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Interfacial delamination of double-ceramic-layer thermal barrier coating system

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Abstract

Thermal barrier coating system (TBCs) must withstand the most demanding high temperature conditions where state-of-the-art top coat material Y_2O_3–stabilized ZrO_2 may undergo significant sintering and phase change. The concept of double-ceramic-layer (DCL) TBCs seems to be an effective way to meet the need for both thermal stability and transformation toughening. In this paper, a virtual crack closure technique based interface element method is introduced to study the mechanics associated with the interfacial delamination of DCL TBCs. The evolution of energy release rate of interfacial delamination is explored for DCL TBCs with various geometrical and material parameters. Analysis of fracture mechanisms of delamination reveals that considering the integrated thermal and mechanical functionalities of coatings an optimal thickness ratio of outer to inner ceramic layers exists, which can be preliminarily evaluated by running numerical calculations of fracture parameters and performing thermal life experiments over a wide range of thickness ratios of outer to inner coating layers. In addition, the influence of separation centered at the interface of two ceramic layers is also examined. It is demonstrated that the local separation between two ceramic layers makes delamination readily to form and propagate at the interface between the inner coating and the underlying layer.

Keywords: A: Films; B: Failure analysis; C: Fracture; E: Substrates

1. Introduction

The thermal efficiency of gas turbine for power generation relies on the development of heat resistant materials as well as turbine cooling technology and thermal barrier coating system (TBCs). It has been proved that the turbine inlet temperature increase facilitated with the application of TBCs, in conjunction with advanced air-cooling technology, is much greater than that enabled by heat resistant materials development [1,2], which driving researchers to make every effort to pursuit advantaged TBCs [3]. Due to its low thermal conductivity and high environmental durability, Y_2O_3-stabilized ZrO_2 (YSZ) is increasingly used as the thermal resistant material of TBCs on the surface of metallic parts in the hottest part of gas turbine engines. Further improvement in the energy efficiency of future gas turbine engines makes the surface temperatures of the top coat (TC) and the bond coat (BC) are higher than those in today's conventional TBCs, which may lead to the deterioration of material properties and thus the decreases of efficiency and reliability [1,4]. The state-of-the-art TC material YSZ performs quite well up to current service temperatures. However, at still higher temperatures, the YSZ mainly undergo two significant detrimental changes: sintering and phase change [5,6]. Over long time high temperature operation, YSZ strongly sinters which leads to microstructure changes and increases in the thermal conductivity and Young's modulus, and hence a reduction of the strain tolerance [5]. On the other hand, the phase transition in YSZ is accompanied by an undesirable volume expansion of about 4% and a considerable reduction of thermal cycling life of TBCs [6].

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As a consequence, these disadvantaged high temperature properties of YSZ promoted a worldwide search for candidate materials with superior low thermal conductivity, high melting point, resistance to sintering, and long life properties [3]. Over the past decades, various materials have been developed and considered to be the candidate materials for the future coating [1,7]. A detailed overview on the development of new TBCs material systems was given by Clarke and Levi [3]. It has been proved that the coefficients of thermal expansion (CTE) of these promising candidate materials are typically lower than that of YSZ, which results in higher thermal stresses and thus premature failure of TBCs [8]. Previous studies showed that the need for thermal stability seems contradict with the ability of transformation toughening. Since no single material satisfies all requirements for advanced TBCs, the concept of multilayer seems to be an effective way to overcome this shortcoming. Due to its relatively high CTE and high toughness, traditional YSZ layer is coated to the BC layer. Meanwhile, to protect the inner YSZ layer an additional outer layer with high phase stability and low thermal conductivity is coated on the top of traditional YSZ layer. As a result, a double-ceramic-layer (DCL) coating is formed.

Most of investigations focus on the preparation, characterization, and thermal shock resistance of multilayer thin film/substrate system [8–12]. Relatively little effort has been devoted to the mechanisms governing failure of DCL TBCs. Since the DCL TBCs are composed of multilayer materials with obviously different material properties, relatively large thermal stresses can be induced inevitable in the coatings [13,14]. As a result, interfacial delamination forms, which is believed to govern the durability of coating system [15,16]. The final failure of TBCs happens by spallation of coatings when a separation becomes large enough to create a large scale buckle or an edge delamination [17–19]. The delamination failure is driven by the difference between the stored energy of the debonded and adhered systems. This energy is released during the propagation of the delamination at weak interfaces. Therefore, the central scientific and engineering issue for the application of new developed DCL TBCs is to understand the mechanics of interfacial delamination in terms of energy. Lacking detailed knowledge of failure mechanisms will preclude the application of DCL TBCs in practical gas turbine engines.

In this paper, the evolution of interfacial delamination as well as its dominated material and geometrical parameters is explored numerically. Section 2 briefly reviews the interface fracture mechanics and the concept of an interfacial delamination emanating from the root of a long, straight channel crack. In addition, a user defined element technique based finite element method (FEM) is introduced to calculate the strain energy release rate (SERR) for interfacial delamination. In Section 3, the interfacial delamination of a DCL TBCs structure is investigated by analyzing the effects of material and geometrical parameters of an additional outer coating layer. The influence of separation centered at the interface between two coating layers on the evolution of SERR is also analyzed. Finally, some discussions and concluding remarks are presented in Section 4.

2. Statement of the problem

2.1. Bi–material interface crack

In thin film/substrate structures, two dominate failure modes have been investigated extensively, one for cohesive fracture and the other for interfacial delamination [20]. Multiple surface cracking is the common form of cohesive fracture in thin film structure [21–24]. Once the surface cracks grow sufficiently long compare with the film thickness, a steady state is reached where the energy released per unit advance keeps constant and the crack driving force become independent of the surface crack length and initial flaw geometry [25]. In this case, the steady state SERR of the surface channeling crack can be calculated from a two-dimensional (2D) model [26], which provides a simplified solution that is directly relevant to design against fracture. The previous research found that depending on the elastic mismatch and interface roughness delaminations can be triggered at the roots of the surface channeling cracks [27–29]. In this paper, we consider the mechanisms governing the failure of an interfacial delamination emanating from the root of the surface channel crack at each side in the DCL TBCs, as shown in Fig. 1.

Since the interface of different components is usually a low–toughness fracture path, the delamination is assumed to propagate along the interface. As a sequence, the problem must be concerned with mixed mode crack propagation. Dundurs (1969) has observed that the fracture behavior of an interfacial crack depends on only two non-dimensional combinations of the elastic modulus, known as the Dundurs' elastic mismatch parameters α and β. For the studied 2D plane strain problem, the Dundurs' parameters α and β are expressed as

$$\alpha=\frac{\overline{E}_1-\overline{E}_2}{\overline{E}_1+\overline{E}_2} \tag{1}$$

$$\beta=\frac{1}{2}\frac{\mu_1(1-2\nu_2)-\mu_2(1-2\nu_1)}{\mu_1(1-\nu_2)+\mu_2(1-\nu_1)} \tag{2}$$

where $\overline{E}_i=E_i/(1-\nu_i^2)$, E_i, ν_i and $\mu_i (i=1,2)$ are the plane strain modulus, Young's modulus, Poisson's ratio, and shear modulus of the respective materials, respectively. For most problems, α is more important than β. In case of $E_1=E_2$, we have $\alpha=\beta=0$, in other words, the material mismatch vanishes, and the problem reduces to the conventional homogeneous isotropic fracture problem.

The singularity at the crack tips along the interface between two dissimilar isotropic materials is of the form (½ $\pm i\varepsilon$) where the bi–material constant ε is defined as

$$\varepsilon=\frac{1}{2\pi}\ln\frac{1-\beta}{1+\beta} \tag{3}$$

The singular stress, σ, on the interface directly ahead of the crack tip can be written in the following form [30]

$$\sigma_{yy}+i\sigma_{xy}=(K_1+iK_2)(2\pi r)^{-1/2}r^{i\varepsilon} \tag{4}$$

where $i=\sqrt{-1}$, $r^{i\varepsilon}=\cos(\varepsilon\ 1n\ r)+i\ \sin(\varepsilon\ 1n\ r)$ is the so-called oscillatory singularity parameter for bi–material interface