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Simulation of damage and failure processes of thermal barrier coatings subjected to a uniaxial tensile load

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ABSTRACT

The tensile bond strength of thermal barrier coatings (TBCs) is an important criterion in evaluating the quality of coatings, which depends significantly on the coatings' complex microstructures. In the current study, a three-dimensional (3D) microscopic structural model reflecting the actual interface morphology and pore distribution of TBCs is built using microcomputer tomography (micro-CT). The model is then applied to investigate the 3D spatial evolution processes of damage and failure under uniaxial tension using FE techniques. To validate the numerical simulation results, the tensile responses of the TBCs are measured and a follow-up quantitative description of the tensile fracture morphology is obtained with a 3D surface profiler. The simulation results are in good agreement with the experimental data. Our simulation results show that the local stress concentration induces two types of crack sources located either at the top coat (TC)/bond coat (BC) interface or along the pore boundaries; as the load increases, only the microcracks at the interface amalgamate and begin to form a primary crack; then the primary crack propagates rapidly horizontally along the interface, eventually inducing an undulating fracture morphology.

1. Introduction

Thermal barrier coatings (TBCs) applied by atmospheric plasma spraying (APS) are widely used for hot-section blades in gas turbine engines [1–3]. Such coatings can provide protection for the metallic substrate, which results in an improved component durability [4–6]. Increased efficiency can be achieved by allowing an increase of the turbine inlet temperatures. APS TBCs comprise metal and ceramic multilayers. The ceramic layer, normally yttria-stabilized zirconia (YSZ), is used as a top coat (TC) and it provides thermal insulation, whereas the metal layer, called the bond coat (BC), is typically made from an MCrAlY alloy (where M stands for Fe, Ni, Co, or a combination of these elements). The BC provides adherence for the ceramic TC [7].

As we all know, the service life of TBCs is typically limited by spallation and delamination of the ceramic coatings [8]. For the past few years, many different types of failure modes leading to TBC spallation have been studied in laboratory experiments, and the most commonly used testing methods are tension [9–11] and bending tests [12,13]. These studies emphasize that the delamination failure of top coats normally results from the initiation and propagation of cracks either at the bottom of the TC layer or near the TC/BC interface, which severely limits the application of TBCs [14]. However, it is difficult to track or observe the crack propagation processes in real-time using the current experimental techniques. Therefore, to have a better understanding of the intrinsic failure mechanisms in TBC systems, numerical simulation methods with a variety of finite element models have been developed [15]. In most of the earlier works, a two-dimensional (2D) or three-dimensional (3D) sinusoidal wave profile has been chosen as a simplification to represent the TBC interface [16–26]. A crack propagation model was proposed by Ranjbar et al. [16] and Bialas [17] to analyze the stress distribution in TBCs using a 2D wave profile to represent the TC/BC interface. Ranjbar used both uniform and non-uniform amplitudes to represent the wave profile and an inhomogeneous top coat layer with an artificial lamellar structure. It was concluded that the cracking depends mainly on the interface morphology. Failure mechanisms were analyzed by Evans [20] with the help of a 2D finite element model representing the interface as a sine wave profile. Similarly, lifetime prediction models were made by Vassen et al. [21], Shen et al. [22], and He et al. [23] based on the growth of delamination cracks using a 2D sine wave profile to model the interface. Recently, Jinnestrand et al. [24] developed a model using a 3D sine wave profile to represent the interface to analyze the stress distribution.

However, a simplified roughness profile might not lead to precise predictions as it does not incorporate the actual complex surface topography created by plasma spraying. An attempt was made by Shen [7] and Bolelli [27] to overcome this limitation by generating a finite element geometric model of TBCs based on an actual 2D microstructural image. Using this method, damage accumulation and microcrack growth were clearly observed during the simulation. However, no additional 3D information of the microstructure and the failure mechanisms could be obtained because of the 2D modeling method. Gupta [28]

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Table 1
Basic operating parameters of plasma spraying.

	Primary gas, Ar (SCFH)	Secondary gas, H_2 (SCFH)	Carrier gas, Ar (SCFH)	Electric current (A)	Powder rate (RPM)	Spraying distance (mm)
Bond coat	120	20	10	700	2	75
Top coat	75	45	8	850	5	75

represented the 3D TC/BC interface successfully by using actual BC surface topographies scanned with a white-light interferometry technique before spraying the top coat layer. However, the representation of pores and microcracks with irregular shapes and distributions, which influence the mechanical behavior of the coatings dramatically, cannot be taken into account in this method [29,30]. In this case, some new approaches were developed to relate 3D pores and crack interconnections [31–34]. In Amsellem's study [32], for example, X-ray micro-tomography (XMT) was performed at the European Synchrotron Radiation Facility (ESRF) using beamline ID19 (a high-resolution diffraction topography beamline) to reconstruct the microstructures of plasma-sprayed alumina.

However, up to the present time, existing models are not yet sufficiently mature to allow reliable prediction of the tensile bond strength of TBCs. In this study, a 3D microscopic structural model of TBCs that reflects the actual interface morphology and pore distribution was built using common laboratory microcomputer tomography (micro-CT) for the first time. This method is helpful for characterizing tension delamination properties and for revealing the failure mechanisms in TBC systems. The crack initiation and propagation path in 3D space were taken into account and the modeling results, including tensile bond strength and fracture surface morphology, were investigated and quantitatively compared with the observed experimental results.

2. Experimental methods and characterization

2.1. Materials and specimen

The thermal barrier coatings investigated in this study were a ceramic/metal bilayer system prepared using a Praxair SG-100 plasma spray gun (Praxair Inc., Danbury, Connecticut, USA), and the basic operating parameters used for deposition of the coatings are listed in Table 1. Prior to spraying, the surface of GH4169 superalloy substrates with thicknesses of 10 mm and diameters of 25 mm were cleaned with alcohol and then NiCoCrAlY bond coats (CO-210 alloy powder, Praxair Inc., USA) with thicknesses of 100 μm were plasma-sprayed onto the substrate surfaces. Subsequently, nanostructured ceramic top coats produced using 8 wt.% yttria-stabilized zirconia powder were applied on the bond coats with an 8 mm nozzle. The thicknesses of the top coat layer were approximately 150 to 160 μm. Fig. 1 shows a typical scanning electron microscope (SEM) image of the cross-sectional microstructures of a TBC for the coating porosity measurement; the white box shows the area used for statistical analysis. In this study, a total of 20 random SEM images from four different specimens were employed, and the average final porosity for the TBCs was 9.4 ± 0.1%.

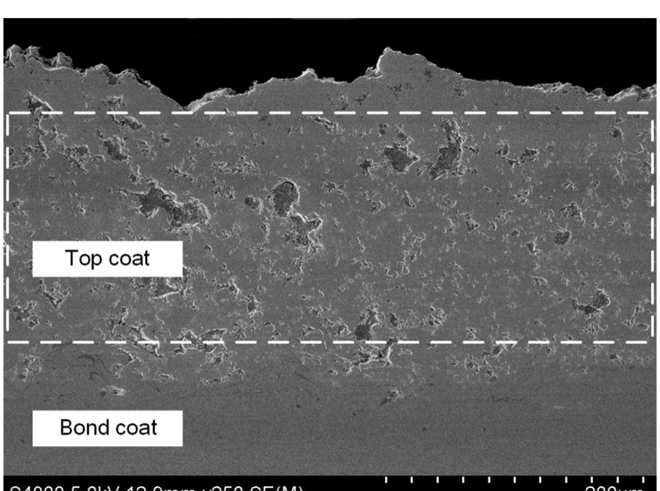

Fig. 1. SEM image of the cross-sectional microstructures of a TBC.

2.2. Tension delamination experiment

One of the simplest and most widely used methods to determine the bond strength of an interface is the tension delamination experiment. The specimens for such an experiment are bonded on both sides onto steel tension bars using a commercial epoxy (Araldite AW106/HV953). The specimens are then cured at 150 °C for 20 min. A schematic of a specimen prepared in this manner is shown in Fig. 2. According to the Chinese National Standard GB/T 8642-2002, the tensile bond strength, R_H is calculated by Eq. (1):

$$R_H = \frac{F_m}{S} \quad (1)$$

where F_m is the maximum loading force; S is the cross-sectional area of TBC specimen.

Ten TBC specimens were tested in this study and their responses were reasonably consistent. Ten TBC specimens were tested in this

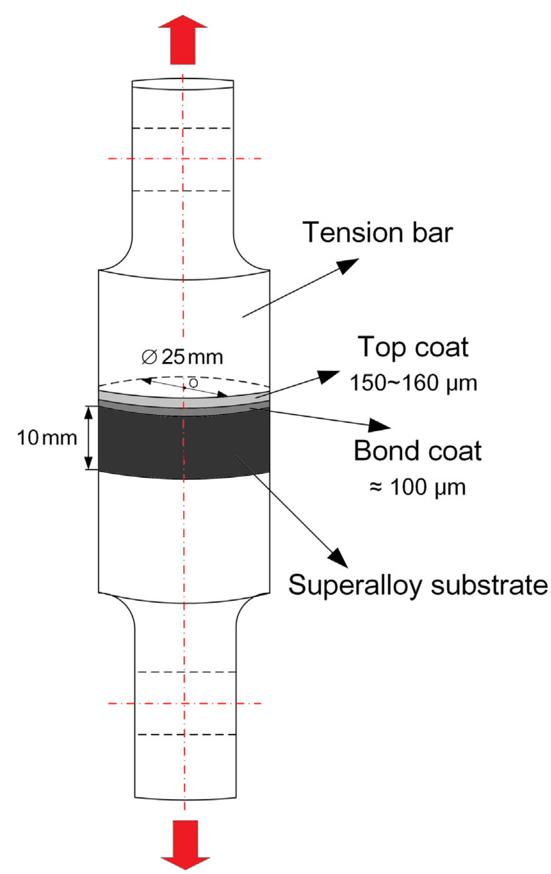

Fig. 2. Schematic of the tension specimen with dimensions.