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In-situ and real-time tests on the damage evolution and fracture of thermal barrier coatings under tension: A coupled acoustic emission and digital image correlation method

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ABSTRACT

By using a coupled acoustic emission (AE) and digital image correlation (DIC) technique, the failure behavior of air plasma sprayed thermal barrier coatings (TBCs) was investigated. The *in-situ* DIC observations show that the characteristics of AE signals, extracted from the fast Fourier transform, are closely related to the failure modes of a TBC system, which was applied to real-time reveal its damage evolution during tension. It is shown that there is a typical power-law relationship between the vertical crack density in coating and strain in substrate. A damage variable defined as a function of the cumulative AE events can be used to characterize the different fracture stages of a TBC system. With the increase of strain in substrate, the AE-b value estimated by the Gutenberg–Richter law varies from 2.0 at the initial regime to a plateau value of 1.2.

1. Introduction

To reduce the surface temperature of superalloys and prolong the lifetime of high-temperature components, thermal barrier coatings (TBCs) have been widely used in gas turbines and aero engines. A typical TBC system usually consists of ceramic coating, thermally grown oxide, bond coat and substrate. The merits of ceramic coating include a potential increase in engine operating temperature with lower cooling requirements, resulting in significant improvements on its thermal efficiency, performance, and reliability [1–4]. However, top ceramic coatings are inevitably subjected to mechanical loads, thermal or residual stresses, sintering and thermal shock in service [2], which strongly influence their mechanical properties and trigger the damage evolution. Thus, the crack nucleation and propagation gradually occur in coatings, which accelerates their delamination or spallation [1,3,4]. Many different techniques have been developed to study failure mechanisms of TBCs and appraise their reliabilities, such as acoustic emission (AE) [5,6], digital image correlation (DIC) [7–9], photoluminescence piezo spectroscopy [10–12], and indentation methods [7,13]. Among these methods, AE signals that are produced by elastic stress waves during a deformation and fracture process can be used to identify the internal damage evolution prior to failure of structural and functional coatings under loads. For example, Ma et al. studied the fracture dynamics of air plasma sprayed TBCs by using the waveform simulation of AE signals monitored by displacement sensitive sensors. Based on the inverse processing of AE signals, they estimated the relationship between an AE signal and its cracking mode [14]. Ray et al. investigated, by using the AE technique, the mechanical properties of NiCoCrAlY bond coat during room and high temperature tensile tests. The relationship of AE events and cracks in a bond coat and substrate system was summarized under tensions at 800 °C [15]. By using the wavelet analysis of AE signals, Yang et al. measured the fracture process of TBCs subjected to heating and cooling cycles, and identified their damage modes during tensile loads [16]. Based on the wavelet or fast Fourier transform analysis together with scanning electron microscope (SEM) or optical microscope observations [16–20], considerable efforts have been made to establish the relationships between the characteristics of AE signals and their deformation and fracture modes in various materials. However, these observations are not *in-situ*, which are usually done after failure or unloading. In addition, it is difficult to trace the dynamic evolution of deformation and fracture of a sample from the gathered AE signals, especially at the micro-scales. Therefore, it is urgent to develop a real-time method that can reveal both the AE events and the damage process of TBCs.

The DIC technique, which measures a strain field by tracking random speckle patterns on a specimen surface [8,21,22], is suitable for continuously detecting micro and nano-scale deformations [23,24]. Combined

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with the AE technique, these methods have been simultaneously applied to study the crack profile, localized plastic strain evolution and the full strain field of bulk materials, especially metal alloys with different scales [25–30]. In our previous works, the full/local strain field in air plasma sprayed TBC systems under tension was successfully monitored by using the DIC technique [8]. The AE signals of TBCs during tension were extracted by the fast Fourier transform, and their characteristic frequency spectrums and dominant bands were obtained to qualitatively explain the fracture modes observed by SEM [17]. However, there is still lack of a relationship of DIC and AE results in a TBC system under tension. In this paper, the damage evolution of TBCs is *in-situ* measured and evaluated by a coupled AE and DIC method under uniaxial tension. The DIC data provide more detailed *in-situ* information on the deformation and fracture at micro scales to clarify the features of AE signals. Then, based on the statistical analysis of AE signals, the characteristic parameters of AE events are correlated to the different damage stages of TBCs. A shear lag model is introduced to analyze the relationship between the vertical crack density on the coating surface and the applied strain in substrate.

2. Experimental

A dog-bone-shaped stainless steel (AISI304) was selected as substrate, with a cross-section of 10×2 mm^2 and a gage length of 80 mm. The NiCoCrAlY powder was sprayed on the substrate surface as bond coat and then a conventional 8 wt.% Y_2O_3–ZrO_2 (8YSZ) ceramic coat was prepared on bond coat by the air plasma sprayed technique [31]. During the air plasma spraying, substrate was cooled down with the compressed air, resulting in deposition temperatures between 200 and 250 °C. The thicknesses of bond and ceramic coats are about 100 and 300 μm, respectively. The porosity of the top coating is 15.00 ± 0.55%, measured by the digital image analysis. The SEM morphology of an as-received TBC sample is shown in Fig. 1. Air plasma sprayed TBCs usually include a lamellar structure with high interconnected porosities due to the influence of spraying parameters. The total number of samples is 10. To *in-situ* monitor the strain evolution of a sample during tension, two commercial black and white paintings (aerosol paint, SANO Co. Ltd, Guangdong, China) were sprayed on the polished coating surface and lateral sides by an airbrush prior to the DIC tests, which forms a random speckle pattern. A 1624×1236 pixel charge coupled device camera equipped with a lens of 50 mm focal length was used to *in-situ* measure the macroscopic morphology and strain evolution of the monitored region (4×3 mm^2) with a sampling rate of two images per second (see Fig. 2). To analyze the evolution of a strain field, the post-processing on data was done with the commercially

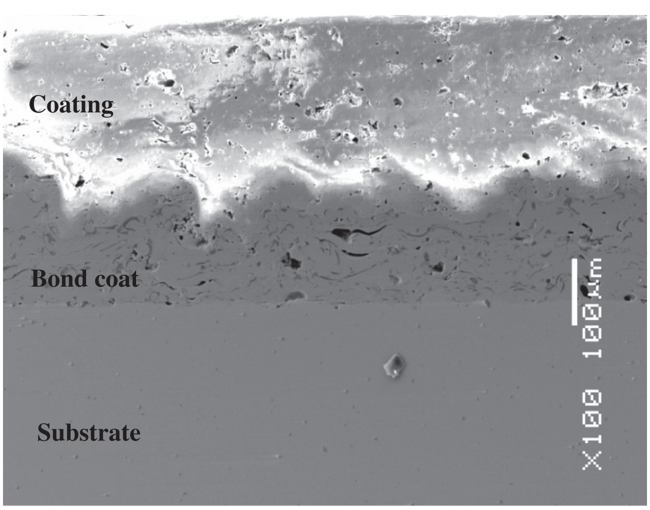

Fig. 1. SEM observation of a typical cross-section structure in an as-sprayed TBCs sample.

available DIC software (ARAMIS 3D 2 M, GOM Co. Ltd, Germany). The measuring error of strain was limited to less than 0.05% [32,33].

Tensile tests were carried out at room temperature by a universal testing machine (REGER 2000) with a loading rate of 0.3 mm/min. It is worth noting that only the substrate was loaded under tension. The whole coating would break into many small segments by the interface stress transfer due to the deformation of substrate. There may be a little release of the normal stress σ_{xx} along the tensile direction in coating, but the external load applied in substrate monotonically increases, which results in the increase of the normal stress in coating. Finally, more parallel cracks form on the coating surface. The tensile fracture process of TBCs was monitored with a coupled AE and DIC measurement system. Two piezoelectric sensors (PCI-2) were attached on the bottom surface of substrate. AE signals were recorded with a sampling rate of 1 MHz and their thresholds were set at 38 dB to filter noise. All experimental data, including the critical tensile load, strain field, and crack initiation and propagation, were real-time recorded by computers, as illustrated in Fig. 2.

3. Results and discussion

3.1. Character of the strain evolution

A typical stress–strain curve of TBCs under tension is shown in Fig. 3. All experimental data are synchronized with the testing time, including the strain maps monitored by DIC and stress–strain data in substrate recorded by a universal test machine. Five points A to E marked along the curve reflect the crack nucleation, initiation and propagation in the coating with the increase of the external strain (ε_s) in substrate, where their corresponding strain maps A to E denote the full-field strain (ε_{xx}) evolution on the coating surface obtained by DIC. During the initial stage or the small ε_s, coating undergoes transient elastic deformation. However, as ε_s increases, strain on the coating surface is heterogeneously distributed, as shown in inset A of Fig. 3. When substrate deforms from the elastic to plastic stages, a few of strain concentration regions appear within the monitored coating area and they gradually propagate perpendicular to the tensile (x-axis) direction. As ε_s increases further, a series of apparent strain concentration domains emerge on the surface, as displayed in inset E of Fig. 3. It is obvious that the first vertical crack easily occurs in a location with the highest strain concentration in the coating, whose direction is perpendicular to the coating/bond coat interface. Based on the DIC data, the effective fracture strength of coating was evaluated as 35.0 ± 4.6 MPa [8]. With the increase of ε_s, micro-cracks among these strain concentration regions rapidly propagate through the width and thickness directions of coating. Then, other subsequent surface vertical cracks gradually occur, which eventually forms an array of multiple channel cracks and segments in the coating.

The variations of ε_{xx} and ε_{zz} in the coating cross-section region under tension are, respectively, shown by images of A1 − D1 and A2 − D2 in Fig. 4. Here, the magnitudes of their applied tensile loads in substrate correspond to insets A, B, C and D in Fig. 3, respectively. It is seen from insets A1–D1 that the evolution of ε_{xx} in the monitored region shows heterogeneous characteristics due to the special void-and-lamellar structure. Several strain concentrations gradually form, whose directions are vertical to the interface. These regions would evolve into vertical cracks that firstly initiate on the coating surface, then quickly extend through its thickness, and finally approach to the coating and bond coat interface. Meanwhile, most of these cracks deflect into the interface cracking or delamination, and then continue to grow and interconnect between different segmented coatings along the interface, as shown by images A2–D2 in Fig. 4. Finally, interfacial cracks in different regions may meet near the middle region of the segmented coating bottom, which results in delamination. Therefore, the dynamic change of a full strain field monitored by DIC can reflect the fracture characteristics of a multiple-layered TBC system, which is more apparent than that obtained by conventional strain gauge measurements.

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