Evaluation of thermal conduction anisotropy on Thermal Barrier Coating

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Abstract

The microstructural analysis of Thermal Barrier Coatings, deposited according to the Air Plasma Spray technology, furnishes information according which a strong orthotropic thermal conductivity is expected to be measured for such a material. Pulsed experiment with a localized heating source and thermographic temperature recording, permit to evaluate both the in-depth and in-plane components of the conductivity tensor. The utilization of a gaussian shaped heating function permits to compare both the direct solution and the one obtained by a spatial Fourier Transform.

1. Introduction

Ceramic thermal barrier coatings (TBC) are widely applied for protecting hot path components of gas turbines from combustion gases [1]. Notwithstanding the wide utilization and the long time (almost 30 years) since their appearance, TBC are still argument of research in the field of material science [2,3]. The thermal properties and the elastic one depend more on the porous microstructure than on the bulk material characteristics. Therefore the microstructure, which on its turn depends on the deposition process, is often and often the object of research that try to model it in relation to the heat diffusion equation and the stress-strain mechanics [4,5]. Another important topic is that this microstructure is going to be modified as the TBC are submitted to the heating cycles during their working conditions. In such a case, the ageing of the material is studied, together with the kinetic of sintering, that finally modify the original microstructure of the TBC [6,7]. As a consequence of ageing (sintering), a deterioration of both the insulating properties and the elastic one leads to a detachment of the TBC from the substrate that it should protect.

Recently, a careful analysis of the microstructure of a typical TBC, deposited with the Air Plasma Spray (APS) technique, revealed the presence of a consistent fraction of lamellar porosity oriented, in the average, with the long dimension parallel to the TBC surface [8]. It means that a consistent thermal resistance to heat, flowing in-depth of the TBC layer, is generated, while the in-plane diffusion should not be affected significantly. The model provides a ratio between the in-plane and the in-depth thermal diffusivity (conductivity) approximately of 2:1. To experimentally verify what the model forecasts, the thermal diffusivity of a sample of TBC deposited with the APS technique is measured using pulsed thermography [9].

2. Rationale

By means of the microstructural analysis, we state that the material owns a transversely isotropic simmetry, which means the conductivity tensor is diagonal and the in-plane components are equal and different from the in-depth one. The Fourier conduction equation is therefore:

$$\begin{bmatrix}\theta_\xi\\ \theta_\psi\\ \theta_\zeta\end{bmatrix}=-\begin{bmatrix}\lambda_\Pi & 0 & 0\\ 0 & \lambda_\Pi & 0\\ 0 & 0 & \lambda_N\end{bmatrix}\begin{bmatrix}\partial T/\partial\xi\\ \partial T/\partial\psi\\ \partial T/\partial\zeta\end{bmatrix} \qquad (1)$$

where q_i are the heat flux components along the coordinate axes, λ_j the conductivity tensor components and in the right square bracket are enclosed the temperature gradient components. With the TBC surface layed on the *x,y* plane, a localized heating shot on the surface is able to determine a temperature field that permits to measure both the normal component α_N of the thermal diffusivity and the parallel one α_P. A very effective shape for the shot is the gaussian one [10]. It gives a very convenient solution that consists of two factors. The first represents the in-depth diffusion for the slab (in adiabatic condition) and depends only on α_N. The second represents the spreading of heat in plane and depends only on α_P. The solution on the surface is the following:

$$T(\rho,\tau)=\left\{\frac{2\Theta}{\varepsilon\sqrt{\pi^3\tau}}\sum_{\nu=-A}^{A}\varepsilon\xi\pi\left[-\frac{((\nu-1)\Lambda)^2}{\alpha_N\tau}\right]\right\}\cdot\left\{\frac{1}{(P^2+8\alpha_\Pi\tau)}\varepsilon\xi\pi\left[-\frac{2\rho^2}{P^2+8\alpha_\Pi\tau}\right]\right\} \qquad (2)$$

where $r=(x^2+y^2)^{1/2}$, L is the slab thickness, R the gaussian shot radius, $\varepsilon=(\lambda_N\rho c)$ the thermal effusivity (composed by the normal thermal conductivity, density and specific heat), and t is time. Eq. 2 is suitable to be evaluated in its spatial Fourier Transform, being the FT of a gaussian still a gaussian. The algorithm to identify the thermal diffusivity by analysing the time evolution of the spatial FT suffers of a low signal to noise ratio due to the spreading of the energy on several spatial frequencies. The possibility to compare the diffusivity identification algorithm both in its direct and transformed space expression gives the opportunity to evaluate the effectiveness of the two approaches.

3. Experiment

A sample of TBC, deposited with the APS technique and free standing (detached from the substrate, is submitted to a shot (duration 1/100 s) of gaussian shape (radius 0.005 m). An infrared camera records a sequence of images of the surface temperature evolution. In the first step, every image in the sequence is integrated spatially to obtain a value that change in time. Such a value is supposed to behave like the temperature of the same slab if it were uniformly heated on its surface. By this analysis the normal component of diffusivity α_N is obtained. As a second step a gaussian function is used to fit for every time the surface temperature shape. It permits to obtain the radius of the gaussian for every time that is supposed to increase linearly with time, according to eq. 2. The slope of the line gives the in-plane thermal diffusivity α_P. Alternatively, the spatial FT of each image is computed, and the strongest spatial components are analysed in time, once divided for the continuous one. They decrease their amplitude exponentially, with a time constant depending on α_P.

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