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Effects of residual stress on the mechanical properties of plasma-sprayed thermal barrier coatings

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ABSTRACT

This paper was aimed to address the effect of residual stress on the deformation and cracking behavior of plasma-sprayed yttria-stabilized zirconia (YSZ) thermal barrier coatings (TBCs) deposited at different deposition temperatures. The residual stress within a coating was evaluated by measuring the temperature-curvature plot during the spraying process. The deformation and cracking behavior of the coatings was studied by using the four-point bending tests and their fracture properties were determined. By changing the direction of coating-substrate couple, tensile or compressive stress was applied to the coating. The variation of cracking density along with the applied tensile strain was measured. An analytical model was developed to evaluate the bending strength and fracture energy of the coatings subjected to bending load with taking account of residual stress. Results showed that the crack resistance of the YSZ TBC increased with increasing the deposition temperature due to increment of compressive residual stress within it. The critical strain for cracking, fracture strength and mode I fracture toughness of the YSZ TBC generally increased with increasing the deposition temperature and the compressive residual stress in it. The predicted crack densities against applied strain exhibited similar trends with the experimental results for higher applied strain in the case of the coatings with compressive residual stress larger than 20 MPa.

1. Introduction

Plasma-sprayed yttria-stabilized zirconia (YSZ) have been widely used as thermal barrier coatings (TBCs) to provide thermal insulation to metallic components from the hot gas stream in gas-turbine engines used for aircraft, propulsion, and power generation [1–4]. However, there still remained some reliability issues such as premature failure of YSZ TBCs due to cracking accompanied with delamination. It was believed that the failure of YSZ TBCs was often caused by the combination of residual stresses with service stresses. The residual stresses were inevitably generated in the coating, which alone can also act as the driving force of cracking and delamination of YSZ coating. For instance, segmentation cracks were often observed in the coatings with high thicknesses just after deposition [5]. It is generally accepted that the quenching and thermal stresses are the two major sources of residual stresses within the plasma-sprayed coatings. They are respectively generated owing to the rapid shrinkage and contraction of the molten splats during coating deposition stage [6,7] and the thermo-mechanical mismatch between the coating and substrate in the post-deposition cooling stage. Since the misfit strains generated in the coating result in bending deformation of the substrate [8], *in situ* curvature monitoring techniques for measuring the stress evolution in the plasma-sprayed coatings has been developed [9,10].

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Nomenclature

x, y, z	Cartesian coordinate system
$\varepsilon_x, \varepsilon_y$	strain along x and y coordinates
σ_x, σ_y	stress along x and y coordinates
σ_r	residual stress in a coating
t_c	coating thickness
t_s	substrate thickness
$\varepsilon(z)$	applied strain distributon along z-axis
k	curvature of a coating/substrate system
δ	distance from a neutral axis
E_s	elastic modulus of a substrate
E_c	elastic modulus of a coating
l	half width of a segment
β	parameter related to stress transfer at an interface
v_c	Poisson's ratios of coating
v_s	Poisson's ratios of substrate
ε_c	critical strain for cracking
σ_{str}	fracture strength of a coating
ε_c	applied bending strain at $z = t_c$
U_i	elastic strain energy in a coating segment
Γ	fracture energy
K_{IC}	apparent fracture toughness

Two types of fracture properties need to be considered: one is related to the adhesion of TBC such as delamination resistance and interfacial fracture toughness, and the other is of the TBC itself, such as fracture toughness, fracture energy and strength of sprayed coating. They have been evaluated by using several experimental approaches. In such a case, the cracking of the coating due to residual stress combined with stress applied on the coating-based system was of practical interest. Various mechanical testing methods, such as tension, indentation, and bending, have been developed so far to characterize the fracture properties of coatings. Among these methods, the four-point bend test offers a number of advantages over the other testing methods [11]. For instance, it produces a uniform moment between the two inner loading pins on the specimen, giving rise to a uniform stress distribution on the specimen surface. Moreover, the four-point bend test can also be used to evaluate the interfacial crack extension energy in the coating-based system containing a pre-crack [12–14]. Generally, the process of coating failure involves four steps when the coating was subjected to tension in four-point bend, namely deformation of the coating-based system, vertical cracking of the coating perpendicular to the loading direction, saturation of multiple cracking density, and delamination of coating due to link-up of the parallel vertical cracks and transverse cracks [15,16]. The relationship between the crack density and the applied strain in the second and third steps can be used to qualitatively evaluate the cracking resistance of coating. The interfacial fracture energy of a coating-based system can be evaluated through measuring the crack length in the last step [14]. Despite the existence of a large amount of observational data on multiple cracking of coatings, the residual stress was often neglected in evaluation of fracture strength and strain energy release rate of coatings [4,17].

The main motivation of this work has been to investigate the effect of residual stresses on the fracture properties of YSZ TBCs by using an analytical model and experimental data obtained from four-point bend tests. This article was divided into 5 sections. In the second section, an analytical model was developed to predict the fracture properties under the combined influence of applied stress and residual stress. The experimental procedures including the preparation of YSZ TBCs and four-point bend testing were introduced in Section 3. The main results and related discussion were given in Section 4. The main conclusions were summarized in the last section.

2. Analytical modeling

2.1. Model description

The coating-based system subjected to the four-point bend is schematically shown in Fig. 1, where the coordinates x, y, and z are defined. The thicknesses of the coating and substrate are denoted as t_c and t_s, respectively. Prior to bend loading, the coating is only subjected to the residual stress due to the mismatch strain between the coating and substrate generated in the deposition process. A uniform moment between the two inner loading pins is generated in the specimen after bending, leading to the deformation of the coating-based system, as shown in Fig. 1b. However, in such a case, the applied strain in the coating-based system, $\varepsilon(z)$, should be expressed as

$$\varepsilon(z) = k(z + \delta) \tag{1}$$