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Original Research

Damage evolution and failure mechanism of thermal barrier coatings under Vickers indentation by using acoustic emission technique

Caicai Li, Xing Qiao, Teng Wang, Weixiang Weng, Qiang Li*

School of Materials Science and Engineering, Fuzhou University, Fuzhou 350116, China

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ABSTRACT

Acoustic emission (AE) technique was adopted to monitor the damage evolution of air plasma- sprayed (APS) yttria-partially-stabilized zirconia (YSZ) thermal barrier coatings (TBCs) during instrumented indentation testing, and then the failure mechanisms were investigated by cluster analysis and wavelet transform methods. The results of cluster analysis showed that there were three classes associated with distinct failure types for the 8YSZ coatings under Vickers indentation. Based on wavelet transform, these three clusters could be clearly distinguished from their dominant frequency bands, which were concentrated on levels A5 (0–156.25 kHz), D5 (156.25–312.5 kHz) and D4 (312.5–625 kHz), respectively. Thus, the failure mechanism of 8YSZ coatings under Vickers indentation could be clarified by the distribution of different failure types in indentation depth. To sum up, as indentation load increases, the 8YSZ coatings can accommodate the indenter by elastic or little plastic deformation, microcracks propagation and then debonding at the splat boundaries. By comparing the distribution of AE signals induced by different failure types in indentation depth for samples with different thermal exposure time, it can be inferred that thermal exposure treatment can accelerate the degradation of APS 8YSZ TBCs.

1. Introduction

Thermal barrier coatings (TBCs) have been widely used in gas turbine due to their good thermal insulation, corrosion protection and wear resistance, which has been developed to protect the superalloy components against high temperature and improve engine efficiency [1–3]. A typical TBC system generally consists of a multilayer structure with a NiCoCrAlY or Pt/Al diffusion bond coat applied on a Ni-based superalloy substrate, a yttria-stabilized zirconia (YSZ) coating deposited on top as the outer low-conductivity thermal barrier and a thermally grown oxide (TGO) formed at the interface between the bond coat and top coat as a consequence of an aluminum diffusion-reaction process [1,2]. TBCs are inevitably subjected to mechanical loads, thermal stresses, sintering and thermal shock in service, which strongly affect their mechanical properties and may trigger the damage evolution [4,5]. In general, the nucleation, propagation and coalescence of cracks gradually occur in ceramic coatings, which accelerates their delamination or spallation, thereby resulting in failure of TBCs [6,7]. Therefore, for better design and application of TBCs, it is of great importance to have a better understanding on their failure mechanism.

However, owing to heterogeneous and complex microstructures of plasma-sprayed TBCs, along with harsh operating conditions, their failure always occurs in the way of unpredictable time, position and types, which make the identification of their failure mechanism and prediction of their service life by traditional strength theories or experimental mechanics methods very difficult and even intractable [1,2]. Significant efforts have been dedicated towards making effective assessments of failure behavior of TBCs and appraising their reliabilities by nondestructive testing techniques [8–10]. Wu et al. [8] studied the behavior of surface cracking and interfacial delamination in TBCs under tension by using a digital image correlation technique. Wang et al. [9] employed photoluminescence piezo-spectroscopy to reveal two-dimensional details of the delamination induced by cross-sectional nanoindentation. Hille et al. [10] have investigated damage growth triggered by interface irregularities in thermal barrier coatings with the help of finite element modeling. These techniques have been proven, in particular, to be helpful in the coatings lifetime prediction. Unfortunately, these nondestructive testing techniques can only be used to observe the damage evolution in a very small region, and moreover, their applications require strict experimental conditions so that there is of very limited use in the failure testing of complex coating systems [11]. Thus, it is desirable to develop a real-time nondestructive testing

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* Corresponding author.

E-mail address: qli@fzu.edu.cn (Q. Li).

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technique to track the failure process and further understand the failure mechanism of TBCs.

In recent years, acoustic emission (AE) technique has attracted ever-increasing interest because AE signals that are produced by elastic stress waves during a deformation and fracture process can be used to continuously detect slight deformation and internal damage evolution prior to failure of structural and functional coatings under loads without strict experimental conditions [12–15]. The failure behavior of TBCs under mechanical loads such as indentation [13], uniaxial tension [14] and bending [15], has been qualitatively investigated by the amplitude, ring-down count, energy and duration of AE signals. Among these mechanical loads, indentation loads can be fast to perform with simple preparation involving low cost and do not require removing the coatings from their substrates. Instrumented indentation testing (IIT) is a relatively novel method, which has been developed recently due to its excellence for being able to continuously control and monitor the load and displacement of an indenter as it is driven into and withdrawn from a material [16,17]. Thus, the combination of IIT method and AE technology enables us to investigate failure mechanism of TBCs more conveniently and viably than before [18]. Generally, there are kinds of failure modes for ceramic coatings during the indentation testing, for example, elastic or plastic deformation, the initiation and propagation of microcracks, debonding between the splats or a combination of these failure modes [18,19]. Therefore, the major concern to analyze the failure mechanism of the ceramic coatings by using the AE technique is how to discriminate these failure modes from their AE signals.

It has been shown that the AE signals associated with the same failure mechanism are similar but those from different failure mechanisms are distinctly different in a failure process with an identical measurement condition [12,18]. Thus it is possible to discriminate the failure modes via the similarity analysis of AE signals based on the inverse processing of AE signals. Cluster analysis based on multivariate statistics has been performed to recognize the patterns of AE signals. As one of the unsupervised pattern recognition methods, the AE signals can be clustered on the basis of their characteristics without introducing any assumptions on the number or structure in advance [20]. The similarity between the signals is measured and then separated from each other according to a criterion in the space by choosing a parameter such as the similarity coefficient or distance in a certain parameter space [21]. In addition, previous studies have shown that the frequency spectra of AE signals are strongly dependent on the fracture types of monitored materials [22,23]. Based on this finding, a signal processing method such as wavelet transform which can demonstrate both the time and frequency domains of AE signals, is proposed in this paper to verify the reliability of cluster analysis results and clarify the failure mechanism of TBCs. To the best of our knowledge, there have been few studies where both cluster analysis and wavelet transform are applied to investigate the failure process of TBCs during the indentation testing.

In this paper, we proposed a combined experimental method of IIT and AE techniques to realize in-situ and real-time tests of the damage evolution of 8YSZ coatings. A processing method, combing cluster analysis with wavelet transform of AE signals, was used to investigate the failure mechanism of 8YSZ coatings. In addition, the effect of thermal exposure treatment on coating damage evolution was studied as well.

2. Materials and experimental methods

2.1. Samples preparation

The TBC system investigated in present work were prepared by an APS-2000 air plasma spraying system (Beijing Aeronautical Manufacturing Technology Research Institute, China). CoNiCrAlY alloy powders (AMDRY 995 C, Oerlikon Metco Inc., US) with a particle size distribution in the range of 45–90 μm was used to deposit the bond coating on a grit-blasted Inconel 718 superalloy substrate with dimensions of $20 \times 10 \times 4$ mm^3. The ceramic top coating was produced using agglomerated and plasma-densified 8 wt% yttria-stabilized zirconia powder (Metco 204B-NS, Oerlikon Metco Inc., US) with a particle size distribution in the range of 45–75 μm onto the bond coating. The thickness of the top coat and the bond coating were approximately 350 μm and 100 μm, respectively. The plasma spraying process parameters of the bond and top coatings are shown in Table 1. After completing the spraying process, some samples were kept in the as-sprayed condition, while the others were subjected to thermal exposure at a temperature of 1100 °C in a normal atmosphere for 100 and 350 h, respectively. Cross sections of all samples for indentation testing were prepared by grinding on waterproof abrasive papers at successively decreasing grit sizes followed by polishing with an abrasive diamond suspension of 3.5, 1, and 0.25 μm grit sizes, respectively. The typical SEM morphology of an as-sprayed TBC sample is shown in Fig. 1.

Table 1
Plasma spraying parameters for CoNiCrAlY bond coat and 8YSZ top coat.

Parameter	Material	
	CoNiCrAlY	8YSZ
Arc current (A)	500	600
Arc voltage (V)	65	70
Ar flow rate (slm[a])	45	45
H_2 flow rate (slm[a])	8	10
Powder feeding rate (g/min)	60	30
Spray distance (mm)	120–150	80–100

[a] slm = Standard litres per minute.

2.2. Indentation testing and AE monitoring

The polished cross sections of the top coat were indented with a Vickers indenter at a loading and unloading rate of 1 N/s by using an instrumented indentation testing system. Indentation load and the indentation depth were recorded accurately by a load cell and a displacement transducer, respectively. Each indentation was kept separated from the previous one by at least 4 mm to avoid interference of the strain fields generated by multiple indentations and was carried out roughly at the same location kept 100 μm from the interface of top coat and bond coat for each sample. During the indentation testing, the failure process of the 8YSZ TBCs was monitored by using a Micro-II digital AE system of Physical Acoustics Corporation (PAC), with a 18-bit data acquisition board (PCI-2, PAC, USA). A miniature piezoelectric transducer with an operating frequency of 125–750 kHz was held onto the side of substrate using masking tape and vacuum grease (VC-101, PAC, USA). The signals from the transducer were amplified and band pass filtered by a 2/4/6 preamplifier, which was set at 40 dB gain. AE signals were recorded by the AEwin™ software with a sampling rate of

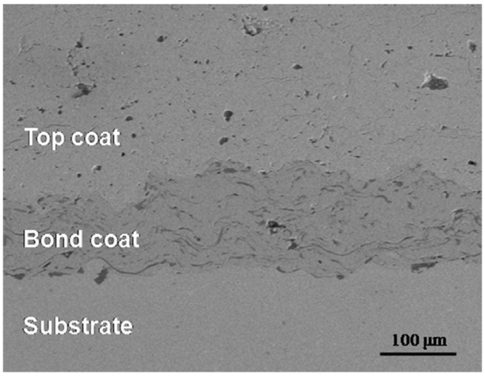

Fig. 1. SEM observation of a typical cross-sectional microstructure in an as-sprayed TBC sample, containing a lamellar structure with pores and cracks.