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Microstructural, mechanical and tribological properties of nanostructured YSZ coatings produced with different APS process parameters

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Abstract

Plasma sprayed ceramic coatings can be used in turbine engines as thermal barrier or abradable coatings, in order to improve the durability of the components as well as the efficiency. The presence of nanostructures, deriving from partial melting of agglomerated nanostructured particles, represents an interesting technological solution in order to improve their functional characteristics. In this work nanostructured yttria stabilized zirconia (YSZ) coatings were deposited by air plasma spraying (APS). The influence of the main process parameters on their microstructural, mechanical and tribological properties was investigated by scanning electron microscopy (SEM), indentation techniques at micro- and nano-scale and wear tests, respectively. Their porous microstructure was composed of well melted overlapped splats and partially melted nanostructured areas. This bimodal microstructure led to a bimodal distribution of the mechanical properties. An increase of plasma power and spraying distance was able to produce denser coatings, with lower content of embedded nanostructures, which exhibited higher elastic modulus and hardness as well as lower wear rate.

Keywords: C. Hardness; C. Wear resistance; Plasma spraying; Young's modulus; Zirconia

1. Introduction

Ceramic coatings are suitable to be employed for thermal protection of Ni-based superalloy turbine components operating in power plants and aircraft engines. Their application allows improving their high-temperature capability and durability, by reducing the heat flux and the temperature at the metal surface. Significant improvements in terms of engine efficiency and lower pollution are then expected [1,2]. A thermal barrier coating (TBC) system is usually composed of a metal substrate, a metallic bond coat and a ceramic top coat [3]. The intermediate bond coat (MCrAlY) plays a meaningful role on the adhesion of the ceramic top coat and provides better resistance to the attack typically promoted by oxygen and molten salts in severe working environments [4]. Ceramic materials with low thermal conductivity and heat capacity are good TBC candidates.

Partially-yttria stabilized zirconia (8YSZ) is the most common used TBC material, owing to its satisfactory thermal and mechanical properties (low thermal conductivity, relatively high thermal expansion coefficient, low Young's modulus, high hardness and toughness) [5,6].

Plasma spraying is suitable for fabrication of thick porous coatings on complex metal parts. In such process powder particles are injected in the plasma jet by an inert gas, melted and accelerated toward the substrate, where they impact at high speed and quench, thus producing the build-up of a coating with typical microstructural defects such as splat boundaries, pores and microcracks [7].

During service at high temperature the infiltration of oxygen through the microcracks and interconnected pinholes of the ceramic TBC and the outward diffusion of bond coat constituents, such as Al, Cr and Ni, lead to the oxidation of the bond coat surface and to the following formation of the TGO

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(thermally grown oxide) at the interface. The gradual growth of the TGO layer assists the evolution of tensile stresses and the growth of horizontal cracks at the interface, thus leading to TBC spallation and to the failure of the whole TBC system [8,9]. To this purpose it has been reported that the use of nanostructured materials is able to promote the formation of a thin, uniform and dense TGO, partially suppressing the fast growth of other mixed oxides, reducing the oxidation rate and prolonging the lifetime of TBC systems exposed at 1000 °C and 1150 °C under cycling conditions [10,11]. Indeed, the mixed oxides are usually characterized by high brittleness and microcrack growth.

Concerning ceramic TBCs it has been reported that significant enhancements can be achieved by using nanostructured materials in substitution of conventional ones. Indeed, the reduction of the grain size typically involves better mechanical strength and toughness [12,13]. The nanostructured coatings are characterized by higher interlamellar strength, i.e. the lamellae are well bonded each other in comparison with the conventional coatings owing to better filling and compactness between at splat boundary, as well as by higher crack propagation resistance, because the nanozones typically embedded within the microstructure act as crack arresters. The high porosity of nanostructured coatings also involves better thermal properties and thermal shock characteristics [12].

It is worth noting that single nanoparticles cannot be carried by plasma jet and deposited on the substrate, so that they are commonly pre-synthesized in micronsized particle agglomerates. To this purpose, these agglomerates should be only partially melted to preserve part of their starting nanostructure. On the contrary, if the agglomerates are totally melted, the grain growth occurs and the final microstructure resembles that of a conventional coating [14].

In the present work different process parameters were employed for coating manufacturing in order to control the degree of melting of the powder particles and to obtain coatings with well-tailored characteristics. The morphology and the microstructure of nanostructured YSZ coatings were investigated by scanning electron microscopy (SEM). Nano- and Micro-Indentation (NI, MI) tests were employed to study the evolution of the main mechanical properties, such as Young's modulus and hardness, whereas the wear rate was obtained by means of a ball-on-disk test. A statistical approach was used to study the mechanical properties of YSZ coatings and their relationship with the microstructure.

2. Experimental procedure

2.1. Plasma spraying

YSZ ceramic coatings were deposited on Ni superalloy disks (IN738, $\phi = 25$ mm, thickness = 4 mm). The substrates were sand blasted using an alumina abrasive powder to increase their surface roughness and to improve the mechanical interlocking between coating and substrate. The substrate roughness, measured using a three dimensional optical surface profilometer, was found to be 6.9 ± 1.1 μm. An atmospheric plasma spraying equipment, with a 4F-MB plasma torch with a 6 mm internal diameter nozzle, was used for coating deposition. A metallic CoNiCrAlY coating (Amdry 995C, Sulzer Metco) with thickness of 150 μm was previously applied as bond coat on the substrate surface.

Nanostructured partially yttria stabilized zirconia TBCs were then deposited using the nanostructured ZrO_2–7 wt% Y_2O_3 powder feedstock (Nanox S4007, Inframat, US). The final thickness of the coatings was of about 300 μm whereas their roughness was equal to 8.3 ± 1.0 μm (no significant changes were appreciated for the samples produced using different process parameters). Two sets of six different samples were produced. The six samples of each set differ in the process parameters employed: the arc current was varied on three levels (500 A, 565 A and 630 A) and the substrate–torch distance on two levels (80 mm and 100 mm). The other parameters were kept constant and can be summarized as follows: primary gas flow rate (Ar) 40 slpm, secondary gas flow rate (H_2) 12 slpm, powder flow rate 28.5 g/min, and substrate tangential speed 2086 mm/s.

2.2. Microstructure

The phase composition of nanostructured zirconia powder and coatings produced using different processing parameters was investigated by an x-ray powder diffractometer (XRD PW 1880, Philips, Almelo, Netherlands) operating with CuKα radiation ($\lambda = 0.154186$ nm) produced at 40 kV and 40 mA. The analyzed range of the diffraction angle 2θ was between 20° and 80°, by a step width of 0.02° and a time per step equal to 5 s.

The morphology and the microstructure of powder feedstock and as-sprayed YSZ coatings were analyzed by scanning electron microscopy (SEM-LEO 438 VP, Carl Zeiss AG, Oberkochen, Germany). The SEM pictures were then processed by image analysis software (Image J, U.S. National Institutes of Health, Bethesda, MD, USA) to measure the percentage of molten and semi-molten areas embedded in coating microstructure, and the distribution of the nanostructured areas. The size of the regions used for porosity measurements was 350×250 μm^2.

2.3. Mechanical properties

The mechanical properties of YSZ coatings were determined by Micro- and Nano-Indentation tests. A measuring system of CSM Instruments SA, Peseux, Switzerland, equipped with three objective lenses (with magnitude of 5×, 20× and 100×) and a ConScan, was used.

In order to perform indentation tests the cross sections of the first set of coated samples were prepared using a standard metallographic procedure for ceramic coatings, including low-speed sectioning, cold mounting in vacuum in two-part epoxy resin, grinding, polishing and finishing to 0.25 μm.

The indentations were performed on a portion of the ceramic top coat containing areas with different melting degrees and