Applied Surface Science 315 (2014) 292–298

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Numerical study on interaction of surface cracking and interfacial delamination in thermal barrier coatings under tension

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ARTICLE INFO

Article history:
Received 16 May 2014
Received in revised form 23 July 2014
Accepted 23 July 2014
Available online 1 August 2014

Keywords:
Surface cracking
Interfacial delamination
Thermal barrier coatings
Cohesive zone model

ABSTRACT

The interaction of surface cracking and interfacial delamination in thermal barrier coatings under tension is investigated by using a cohesive zone finite element model. It is found that the surface crack density has a significant effect on the initiation and propagation of interfacial delamination. The interfacial delamination length decreases with increase of the surface crack density. The influence of ceramic coating thickness and interfacial adhesion parameters on surface cracking and interfacial delamination is discussed. It is shown that the saturated crack densities decrease with increase of the ceramic coating thickness and interfacial delamination length, and the critical surface crack density without interfacial delamination decreases as the interfacial adhesion energy increases. The results imply that the larger the surface crack density and interfacial adhesion energy are, the less the probability of interfacial delamination.

1. Introduction

Due to the excellent wear and corrosion resistance, high hardness and thermal insulation, thermal barrier coatings (TBCs) have been widely used in gas turbines and aero engines, to improve the thermal efficiency of engines and prolong the lifetime of turbine blades [1–4]. A typical TBC system usually consists of ceramic coating (8 wt.% Y_2O_3–ZrO_2 or 8YSZ), thermally grown oxide, bond coat, and superalloy substrate [5–8]. TBCs are subjected to mechanical loads, thermal stresses, sintering and thermal shock in service [9–14], and because of huge differences between their physical, thermal and mechanical properties, large residual stresses developed in TBCs may result in coating failure. The major failure mode of TBCs under tension is spallation and delamination of ceramic coatings, which results from the nucleation, propagation and coalescence of surface cracks and interfacial delamination [15–17]. Therefore, for better design and application of TBCs, it is important to have a good understanding on their failure mechanism.

A number of analytical models have been developed to study surface cracking and interfacial fracture [18–25]. For example, based on the shear stress distribution, models for the interfacial shear strength of coatings were proposed [21,22]. Taking the effect of strain-gradient into account, the shear-lag model was modified to evaluate the interface shear strength and surface crack density [24,25]. However, in these models, coating was assumed to be well bonded to substrate and there is no interfacial delamination. Also considerable works on numerical models have been done [26–34]. By using the finite element method, the influence of preexisting surface cracks on interfacial thermal fracture of TBCs [26,27] and the distribution of interfacial stress [28] were discussed. Fan et al. [30–32] analyzed the influence of crack length and spacing, film thickness, and material properties on the driving force of multiple surface cracking in films. Using the *J*-integral method, the effects of geometrical and material parameters of top and bond coats on interfacial fracture in TBCs were investigated [34]. However, in previous works with the finite element method are only considered preexisting cracks introduced in the coating or the initiation and propagation of surface cracking, and there are few studies that considered the interaction of surface cracking and interfacial delamination.

Based on experimental observations, it has been shown that surface cracking always accompanies interfacial delamination [24,35–37]. For example, the behavior of surface cracking and interfacial delamination in TBCs under tension was studied by combining acoustic emission testing and a digital image correlation method [24,36,37]. It is found that, with the increase of tensile strain, surface cracks initiate and propagate, and then interface

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http://dx.doi.org/10.1016/j.apsusc.2014.07.142
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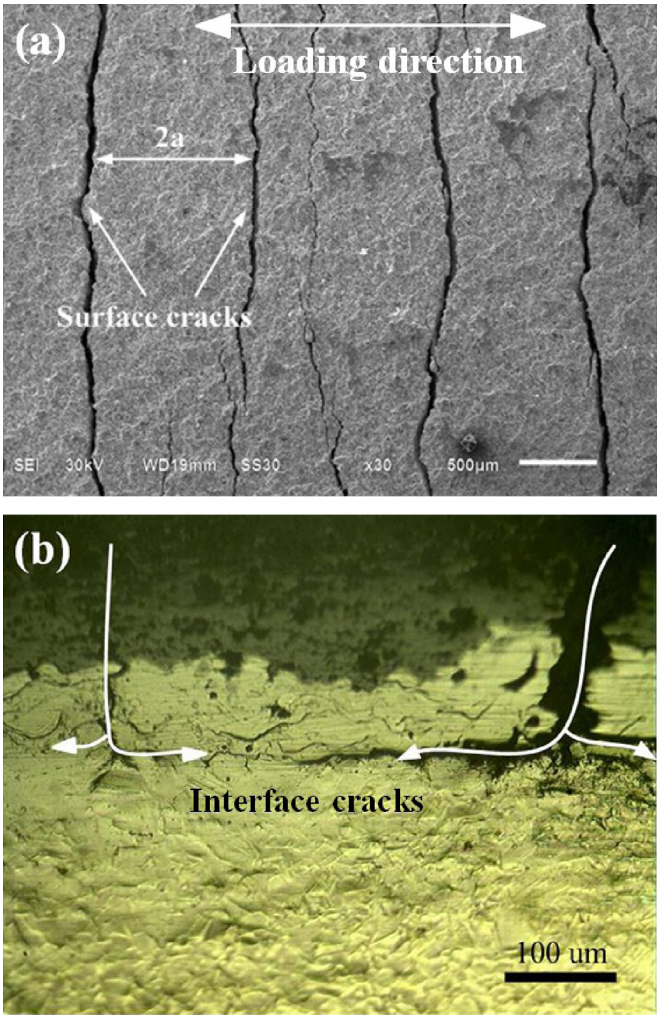

Fig. 1. Failure modes of TBCs: (a) multiple surface cracks observed on the surface by scanning electron microscopy and (b) a cross-section image of surface cracking and interfacial delamination.

cracks originate from the roots of surface cracks that eventually tend to a saturation state. The similar phenomenon on failure of TBCs was obtained in our experiments, as shown in Fig. 1. In this paper, the interaction of surface cracking and interfacial delamination in TBCs under tension is investigated by using a cohesive zone finite element model. The paper is organized as follows. In Section 2, the detail model description is presented. In Section 3, the effects of ceramic coating thickness on the crack initiation and saturation of surface cracks are examined, and the variations of interfacial delamination lengths with the surface crack density are discussed. Furthermore, the influences of interfacial cohesive zone parameters on interfacial delamination lengths are studied. Finally, a summary with concluding remarks is given in Section 4.

2. Finite element model

Based on the ABAQUS® finite element environment, a two-dimensional, plane strain model was constructed. Here, it is worth noting that residual stress and thermally grown oxide were not considered in this work.

2.1. Geometric and material parameters

As illustrated in Fig. 2, the geometric model includes three layers: ceramic coating, bond coating and substrate with h, h_b and h_s being their thicknesses, respectively, L the length of a unit cell used in finite element simulation, and a the interfacial crack length. Under tension, ceramic coating is subjected to surface channel cracking, and as it reaches the interface between ceramic and bond coating, interfacial delamination occurs. For simplification, we assume surface channel and interface cracks in TBCs are uniformly spaced. Taking symmetry into account, only a unit cell is considered (see Fig. 2(b)). Two cohesive zones are used to simulate the initiation and propagation of surface and interface cracks: one is located in the middle of ceramic coating and the other is inserted in the interface between ceramic and bond coating. In simulation models, ceramic coating is chosen as a layer with the thickness of h, varying from 100 μm to 300 μm, and thicknesses of bond coating and substrate are $h_b = 100$ μm and $h_s = 1.5$ mm, respectively. The surface crack density ρ is defined by the number of cracks per millimeter, which can be written as, $\rho = 2/L$.

Ceramic coating is considered as a homogeneous, isotropic and linear elastic material with Young's modulus of 48 GPa and Poisson's ratio of 0.22 [38]. Both bond coating and superalloy substrate are assumed to be elastic-plastic, whose constitutive relationships are given by

$$\varepsilon = \begin{cases} \sigma/E & \sigma \le \sigma_y \\ (\sigma_y/E)/(\sigma/\sigma_y)^{1/n} & \sigma > \sigma_y \end{cases}, \tag{1}$$

where ε is strain, σ is stress, σ_y is the yield stress, and E and n are Young's modulus and power hardening exponent, respectively. The material parameters of bond coating are defined with Young's modulus of 80 GPa [39], yield stress of 170 MPa, Poisson's ratio of 0.3 and power hardening exponent of 0.12. The superalloy substrate is modeled with Young's modulus of 175 GPa, yield stress of 280 MPa. The Poisson's ratio and power hardening exponent of bond coating are chosen the same as substrate, which are 0.3 and 0.12, respectively [7].

2.2. Meshing and boundary conditions

The finite element meshing and boundary conditions are shown in Fig. 3. The four-node bilinear plane strain quadrilateral reduced integration element (CPE4R) is adopted to mesh ceramic coating, bond coating and substrate, and the four-node two-dimensional interface cohesive element (COH2D4) is used between ceramic and bond coatings. Finer meshes are used around the cohesive zones in the middle of ceramic coating and the interface between ceramic and bond coatings to improve the accuracy of simulation results (see inset in Fig. 3). Considering the balance between the solution efficiency and accuracy, a proper mesh density is chosen to obtain mesh-independent results. The vertical fixed boundary condition is applied at the bottom of substrate, where the nodes can move in the horizontal direction but the vertical displacement is set to zero. Only substrate is strained by applying a uniform axial displacement Δx in two (left and right) sides, so that the coating segment is pulled by the substrate deformation. According to experiments, the applied strain defined by $\varepsilon = 2\Delta x/L$ is chosen as 3%. Stress free boundary conditions are applied on the rest of surfaces.

2.3. Cohesive zone model

The surface channel cracks lead to stress concentration in substrate near the channel roots, which could be severe enough to cause interfacial delamination along the ceramic/bond coating interface. Here, surface cracking and interfacial delamination are simulated by introducing cohesive zones at the center of ceramic coating and at the ceramic/bond coating interface. The cohesive zone model is characterized by a tensile and shear traction-separation law with six parameters: the interfacial tensile strength