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The application of photoluminescence piezospectroscopy for residual stresses measurement in thermally sprayed TBCs

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ABSTRACT

Photoluminescence piezospectroscopy (PLPS) was used as a non-destructive technique for the measurement of residual stresses within the thermally grown oxide (TGO) layer beneath plasma-spray thermal barrier coatings (TBC). The technique has proved to be very effective for such measurements in YSZ thermal barrier coatings applied by EB-PVD but its application to thermal sprayed coatings has been hindered by optical scattering in plasma sprayed coatings of usual thicknesses. PLPS experiments were performed on TBCs with cold sprayed bond coatings and several different ceramic layer thicknesses after thermal cycling. The results are discussed as a function of the coating characteristics like bond coat spraying process, thickness of both bond and top coat, microstructural features, and damage accumulation.

1. Introduction

Thermal barrier coatings (TBC) are the best way to protect components of gas turbine engines and the demand for such coatings is becoming more important as higher temperature engines are being developed [1–3]. A TBC system generally consists of a ceramic top coat as a thermal insulator and a metallic bond coat (BC) on the underlying high-temperature alloy component [4,5]. The ceramic layer is normally 7–8% yttria partially stabilized zirconia (YSZ) [5–8] applied by atmospheric plasma spray (APS) or electron bean assisted physical vapor deposition (EB-PVD) [3,8]. The bond coat usually consists of either platinum modified nickel aluminide (Ni, Pt)Al (applied by electroplating and chemical vapor deposition – CVD) or a MCrAlY alloy, where M stands for Ni, Fe, Co or some combination of them. The alloys also usually include Hf, Ta or Re [8,10]. The main functions of the bond-coat alloy are to ensure good bonding between the high-temperature alloy component and the top coat as well as providing some oxidation and hot corrosion protection [4,5]. In use, a thin aluminum oxide scale forms on the bond-coat at its interface with the top-coat. The TBC lifetime often depends on the growth and internal stresses of this thermally grown oxide (TGO). Cracks nucleate at the thermally grown oxide and grow over the lifetime of the coating, eventually leading to the coating failure [8–11]. Actually, the failure of a TBC is a complex phenomenon that has instigated several research works. It has been accepted that cracks can start both in the TGO and in the YSZ close to the rough TGO mainly due to the complex stress state close to the rough YSZ/TGO/bond coat interface [12–14].

The formation of a dense and uniform α-Al_2O_3 scale is desirable due to its low oxygen diffusivity and low growth rate compared to other oxides. Other oxides, such as Cr and Ni oxides as well as spinels are undesirable due to their volume changes as they grow, and in the worst case can create protrusions contributing to the increase in local stresses and consequent failure [5,9]. The morphology, adherence and stresses in the TGO are very important issues in TBC evaluation and for life prediction. It has been observed that in EB-PVD TBC coatings, after a certain period of service life, the failure cracks typically follow the top coat/TGO interface. In a less extension, cracks can form at the “ridges” present on the bond coat surface before top-coat deposition [15]. For plasma sprayed TBC coatings, failure cracks propagate partly within the top coat (close to the TGO interface). It should be noted that even after coating general failure some adherent ceramic residues can be found [4,5,16–18].

Air plasma spray (APS), vacuum plasma spraying (VPS) and low-pressure plasma spray (LPPS) are the main techniques to apply bond coat onto superalloys [3,19]. These techniques provide fast manufacturing and a strong bonding with the part; but the main drawback is related to high temperatures that inevitably modify the coating microstructure by forming oxides. The oxide content is the principal problem for the aluminum depletion. It hinders the aluminum diffusion to the top of the BC, triggering the formation of Ni/Cr oxides and spinels in the TGO that are undesirable because of their volume change during formation. This volume change creates protrusions contributing to the increase of stresses and consequent failure. HVOF spraying has been

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more recently used as an alternative deposition method because of its low cost and high quality deposits, which have oxidation rates at high temperature at the same level or even lower than those of similar VPS or LPPS coatings [11,17,18]. With this low oxidation perspective, some recent studies have investigated metallic bond coats formed by cold gas spray (CGS) [19,20].

In contrast to the more traditional coating methods, cold gas spray (CGS) utilizes the kinetic energy of the particles in a supersonic flow to deposit an adherent coating as a result of the severe plastic deformation produced when the particles impact the surface. The main advantages of CGS over conventional thermal spray techniques are related to the absence of thermal energy so there is no grain growth and no particle surface oxidation. As a result, a coating almost free of any oxides is obtained, allowing more free aluminum for diffusion to the surface to form the protective α-Al_2O_3 TGO layer on subsequent high-temperature exposure. As a result, CGS is increasingly being recognized as an alternative for the manufacturing of bond coats for thermal barrier coatings [20,21].

In the search of better understanding and control of the residual stresses leading to the failure of a TBC, several measurement techniques have been adopted. These include X-ray diffraction (XRD) and layer removal methods, among others [22–25]. Photoluminescence piezospectroscopy (PLPS) is a non-destructive technique for the measurement of residual stresses within the thermally grown oxide (TGO), including when formed underneath a ceramic top-coat (TBC) [26]. The technique has proven to be very effective for such measurements in YSZ thermal barrier coatings applied by EB-PVD [26–28]. Its application for thermal sprayed coatings is still not solved since the resulting lamellar structure is said to spread the laser beam then weakening the resulting photoluminescence signals [29]. The piezospectroscopic technique is an optical method that utilizes the luminescence from trace Cr^{3+} dopants incorporated into the aluminum oxide formed by oxidation. The spectrum of aluminum oxide consists of two characteristic R-lines, R1 and R2, due to electronic transitions in Cr impurities. The luminescence is excited by a laser beam with an energy selected to penetrate through the zirconia TBC and still be within the optical absorption band of chromium-doped aluminum oxide [30]. If the oxide is stressed, the frequency of the Cr^{3+} luminescence shifts from its stress-free value, the piezospectroscopic effect. The frequency shift is related to the stress by a general equation and measuring this shift the biaxial stresses can be obtained after some calculation [30].

The objective of this work was to assess residual stresses in TGOs formed on thermally sprayed TBCs with cold sprayed bond coats by PLPS experiments. Optimization of the PLPS data collection parameters was employed to overcome limitation reported in previous works related to scattering issues in plasma sprayed TBC. The results are discussed as a function of the PLPS process parameters, coating thickness and number of thermal cycles.

2. Experimental procedure

The metallic coatings were applied onto Inconel 625 Ni-based superalloy (25 × 20 × 5 mm) specimens. One half of the surface area (25 × 10 mm)was coated with the YSZ coating and the other half was left without any YSZ coating as shown in Fig. 1. Metallic plates were used to protect the substrate (half part) for ceramic spraying. The feedstock bond coat powder was an experimental gas atomized NiCrAlY powder (AE10086, Oerlikon Metco) with composition Co32Ni21Cr8Al0.5Y, a spherical morphology, and a particle size of 35 + 11 μm. The ceramic powder was a commercial YSZ (203 NS - Oerlikon Metco) spray-dried, with spherical morphology, and a particle size of −125 + 11 μm.

Before spraying, all alloy substrates were degreased with acetone and grit blasted with white corundum, using a pressure of 5.6 bar, 45° incidence angle, and blasting distance of 250 mm. The grit blasted surface roughness was 4.5 μm (Ra). The samples were placed in a circular sample holder and were simultaneously sprayed for every material (bond and top coat) with a rotational speed of 500 mm/s at the substrate surface. Cooling with air jet to sample back side was applied during ceramic deposition.

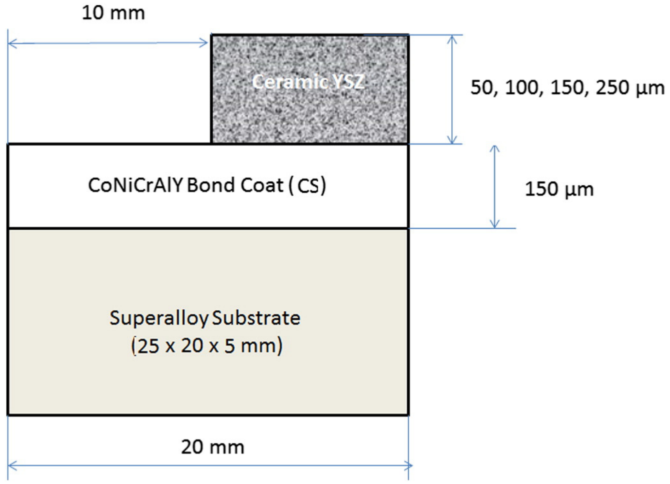

Fig. 1. Scheme of the test specimen.

The morphology of the metallic powders used to form the bond coat is shown in Fig. 2. The chemical compositions of the metallic and ceramic powders are shown in Table 1.

The bond coats were deposited using a Kinetiks® 4000 cold gas spray system (CGT GmbH), with a maximum operating pressure of 40 bar and nitrogen as the propellant gas. A F4-MB plasma spray gun (Plasma Technik, Sulzer Metco, Westbury, USA) was used to apply the ceramic top coats. The thermal spraying parameters used for metallic and ceramic coatings application are shown in Table 2. The bond coat was 150 μm thick whereas four different ceramic top coating thicknesses were prepared: 50, 100, 150 and 250 μm.

Laser Scattering (Microtrac SRA150), Scanning Electron Microscopy (SEM: JEOL JXA840) and flow rate test (ASTM B-213-90) were used for powder particle size distribution and for general powder characterization. XRD (Siemens D-500, Cu Kα = 1.5418 Å, 40KV, 30 mA) was applied to reveal phase content of the starting powder. As sprayed coatings characterization included cross-sectional Optical Microscopy (OM-Leica DMI5000 M) and Scanning Electron Microscopy (JEOL - JXA840), as well as phase analysis by Energy Dispersive Spectroscopy-EDS (Quantum, Kevex). For TGO and thermal cycled coating microstructure analysis, a ZEISS - ULTRA 55 scanning electron microscope was employed. Coating surface roughness was measured in an Olympus

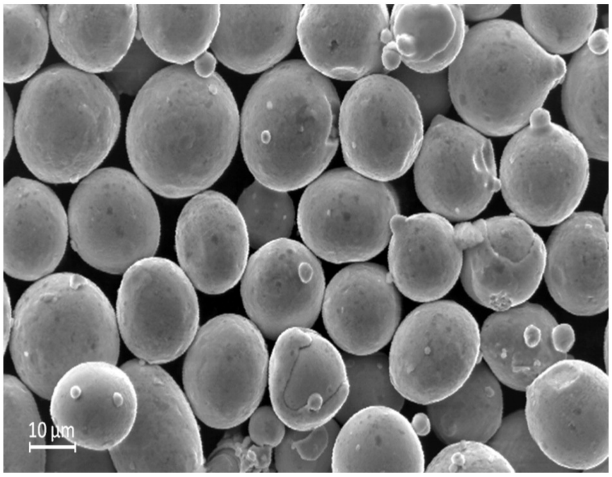

Fig. 2. SEM images of the new CoNiCrAlY powder.

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