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Acoustic emission evaluation of fracture characteristics in thermal barrier coatings under bending

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ABSTRACT

The real-time assessment on the details in damage evolution of thermal barrier coatings (TBCs) is desirable, especially if the key coating performance parameters, such as, the surface and interface fracture toughness, could be accurately characterized. In this paper, the fracture details of as-sprayed and pre-oxidized TBCs under three-point bending are monitored by an acoustic emission (AE) combined with digital image correlation (DIC) methods. The surface and interface toughness of TBCs can be accurately determined on the basis of AE signals and strain images. A linear relationship is found between the energy released from coating failure and that of AE signals, whose slope depends on the fracture modes and properties of TBCs.

1. Introduction

With their high-melting, low heat conductivity, excellent wear resistance and high hardness, thermal barrier coatings (TBCs) have been widely regarded as an attractive material in enhancing the high-temperature limits of gas turbines and internal combustion engines [1–4]. In general, TBCs consist of four layers: a yttria stabilized zirconia (YSZ) ceramic top coating (TC) that increases the operation temperature of turbine components, a nickel-based substrate that endures mechanical loading, a MCrAlY alloy (M represents Ni, Co, or Fe) bond coating (BC) that enhances adhesion of the ceramic coating to substrate and a thermally grown oxide (TGO) layer that formed between bond and top coats due to the diffusion and reaction of oxygen and metal iron during processing and further thermal exposure. Each layer in the multi-layer structure of TBCs has remarkably different physical, thermal and mechanical properties, which result in internal stresses in TBCs. Moreover, the protected components, such as, turbine blades, vanes, combustors, commonly have very complex shape and withstand external mechanical stresses and aggressive environments. The complex shape, structure, and harsh operating conditions lead to unpredictable coating failures with two main types: surface vertical cracking in ceramic coating and cracking along top/bond or TGO interface [5,6].

The resistance to surface or interface crack formation and propagation determines the performance and tolerance for mechanical or thermal loading, which finally governs the durability of TBCs. Therefore, the characterization of the mechanical parameters, such as, surface and interface fracture toughness, which can be used to evaluate cracking resistance in TBCs, has been an important subject of research [7–11]. Compared with the formation of surface or interface cracks, the propagation and coalescence of these cracks are more important to the durability of TBCs because they determine the occurrence time for eventual large-scale cleavage or spallation of coating. Therefore, the assessment of details in surface and interface cracking is necessary to understand the failure mechanism and further predict the service life of TBCs, and become an actively pursuing research issue [12–15].

Various methods have been developed to characterize the surface or interface fracture toughness of TBCs, such as surface or cross section indentation test [7], barb pushout test based on shear stress [8], bending test [9], double cantilever [10] and blister test [11]. Fracture toughness can be evaluated based on the values of critical crack-driven load and corresponding crack length, which should be measured in the experiment. In fact, the initiation of cracking is very difficult to measure because of successive loading and rapid propagation, especially for brittle ceramic coating, which results in difficulty in ascertaining the critical crack-driven load [11]. Therefore, an in-situ microscopy observation, which could provide viable and direct information on the crack evolution, is necessary, and has obtained a growing interest in the development of characterization equipments. However, the in-situ test is of very limited use in the failure evaluation of TBCs due to its small testing area and high cost. Thus, combining a real-time, nondestructive testing technique with a traditional mechanical parameter characterization method is of great importance to track the initiation of a crack and its propagation in a TBC specimen.

The initiation of cracks in a material produces acoustic emission (AE) signals due to the release of locally stored elastic energy. Therefore, the cracking time and corresponding value of critical crack-driven load can

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be directly ascertained by the initiation of AE behavior. Thus, a combination of experiment under destructive loading with real-time nondestructive AE testing is desirable for characterizing the fracture toughness of TBCs. More importantly, with the advantage of loose experimental condition and integral failure testing in a material, AE has been widely applied in the real-time detection of damage in TBCs [16–20]. In our recent works, the surface and interface cracks have been discriminated by using the wavelet analysis and frequency spectra of AE signals [21,22]. A linear correlation between the surface crack density in TBCs and AE events under the cyclic heating has been established [23], based on the assumption of proportional correlation of energy released from cracking and the corresponding AE signals. However, this assumption lacks experimental verification, and the details in fracture behavior, such as the characteristics of evolution in surface and interface cracking, are still intractable.

Contrary to tensile or thermal loading, tensile stress is not uniform in the TC layer along the long axis direction of TBCs under the three-point bending. Thus, only a few surface cracks occur in the region which bears the maximum bending moment. To clearly present the process of surface and interface cracking and limit the number of cracks, a three-point bending test was conducted to characterize the fracture toughness and analyze the evolution feature of TBCs. In addition, the high temperature oxidation results in the growth of TGO at interfaces of TBC layers, and changes the microstructure of the TC layer due to ceramic sintering. Therefore, the high temperature oxidation should be considered because it is a key factor that affects the mechanical properties as well as the failure mechanism.

In this paper, the characterization of fracture toughness, details of fracture behavior, correlation of cracking of TBCs and corresponding AE signals are systematically investigated by using a combination of three-point bending test and AE testing. First, a theoretical analysis on fracture toughness and energy estimation of surface and interface cracking in TBCs is developed. Then, the AE response of TBCs and strain evolution are recorded to characterize fracture toughness and analyze the details of fracture behavior. The results obtained from the AE testing can be used to analyze the correlation between the damage evolution in TBCs and AE characteristics. Finally, the influence of high temperature oxidation on fracture mechanism is analyzed based on AE characteristics.

2. Theoretical analysis

2.1. Fracture toughness and fracture energy for surface cracking

Cracks in TBCs are strongly dependent on the transient stress. Stresses in TBCs consist of external loading and initial residual stress. The former is caused by the thermal or mechanical loading. The latter originates from the rapid contraction of sprayed splat during cooling from the deposition temperature. Residual stresses in ceramic coatings induced by the preparation are compressive because of the small thermal expansion coefficient of ceramic compared to that of the alloy substrate. The BC layer can be simplified to the same layer as substrate because of their similar mechanical properties. Thus, given that TBCs are only subjected to the elastic deformation, stress in the TC layer under bending can be expressed as

$$\sigma = \frac{E^{*}y}{\rho} + \sigma_r \tag{1}$$

where $E^{*} = \frac{E_c h_c + E_s h_s}{h_c + h_s}$, E and h are the Young's modulus and the thickness of layers, subscripts c and s denote the TC layer and substrate, respectively. The initial residual stress σ_r, its measurement details have been described in our previous work [24], is -57 MPa and -200 MPa for as-received and pre-oxidized TC layers, respectively. y and ρ are the distance between coating and the neutral axis of composite beam, and the curvature radius of the neutral axis, as shown in Fig. 1. The curvature radius can be expressed as

$$\rho = \left[(L/2)^2 + \delta^2\right] \Big/ 2\delta \tag{2}$$

where L and δ are the half length of the bending distance and the bending deflection at the middle point of the beam, respectively. The distance between the coating and the neutral axis of the composite beam is

$$y = h_0 + h_c \tag{3}$$

where h_0 is the distance between the top/bond coating interface and the neutral axis of the composite beam. According to the requirement of static equilibrium, the distance can be expressed as

$$h_0 = \left(E_s {h_s}^2 - E_c {h_c}^2\right) \Big/ (2E_s h_s + 2E_c h_c) \tag{4}$$

A vertical surface crack in the ceramic TC layer that is generated during the three-point bending test can be regarded as a model-I crack. Thus, given that the critical crack-driven stress σ_{cr} and the corresponding crack length a_0 are determined, the surface toughness can be calculated by

$$K_{IC} = Y_I \sigma_{cr} \sqrt{\pi a_0}, \quad G_{IC} = \frac{K_{IC}^2}{E_c} \tag{5}$$

where Y_I is a geometry factor, and equals to 1 in the case of bending test [25].

As a typical brittle material, the length of a surface crack can be presented by coating thickness. If the number of surface cracks N is obtained from a metallographic microscope, then the fracture energy E_{FS} can be calculated as

$$E_{FS} = 2h_c b N \frac{K_{IC}^2}{E_c} \tag{6}$$

where b is the width of a TBCs specimen. Assuming that a proportional relationship exists between the AE energy and that released from cracking (fracture energy), the AE energy of surface cracks E_{AE}^{S} can be expressed by

$$E_{FS} = \alpha_s E_{AE}^{S} \tag{7}$$

where α_s is a coefficient.

2.2. Fracture toughness and fracture energy for interface cracking

Under bending or tension, the interface crack energy release rate and interface stress intensity factor of TBCs can be calculated by the Suo–Hutchinson model [26]

$$G = \frac{c_1}{16}\left[\frac{P^2}{Ah_c} + \frac{M^2}{Ih_c^3} + 2\frac{PM}{\sqrt{AI}h_c^2}\sin\gamma\right] \tag{8}$$

$$K = \sqrt{\frac{p^2}{2}\left[\frac{P^2}{Ah_c} + \frac{M^2}{Ih_c^3} + 2\frac{PM}{\sqrt{AI}h_c^2}\sin\gamma\right]} \tag{9}$$

where P and M are the equivalent tensile load and bending moment per unit width, respectively. Under the three point bending loading, they can be determined by the following equations [26].

$$P = \sigma_r h_c + \frac{\Sigma}{I_0}\left(\frac{1}{\eta} - \Delta + \frac{1}{2}\right)\frac{P(t)l}{4bh} \tag{10}$$