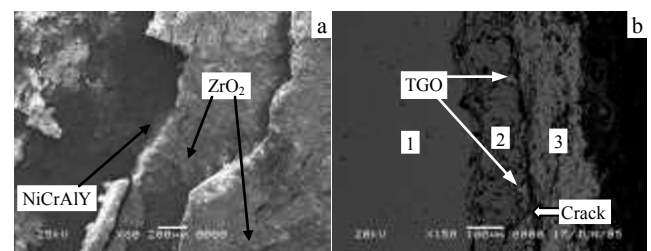

Fig. 2   SEM micrographs of surface (a) and cross-section (b) of failure sample (1, 2, 3 represent substrate, bonding layer and ceramic layer, respectively)