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Experimental investigation of the biaxial strength of thermal barrier coating system

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Received 6 January 2015; received in revised form 22 March 2015; accepted 23 March 2015

Abstract

A piston-on-three-ball assembly is employed to evaluate the biaxial strength of the ceramic top-coat in thermal barrier coating system (TBCs). The design of bi-axial experiment is presented, in which the effects of the specimen geometric parameters, the contact between the specimen and the support, and the plastic deformation of substrate are numerically analyzed. Then, the piston-on-three-ball tests and Scanning Electron Microscopy (SEM) observations are carried out to measure the bi-axial strength and the failure patterns of the ceramic top-coat in TBCs, respectively. We experimentally obtained the bi-axial fracture strength of the ceramic top-coat in thermal barrier coating system, which obeys Weibull distribution function. The fracture patterns of the ceramic top-coat under bi-axial loading exhibit a typical channel network.

Keywords: Thermal barrier coating; Bi-axial strength; Piston-on-three-ball test

1. Introduction

Thermal barrier coating system (TBCs) is widely used in the blades of aircraft engines and gas turbines. The employment of TBCs can allow an increase of the inlet gas temperature of the turbine and can improve the turbine efficiency. TBCs is a multilayer system including three parts: (1) the ceramic top-coat (TC) for the thermal insulation, (2) the bond-coat (BC) protecting the superalloy substrate from oxidation, and (3) the thermally grown oxide (TGO) layer forming between the top-coat and bond-coat in service due to the high temperature oxidation. Concerning the extreme operation environment, the durability of TBCs has been extensively studied in recent years [1–6]. At the operation condition, the significant thermal misfit between the layers can cause a high thermal stress [2]. This high stress level is a lethal threat to the integrity of TBCs, especially that of the brittle ceramic top-coat. Therefore, investigation on the fracture strength of the top-coat is of considerable importance.

Uniaxial tensile and four-point bending tests are two main test assemblies to measure the fracture strength of TBCs [7–11], in which the stress state is uniaxial. However, the stress state in TBCs is bi-axial. Therefore it is desirable to evaluate the bi-axial strength of TBCs for practice applications. In the past decade, different test assemblies were developed to measure the bi-axial strength of brittle materials [12,13]. The most widely accepted one is the piston-on-three-ball test [13–16], in which the thin disc specimen is supported by three same balls near its periphery and the supporting balls are placed symmetrically to the center of disc, as shown in Fig. 1. By pushing the piston, an equi-biaxial stress state can be produced at the center zone of the specimen. As a result, the fracture would occur in this region under a critical piston load, which can be used to calculate the bi-axial strength of the tested material.

This test assembly has been widely used to evaluate the bi-axial strength of monolayer brittle materials [15]. However, it

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http://dx.doi.org/10.1016/j.ceramint.2015.03.168

Please cite this article as: L. Su, et al., Experimental investigation of the biaxial strength of thermal barrier coating system, Ceramics International (2015), http://dx.doi.org/10.1016/j.ceramint.2015.03.168

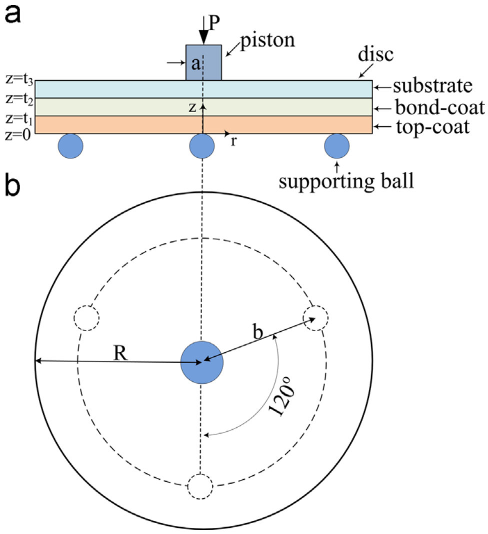

Fig. 1. Scheme of the piston-on-three-ball test: (a) a TBCs disc sample with the top-coat, bond-coat and substrate loaded at the center through a piston, and (b) top view of the test system [13].

is hardly adopted for the multilayer materials or structures such as the thermal barrier coating system, due to the lack of exact knowledge of the relationship between the applied piston load and the tensile biaxial strength (usually defined to be the maximum principal tensile stress [12]). Recently, Hsueh et al. [17] derived the stress formula for the multilayered elastic discs subjected to biaxial flexure load, which may be available for the multilayer structure under piston-on-three-ball or piston-on-ring tests [13]. This provides an opportunity to evaluate the biaxial strength of TBCs by piston-on-three-ball assembly. However, when the piston-on-three-ball assembly is used to measure the bi-axial strength of the top-coat in TBCs, the plastic deformation in the alloy substrate, and the friction and contact in the areas between the top-coat and the supporting balls may cause deviations in the results. So, when this assembly is extended to analyze the bi-axial strength of multilayer TBCs, the reliability should be precisely analyzed before testing, and the essential factors for the design of this assembly should be given.

The objective of this work is to experimentally investigate the bi-axial strength of the top-coat in TBCs by employing the piston-on-three-ball assembly. In Section 2, the design and analysis of the test assembly are carried out. The experimental details and the experimental results are presented and discussed in Sections 3 and 4, respectively. Finally, concluding remarks are drawn in Section 5.

2. Design and analysis of bi-axial experiment

Herein, we extend the piston-on-three-ball assembly, which is originally established for monolayer brittle materials [15], to the case of multilayer TBCs for measuring the bi-axial strength of the top-coat. As the reasons stated above, reliability of the assembly for bi-axial strength testing in TBCs will be verified firstly in this section.

2.1. Bi-axial test

The sample for test is a thin disc with the top-coat, bond-coat and substrate, and is supported symmetrically by three same balls at the top-coat surface, as shown in Fig. 1, where the radiuses of supporting and sample disc are b and R, respectively. The loading is applied to the center of upper surface of the sample (substrate surface) through a small piston with radius a. Thus, a bi-axial tensile stress zone at the center of lower surface (top-coat surface) can be produced. If the piston load for the initial fracture of top-coat is experimentally measured, then the fracture strength of top-coat can be obtained. To precisely evaluate the bi-axial strength, the piston-on-three-ball assembly should be designed carefully, and the relationship between the critical piston load and the bi-axial strength should be known. In what follows, the experiment is theoretically and numerically analyzed, and then the bi-axial test is carried out.

Based on the relation between monolayer disc and multilayer disc subjected to biaxial moment, Hsueh et al. [17,18] obtained the stress–moment relation

$$\sigma_i=\frac{E_i(Z-Z_0)M}{(1-\nu_i)(1+\nu_{ave})D_0},\quad (i=1\ \text{ to }\ n) \tag{1}$$

where E_i and ν_i are Young's modulus and Poisson's ratio for layer i, respectively, and M is the biaxial moment per unit length. The location of neutral plane Z_0, the bending rigidity D_0 and the average Poisson's ratio ν_{ave} of the disc are as follows:

$$Z_0=\frac{\sum_{i=1}^{n}\left(E_ih_i/(1-\nu_i^2)\right)(t_{i-1}+h_i/2)}{\sum_{i=1}^{n}E_ih_i/(1-\nu_i^2)} \tag{2}$$

$$D_0=\sum\nolimits_{i=1}^{n}\frac{E_ih_i}{1-\nu_i^2}\left[t_{i-1}^2+t_{i-1}h_i+\frac{h_i^2}{3}-\left(t_{i-1}+\frac{h_i}{2}\right)Z_0\right] \tag{3}$$

$$\nu_{ave}=\frac{1}{t_n}\sum\nolimits_{i=1}^{n}\nu_ih_i \tag{4}$$

where h_i is the thickness of each layer. Assuming that the bottom of top-coat is located at $z=0$, as shown in Fig. 1, t_0 is defined as zero and t_i can be expressed by

$$t_i=\sum_{k=1}^{i}h_k\ \ (i=1\ \text{ to }\ 3) \tag{5}$$

which describes the location of interface between layer i and layer $i+1$.

The relation between the moment and the piston load is given by [13,19]:

$$M=\frac{-P}{8\pi}\left\{(1+\nu_{ave})\left[1+2\ln\left(\frac{b}{a}\right)\right]+(1-\nu_{ave})\left[\left(1-\frac{a^2}{2b^2}\right)\frac{b^2}{R^2}\right]\right\},\quad (\text{for } r\le a) \tag{6}$$

where p is the load applied through the piston, a is the radius of piston, and b is the supporting radius.

It is clear that if the critical load p_{cr} is obtained experimentally, then the bi-axial stress at the center of TBCs sample can

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