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Measurement of residual stress in plasma-sprayed TBC with a gardient of porosity and chemical composition

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Materials

ABSTRACT

Purpose: The purpose of the research was identification of the residual stress in the top coat of different type of thermal barrier coating with gradient of chemical composition and gradient of porosity.
Design/methodology/approach: The APS technique was used to deposition of gradient coating. As a bond coat the NiCrAlY overlay coating was applied. Top-coat consist in the case of gradient of porosity - YSZ with different thickness and porosity and in the case of chemical composition gradient YSZ with AMDRY 365-2 powder. The research allowed the identification of qualitative and quantitative phase constitution of top coat and residual stress measurement by $\sin^2\psi$ method form surface of coatings.
Findings: It was found that the dominant phase in all the top coats was tetragonal zirconia with minor addition of monoclinic type of ZrO_2 and in the case of residual stress the tensile conditions was observed in the case of gradient porosity and compressive stresses in the case of chemical gradient.
Research limitations/implications: Characterization of stress level in gradient TBC`s give possibility description of degradation mechanism of barrier coating.
Practical implications: The results obtained allow the determination of the degree of life-time lost of the TBC system used as protection for creep resistant alloys.
Originality/value: The results obtained are valuable contribution to the development of new typ of TBC. They enable the identification of the degradation mechanisms in YSZ / MCrAlY / substrate system.
Keywords: Metallic alloys; Thin&thick coatings; TBC; Degradation; Oxidation

1. Introduction

Residual stress, especially the thermal stress, is a dominant factor causing reliability problems of high-temperature coatings and may influence some key performances of coatings, such as the resistance to spalling, delamination, surface crack, etc. The failure expected in a coating system can be predicted based on the knowledge on residual stresses, their redistribution, and the external loads, as well as the interface response. Generally, the magnitudes and distributions of the residual stresses within a high-temperature coating are dependent not only on the thermal history during coating deposition process and the deposition characteristics. During the last decade, research efforts have been devoted to the development and manufacturing of ceramic TBCs on turbine parts because the traditional turbine materials have reached the limits of their temperature capabilities. Thermal barrier coatings (TBCs) are used to sustain the highest temperature on the surface of high temperature superalloy substrates. TBCs have been widely used in hot-section metal components in gas turbines either to increase the inlet temperature with a consequent improvement to the efficiency or to reduce the requirements for the cooling air. Ni-based superalloys have usually been used with thermal barrier coating (TBC) for vanes and blades in gas turbines and jet engines [1–10]. Generally, the TBC applied in gas turbines is made up of two components: a bond coat created by the vacuum or low pressure plasma-sprayed MCrAlY (M = Ni, Co) and a top coat of yttria and partially stabilized zirconia produced by the atmospheric plasma spraying or electron beam-physical vapour deposition (EB-PVD) [11,12]. A typical superalloy/TBC system consists of plasma-sprayed zirconia-yttria ceramic layer with a nickel-chromium-aluminum-yttrium bond coat on a substrate made of nickel-based superalloy. These superalloy/TBC systems can be applied in both aerospace and land-based gas turbine engines. In automotive use, the piston head for diesel engine is coated to enhance lifetime and performance as far as fuel demand reduction and power improvement are concerned. These coatings, nevertheless, exhibit relatively short lifetime, which is the result of the applied material and thermal contrast between the coating and the base metal. Thermal residual stresses occur in TBC/metallic substrate during cooling from the temperature of processing. Environmental effects, specifically oxidation, create additional residual stresses as the oxide layer grows, resulting in additional material mismatch between the oxide surface and the TBC.

These residual stresses could originate micro-cracks including debonding and radial cracks, deeply affect the response of the TBC and cause interfacial damage accumulation and failure. Their understanding is fundamental for the prediction of the functioning of the coatings and their performance [13].

The bond coat seems to be the key element of the TBC system [14]. Its chemistry and microstructure modify the durability of the system via both the structure and the morphology of TGO created during the oxidation. What is more, the performance also appears to be connected to its creep and yield features. There are two categories of barrier coatings: NiCoCrAlY-system-based coatings and Pt-modified diffusion aluminide coatings. The link between BC and TGO, whose morphology is altered in service, is another essential factor: typically, the interfacial zone is subject to a great amount of stress, which results from oxide condensation, thermal expansion mismatch and applied loads. Consequently, a crack can be generated and propagated, which results in the ceramic layer spalling off, inducing the degradation of the system [15].

2. Description of experiments, methodology and materials

The study has been done on AMS 5599 type alloy with 4 different type of thermal coatings with gradient of porosity and gradient of chemical composition. In all the specimens, A365-2 (Ni23Co17Cr12,5Al0,45Y) VPS-sprayed powder was employed as the interlayer. In addition, M204 NS - $ZrO_2 \times 8\% Y_2O_3$ powder (applied on its own or together with A365-2 powder, to form graded coatings of varied porosity and/or chemical content) was used for the outer layer spraying. In addition to that, microstructural analysis has been done. The qualitative phase analysis has been conducted by X-ray diffraction method. The tests were done at JDX-7S JEOL diffractometer. The chemical content microanalysis has been done by EDS method using Six Sigma system attached to Hitachi 3400N microscope.

4 variants of coatings were prepared for further investigation:

- TBC-2 variant (Fig. 1) included the spraying of AMDRY 365-2 interlayer and of 5 successive Metco 204 and Amdry365-5 powder layers of a given thickness, so as to obtain the composition gradient:

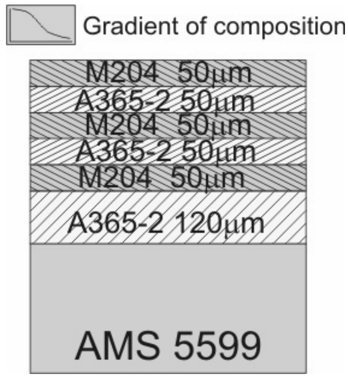

Fig. 1. The conception of TBC system with the gradient of chemical composition

- TBC-3 variant (Fig. 2) included the spraying of AMDRY 365-2 type interlayer and of Metco 204 powder layers of a given thickness, modifying the APS process so as to obtain the following porosity gradient;

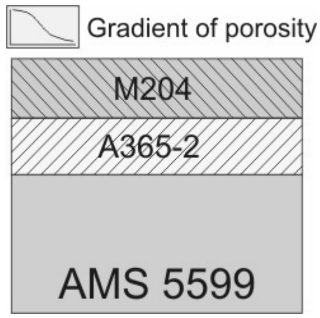

Fig. 2. The conception of TBC system with a gradient of porosity

- TBC-4 variant (Fig. 3) included the spraying of AMDRY 365-2 type powder interlayer and of a layer consisting of Metco 204 and AMDRY 365-2 powders mixture of a particular capacity proportion of both of them, modifying the APS spraying process so as to get the following composition gradient;

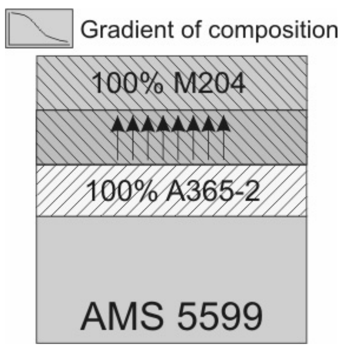

Fig. 3. The conception of TBC system with a gradient of chemical composition

- TBC-5 variant (Fig.4) was parallel to the TBC-3 variant, except for the fact that the ceramic Metco 204 powder layer was substantially thicker and the process was directed so as to obtain the following porosity gradient;

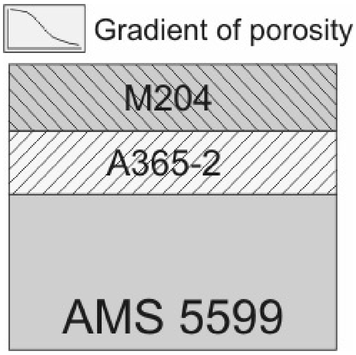

Fig. 4. The conception of TBC system with a gradient of porosity

X-ray measurements in the mode Θ–2Θ angles in the range of 20–80° using Cu Kα (40 kV, 20 mA) radiation in steps of 0.02 were performed in order to access the structural characterization of the coatings. Residual stresses were determined by X-ray diffraction using the $\sin^2\Psi$ technique. Measurements on [620] lattice plane of ZrO_2 were performed to obtain the coatings surface strains. The diffraction angle for this plane occurred at about 2 Θ =144.58. The Ψ angle was scanned from -25° to 25° by steps of 5° in order to get the interplanar distance d_Ψ (Table 1). The biaxial stresses in the plane parallel to the interface were calculated considering an isotropic biaxial stress distribution with s_{33}=0 (Fig. 4). The XRD spectra were acquired for the as-sprayed coatings at initial conditions.

Table 1.
XRD parameters used in the residual stress measurements

Anode current (mA)	20
Anode power (kW)	40
Radiation	Cu $K_{\alpha 1}$
Lattice plane in analysis	[620]
Range of measurement, 2Θ (°)	138 to 150
Ψ range (°)	-25 to 25

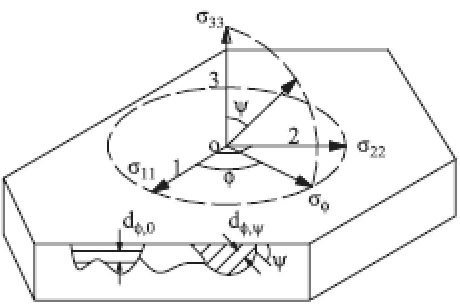

Fig. 4. Model of the in-plane elastic residual stresses (method $\sin^2\Psi$)

Considering Fig. 4, for a biaxial stress in the irradiated layers of the surface TBC coating the lattice strains are related to the stress by:

$$\varepsilon_{\phi,\psi} = \frac{d_{\phi,\psi} - d_0}{d_0} = \frac{1+\nu}{E}\sigma_\phi \sin^2\psi - \frac{\nu}{E}(\sigma_{11} + \sigma_{22}) \quad (1)$$

where d_0 is the unstressed lattice spacing, $d_{\Phi,\Psi}$ is the lattice spacing under stress, σ_ϕ s the stress present in the Φ direction defined in the plane of the coating, Ψ is the tilt angle, σ_{11} and σ_{22} are the stresses along the principal directions, E is the Young's modulus and ν is the Poisson's ratio of the material. Equation predicts a linear relationship between $d_{\Phi,\Psi}$ and $\sin^2\Psi$, and the stresses can be obtained from a least squares fit of experimentally determined d - spacing measured at a number of tilts. The σ_Φ stress along the Φ direction we can calculate by the following equation:

$$\sigma_\phi = \frac{E}{(1+\nu)\sin^2\psi}\left(\frac{d_{\phi,\psi} - d_{\phi,\psi=0}}{d_0}\right). \quad (2)$$

3. Description of achieved results of own researches

The structural analysis was performed to determine the structure for all coatings and to determine the volume of phase modification. Fig. 5 shows some XRD patterns for all plasma sprayed coatings in as-sprayed condition. The X-ray phase content analysis enabled both the qualitative and quantitative evaluation of the outer zone of the investigated graded coatings. The tetragonal phase including monoclinic phase was dominant in all of the studied specimens where the main diffraction peak corresponds to the <011> planes (Fig. 5, Tab. 1). No presence of phases generated by the second element of the graded coatings, i.e. AMDRY 365-2 powder, was detected.

Table 2.
The quantitative results of XRD analysis (fraction of monoclinic phase)

	TBC-2	TBC-3	TBC-4	TBC-5
% wt.	12,50	5,90	7,90	8,15

The average values of the residual stresses at the top - surface of gradient TBC`s systems are presented in Tab. 3. A compressive residual stresses in a chemical composition gradient TBC`s can be seen. In the case of gradient of porosity coating tensile conditions of residual stress was observed.

Table 3.
Residual stresses measured at the top-surface determined with different types of gradient in TBC`s system

	TBC-2	TBC-3	TBC-4	TBC-5
Residual Stress [MPa]	-65	62	-15	45

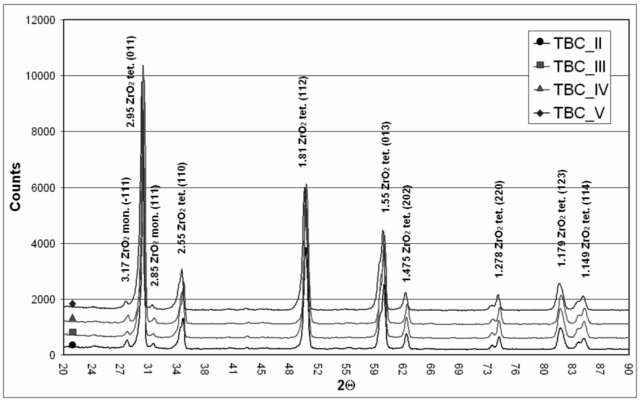

Fig. 5. The results of XRD phases identification from the top surface of gradient TBC.

4. Conclusions

The residual stresses and elastic properties of graded plasma sprayed ZrO_2–8wt.%Y_2O_3 coatings have been measured at room temperature in the as-sprayed coatings for two different type of chemical composition and porosity gradient.

It was demonstrated that both X-ray diffraction are powerful techniques to determine the microstructure and the residual stresses in the coated parts.

The top-surface of TBC presents a dominated tetragonal phase with a preferred orientation on the <011> with minor addition of monoclinic phase.

The graded in porosity thermal barrier coatings (YSZ as top coat/ MCrAlY as bond coat) presents a tensile stress state at the free surface which increase with decreasing of coating thickness.

The residual stresses show an compression type in the case of coating with gradient of chemical composition.

Acknowledgements

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