Materials Science & Engineering A 565 (2013) 142–147

Contents lists available at SciVerse ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

The failure mechanisms of TBC structure by moiré interferometry

Minjin Tang, Huimin Xie *, Jianguo Zhu, Dan Wu

AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 23 August 2012
Received in revised form
3 December 2012
Accepted 4 December 2012
Available online 10 December 2012

Keywords:
Thermal barrier coatings
Moiré interferometry
Fracture analysis
Strain field

ABSTRACT

In order to study the interface failure process and the mechanical properties of thermal barrier coatings (TBCs), the moiré interferometry technique is used to measure the deformation fields of the TBC specimen subjected to three-point bending load. By changing the object lens in the moiré interferometer, both the macro-scale and micro-scale deformation fields can be measured. In the measurement, a cross type moiré grating with frequency 1200 lines/mm is replicated to the TBC sample. The interface moiré patterns at different load parameters can be obtained with the moiré interferometer. And the corresponding displacement and strain distributions are calculated using the moiré patterns. Besides, with aid of the experimental results from moiré interferometry, crack opening displacement (COD) and *J*-integral of the TBC specimen can be measured. Moreover, the initiation and propagation of the crack in TBCs are observed using scanning electronic microscope and optical microscope, respectively. The failure mode of the TBC is summarized.

1. Introduction

Thermal barrier coating (TBC) [1–6] is a kind of ceramic layers with excellent high temperature oxidation resistance and very low thermal conductivity, which is sprayed onto bond coat (NiCrAlY) deposited on the surface of substrate. TBC can effectively reduce the service temperature of the protected substrate and alleviate the thermal shock loading, and has been widely used in the fields of space flight, chemical industry and energy industry.

The interface coalescence and spallation problems always are the key subjects in the investigation of thermal barrier coating. Due to the mismatch in the thermo-mechanical parameters of metals and ceramics, the ceramic coating may delaminate from the substrate under the coupled effects of compression, shear and tensile stresses, and as a result, the degradation and fracture of substrate will occur. Therefore, an in-depth study for the mechanical parameters and fracture properties of the TBC should be conducted.

There are many testing methods that can be used for measuring the fracture properties of the TBC specimen, including bending test [7], tensile test [8], indentation test [9], and sandwich test [10] and so on. From the available literature, we found that the bending test is very convenient to measure the Young's modulus and other mechanics properties of the coating. However, conventional three-point bending test which is based on the load and deflection has several disadvantages: (i) the deformation field of the specimen in macro–micro-scale cannot be obtained; (ii) large errors generated by a great deal of simplification and approximation; (iii) impossible to measure the fracture toughness of non-standard specimen.

Moiré interferometry [11] is an important optical method presenting advantages such as a non-contact nature, full field, and high precision, and has been successfully used in mechanics and materials sciences. With the help of this technique, the extension of the crack can be observed in real time, and the parameters of the fracture mechanics can be measured. Smith et al. [12] measured the crack opening displacement (COD) by moiré interferometry. McDonach et al. [13] proposed a computational method of *J*-integral from displacement fields in three directions. Kang and Hua [14] invested near-tip displacement fields of a crack normal to and terminating at a biomaterial interface. Jiang et al. [15] measured the residual stresses within plasma spray coating using moiré interferometry. Zhu et al. [16] studied the cross-sectional residual stresses in thermal spray coatings. Wood et al. [17] measured the microstrains across loaded resin–dentin interfaces using microscopic moiré interferometry. Park et al. [18] assessed the fracture toughness of ACF flip-chip packages.

In this paper, the interface failure analysis of thermal barrier coatings using moiré interferometry was performed. The three-point bending experiments were performed under a moiré interferometer at room temperature. The full field deformations of the TBC sample were measured at different load parameters with moiré patterns. The advantage of this method is full field, real-time measurement, visualized interface deformation. In addition,

* Corresponding author. Tel.: +86 10 62792286; fax: +86 10 62781824.
E-mail address: xiehm@mail.tsinghua.edu.cn (H. Xie).

0921-5093/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.msea.2012.12.013

it is convenient to measure the parameters of fracture mechanics like crack opening displacement (COD), and *J*-integral of the TBC specimen using the moiré results.

2. Methodology and sample processing

Moiré interferometry is a full-field optical method which can be used to determine the in-plane displacement fields. In moiré interferometry measurement, there exist two key steps: one is to duplicate a high-density diffraction grating on the surface of the specimen, and the other is to generate the moiré fringe pattern under the moiré interferometer and to calculate the deformation using the moiré fringes.

The principle of moiré interferometry is depicted schematically in Fig. 1. A grating with a frequency of 1200 lines/mm is bonded to the surface of the specimen and undergoes the same deformation. When two parallel beams (*A* and *B*) are incident at same angle α, the diffracted beams (diffraction order of $+1$ and -1) will propagate along the normal direction of specimen

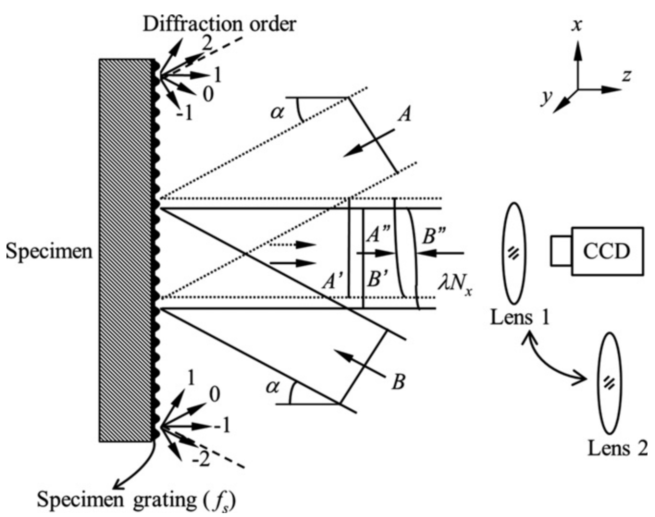

Fig. 1. Principle of moiré interferometry for in-plane displacement measurement (with the adjustable lens).

grating if the grating equation is satisfied with [11]

$$\sin\alpha = \lambda f \tag{1}$$

where λ is the wavelength and f is the grating frequency. Before the specimen deforms, two diffracted beams (A' and B') coexist in space and a virtual grating is generated in the zone of their intersection. Their mutual interference produces a uniform intensity throughout the field. When the load is applied, the specimen and the grating on its surface will deform. As a result the warped wave fronts A'' and B'' will interfere with each other, and moiré fringe patter will occur, which represent contours of constant U and V displacement. The relation between fringe order and displacement components can be described as [11]

$$U = \frac{N_x}{2f_s}, \quad V = \frac{N_y}{2f_s} \tag{2}$$

where N_x is the equal displacement fringe grade of U field and f is the frequency of the grating. The strain components can be extracted from the displacement fields by the following relations [11]:

$$\begin{cases} \varepsilon_x = \frac{\partial U}{\partial x} = \frac{1}{2f}\frac{\partial N_x}{\partial x} \approx \frac{1}{2f}\frac{\Delta N_x}{\Delta x} \\ \varepsilon_y = \frac{\partial V}{\partial y} = \frac{1}{2f}\frac{\partial N_y}{\partial y} \approx \frac{1}{2f}\frac{\Delta N_y}{\Delta y} \\ \gamma_{xy} = \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right) \approx \frac{1}{2f}\left(\frac{\Delta N_x}{\Delta y} + \frac{\Delta N_y}{\Delta x}\right) \end{cases} \tag{3}$$

When a 1200 lines/mm specimen grating is used, two adjacent fringes represent a displacement of 0.417 μm. If the maximum displacement uncertainty within 1 mm is 1/5 fringes, the strain resolution is approximately 80 με.

For conducting the bending test, a TBCs beam specimen was designed. The schematic structure of TBC specimen and its geometrical dimensions are shown in Fig. 2. The thermal barrier coatings consists of a top coating (ZrO_2–8 wt% Y_2O_3, i.e. YSZ) and a bond coating (Ni58Cr17Al2.8Y with a size range of 32–75 μm, i.e. NiCrCoAlY) adhered to a 304 stainless steel substrate. Substrate for deposition has a rectangular dimension of 35 mm × 4 mm × 2 mm (thickness of 2 mm). The average thickness of top coat and bond layer is 500 μm and 100 μm, respectively. YSZ particles are spherical with dimensions ranging from 38 μm to 62 μm. The spraying process was carried out using an APS-2000 plasma spray equipment at the Institute of Process Engineering in Chinese Academy of Science. The 304 stainless steel substrate was exposed to a grit-blasting

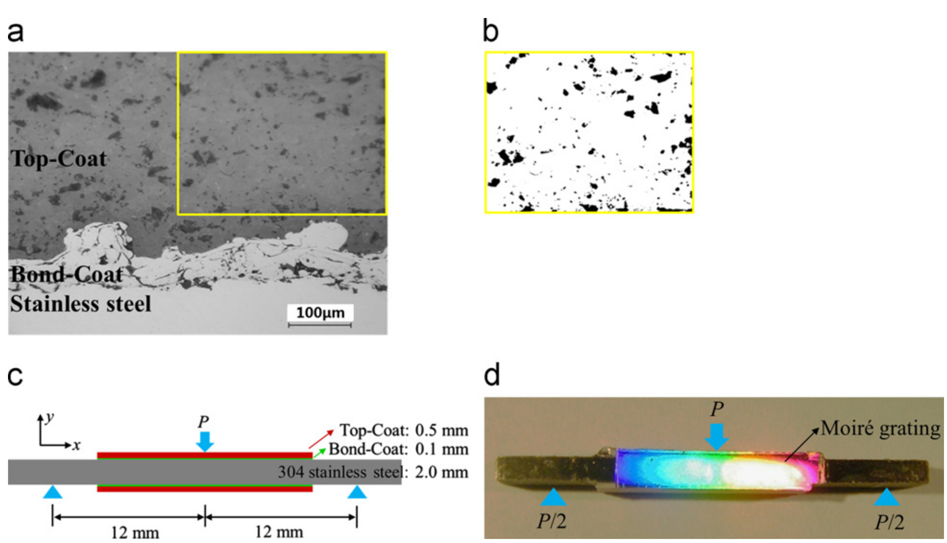

Fig. 2. TBC specimen: (a) the SEM image of TBC; (b) the voids of TBC after binary image segmentation; (c) schematic diagram of TBC specimen; (d) TBC specimen with moiré grating. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)