SOME FAILURE MODES OF PLASMA-SPRAYED THERMAL BARRIER COATINGS

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Recent analytical techniques for incorporating micromorphology in the residual stress analysis of ceramic thermal barrier coatings are reviewed. The influence of various deposition parameters on the stress portrait is analyzed, and the corresponding failure modes upon shock and thermal cycling are discussed. Some new research directions are indicated.

INTRODUCTION

Ceramic coatings on metal structural elements and machine parts have been used for over a decade for thermochemical insulation purposes. Turbine vanes, blades and diesel engine combustion chambers are among their principal application fields. The standard deposition technology for thermochemical barrier coatings (TBC) is the low-pressure plasma-spraying of an yttria-stabilized zirconia layer over a superalloy bond coat previously deposited on the metal.

Low-risk applications of this technology are widespread. However, its development for high-risk design, where the loss of the coating would lead to the loss of the component, requires advances in the understanding of the failure thermomechanics of the coated structures, both in the coating deposition phase and under service conditions.

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Several factors influence the failure characteristics of plasma-sprayed TBC's: Ceramic chemistry, bonding layer selection, granulometry of the injected ceramic powder, plasma temperature, carrier gas selection, gun distance, and others (1). The residual stresses, resulting from the deposition cooldown phase, appear to play a major role in the failure mechanics. These stresses are determined by the anisotropy of each of the coating component layers, by the microstructure gradient throughout the coating, by the non-uniformity of the temperature evolution, and by the thermal expansion mismatch between interfacing phases. As a preliminary to the study of the failure modes, Ferrari and Harding (2), and Ferrari *et al.* (3) have developed means for incorporating the microstructural aspects in the residual stress analysis. Their procedure is reviewed in section two, together with the field equations of thermoelasticity.

The residual normal stresses, generated by the initial cooldown, may be tensile or compressive, resulting in different failure mechanisms, as discussed below. The dominant parameter, in determining the compressive or tensile trend of the stresses, is the temperature of the substrate during the ceramic deposition (4).

The present focus is on the correlation between the deposition temperature and the failure characteristics. This correlation is understood to be of parametric nature, in dependance of the micromorphology of the coating, and hence of the factors that determine the microscopic portrait. Some fundamental aspects of these functional relations are discussed in section three. Here, failure modes are qualitatively discussed. Some indications for research, leading to an optimal deposition technique, in the sense of structural durability, are given in section four.

2. THERMOELASTIC FIELD EQUATIONS / INCORPORATION OF THE MICROSTRUCTURE.

Given a body $B + \partial B$, of boundary ∂B, subject to an eigenstrain field $\underline{\varepsilon}^*$, the field equations governing the displacement $\underline{u}$, the strain $\underline{\varepsilon}$, and the stress $\underline{\tau}$ are:

The strain-displacement relations

$$\underline{\varepsilon} = \mathrm{sym}(\mathrm{grad}(\underline{u})) \qquad (1)_1$$

The constitutive equations

$$\underline{\tau} = \underline{C}\ (\underline{\varepsilon} - \underline{\varepsilon}^*) \qquad (1)_2$$

and the equilibrium conditions

$$\mathrm{div}\,\underset{\sim}{\tau} + \underset{\sim}{f} = 0 \qquad (1)_3$$

Here, $\underset{\sim}{C}$ and $\underset{\sim}{f}$ denote the elastic stiffness tensor field, and the body force vector, respectively, while div(.), grad(.) and sym(.) are the divergence, the gradient, and the symmetric part operators.

Appropriate boundary condition for the field equations (1) are specified as

$$\underset{\sim}{\tau}\,\underset{\sim}{n} = \hat{\underset{\sim}{t}} \qquad \text{on } \partial B_t \qquad (2)_1$$

where $\underset{\sim}{n}$ is the outward unit normal, and

$$\underset{\sim}{u} = \hat{\underset{\sim}{u}} \qquad \text{on } \partial B_u \qquad (2)_2$$

In equations (2), $\hat{\underset{\sim}{t}}$ and $\hat{\underset{\sim}{u}}$ are assigned tractions and displacement vectors, respectively, and ∂B_t and ∂B_u are complementary portions of ∂B.

Plasma-sprayed TBC's contain large void volume fractions. The *quantitative, morphological and textural* distributions of the voids (pores and microcracks among these) is highly inhomogeneous, resulting in highly inhomogeneous effective thermomechanical properties. The approach presently employed, to incorporate the microstructure into the residual stress analysis, is to discretize the coating, according to distributional data coming from either experiment or simulation, assigning effective properties to the sub-regions, and then solving the thermomechanical problem in this piece-wise homogeneous representation of the coating. The homogenizing theory employed thus far is based on the assumption of Mori-Tanaka - by which the *geometry* of the porosities is accounted for, and incorporates the voids' orientational distribution via the methods of harmonic texture analysis.

Applications of the discretization/homogenization procedure are given in references (2, 3), where details on the homogenization technique and further references are also available. A brief summary of the homogenizing formalism, under the assumption of Mori and Tanaka, is given next: The effective stiffness tensor, associated to a material of ideal stiffness C^m, containing N geometrically different void types, denoted by the index i, is

$$C^{MT} = C^m \left(I - \Sigma_i\, \alpha_i < T^i >_i [\alpha_m I + \Sigma_j\, \alpha_j <T^j>_j]^{-1}\right) \qquad (3)$$

where

$$T^i = [I - E^i]^{-1} \tag{4}$$

Here, α_i is the volume fraction occupied by the i-th void family, and E^i is the corresponding Eshelby's tensor (5). This tensor contains the information about the voids' geometry. The textural data are incorporated into the weighted orientational averaging operators $<.>_i$:

$$<.>_i \equiv 1/8\pi^2 \int_0^{\pi}\int_0^{2\pi}\int_0^{2\pi} (.)\ f^i(\varphi_1,\varphi_2,\phi)\ \sin\phi\ d\varphi_1\ d\varphi_2\ d\phi. \tag{5}$$

Here, φ_1, φ_2, and ϕ denote Euler's angles, and f^i is the orientation probability density function for the i-th voids family.

3. FAILURE MODES: EFFECTS OF DEPOSITION TEMPERATURE AND MICROSTRUCTURE.

The temperature, at which the substrate is kept, during the deposition of the TBC, controls the trend of the resulting in-plane residual normal stress in the coating (see Fig. 1). In the following, two limit cases are addressed: Forced cooling of the substrate, kept at ambient temperature, and super-critical temperature distribution in the substrate, resulting in compressive stresses in the coating.

a) Substrate fixed at ambient temperature.

The thermoelastic analysis yields unreasonably high tensile stresses - of the order of several GPa (6) - if the effects of the voids are not accounted for. Incorporating the microstructural data, the stresses are decreased typically to 1 GPa, at the peak value , for coatings, with a global porosity value of about 20% (2,3,4). Higher porosity values, especially in conjunction with a dominance of intergranular "flat" voids, reduce the stresses considerably (7), but decrease the in-plane fracture toughness, thus increasing the risk of failure by linking of transverse fracture planes. Enhanced effective moduli, and thus higher stresses, correspond to lower porosity values, with a dominance of spherical, intragranular voids. These stresses may exceed the strength of the individual ceramic layers, and thus induce structural failure, via formation of a transverse macrocrack. However, the inhomogeneity of the stress profile, in conjunction with localized porosity distributional peaks, may cause individual layers to fail, without implying structural failure, and even increasing the overall durability of the structure: Transverse fracture segmentation is known to enhance the in-plane strain tolerance (1). By this, and other strain tolerance mechanisms, like columnar-growth-induced material segmentation, the structural fracture toughness is sufficiently raised, for the coating not to fail by tensile residual loading, in general. The critical loading mode is compression, as discussed next.

b) Super-critical substrate temperature.

If the substrate reaches sufficiently high temperatures, the coating's transverse normal stresses are compressive. Experimental evidence indicates that this loading mode is the likeliest one to cause failure (1). Two mechanisms are relevant in this connection: Buckling and tensile radial strain in excess of the strain limit.

The buckling of the splats may take place, once the compressive load reaches a bifurcation point, the intensity of which depends on the adhesion & cohesion forces, acting between neighboring particles, as well as on the typical splat geometry. Thus, the buckling mode depends parametrically on the porosity quantitative, qualitative, and textural distributions, as well as on the thermal characteristics - these parameters defining the stress portrait - and also depends on some deposition parameters, such as, say, plasma temperature, powder granulometry, gun distance, since these not only influence the stresses, but also determine the interface actions between splats.

Radial strains in excess of the material limit will cause the coating to fail , by the formation of macrocracks, parallel to the ceramic-bonding layer interface. It is recalled that the radial strains in the ceramic must be positive, when the transverse stresses are compressive (4).

While a quantitative understanding of these modes has not been achieved yet, it may be argued that the former is more likely to occur at lower ceramic densities.

4. RESEARCH DIRECTIONS.

A central issue, in the optimization of the deposition technique, for the achievement of maximal coating service life, is the quantitative understanding of the role of the porosity parameters in the failure modes. Having reached the goal of assessing the relevance of these microstructural aspects in the stress analyisis (2), the major points to be addressed are the understanding of i) the single layer (i.e. material) strength, ii) the relation between the material strength (field), the inter-layer voids' distribution and the structural strength, iii) the relation between the porosity parameters and the two failure modes under compression, described in 3-b.

In parallel with this research tasks, the understanding of the relation between the deposition parameters and the microstructural portrait should be pursued.

Premier macroscopic parameters to be studied are the influence of transverse fracture segmentation on the tensile failure, and the other strain tolerance mechanisms, introduced above.

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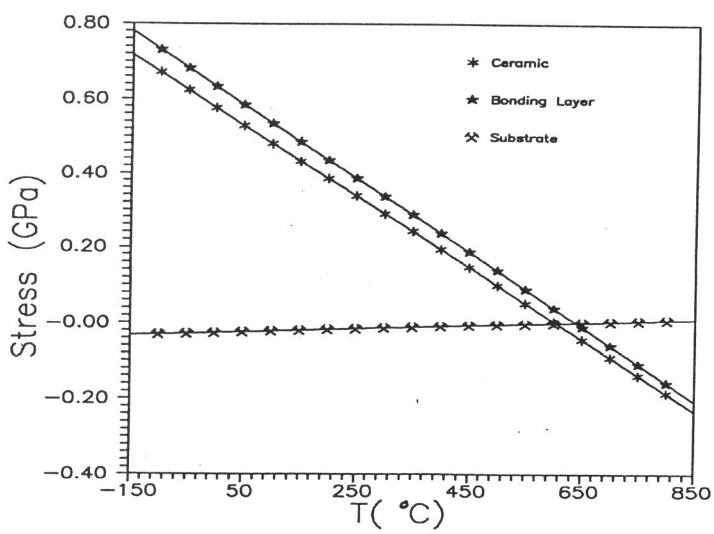

Fig. 1. Trend of the tangential residual stress in the coating system, when brought to 0 °C from various deposition temperatures.