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Letter

Coherent gradient sensing method for measuring thermal stress field of thermal barrier coating structures

Kang Ma, Huimin Xie*

Applied Mechanics Laboratory, School of Aerospace Engineering, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- Coherent gradient sensing method is applied to measure the thermal deformations of thermal barrier coatings at high temperature.
- The thermal stress field through the entire thermal barrier coatings system is obtained by experiment and finite element method (FEM) analysis.
- The residual stress due to the spraying procedure is proved to have little effect on the substrate deformation.

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ABSTRACT

Coherent gradient sensing (CGS) method can be used to measure the slope of a reflective surface, and has the merits of full-field, non-contact, and real-time measurement. In this study, the thermal stress field of thermal barrier coating (TBC) structures is measured by CGS method. Two kinds of powders were sprayed onto Ni-based alloy using a plasma spraying method to obtain two groups of film–substrate specimens. The specimens were then heated with an oxy-acetylene flame. The resulting thermal mismatch between the film and substrate led to out-of-plane deformation of the specimen. The deformation was measured by the reflective CGS method and the thermal stress field of the structure was obtained through calibration with the help of finite element analysis. Both the experiment and numerical results showed that the thermal stress field of TBC structures can be successfully measured by CGS method.

Thermal barrier coatings (TBCs) have been widely applied in the field of aviation as thermal protection structures. They consist of three layers: a ceramic top coating (TC) layer, a metallic bond coating (BC) layer, and substrate [1–3]. Plasma sprayed 8 wt% yttria partially stabilized zirconia (PS-8YSZ) is the most common TC layer owing to its low thermal conductivity, high thermal expansion coefficient, and high toughness [4]. Plasma sprayed NiCoCrAlY is the most common BC layer owing to its appropriate thermal conductivity and thermal expansion coefficient [5]. Ni-based alloy is the most common substrate material owing to its good mechanical properties at high temperature. TBCs can obviously protect blades and further promote efficiency. However, the service life of the system is limited by the mechanical and thermal properties of the three layers [6,7]. Therefore, it is important to study the mechanical behavior of the whole TBC system at high temperature.

The residual stress incurred by the plasma spraying procedure and the thermal stress formed in the high temperature environment are two important factors when studying the failure behavior of TBCs [8,9]. The residual stress field caused by the spraying is usually a complex and non-uniform stress field. Meanwhile, through-thickness stress gradients are introduced in the TBC system by thermal gradients among the three layers. Similarly, the thermal stress produced by service is also a non-uniform stress field.

Several techniques for measuring the residual stress of TBCs have been reported in the available literature, such as the X-ray diffraction (XRD) [10], Raman spectroscopy [11], nano-indentation [12], and destructive methods [13]. All of these methods can only obtain the residual stress at a single point, instead of measuring results for the full field. Additionally, the XRD, Raman spectroscopy, and nano-indentation methods can only measure surface residual stress [10–12]. There is no single experimental non-destructive technique that can measure the stress field through the entire thickness of a TBC.

Coherent gradient sensing (CGS) is a full-field, non-destructive, real-time, and high-precision optical method which is not sensitive to vibration and may be applied to in-site measurement [14,15]. The interference fringes observed in the reflective CGS method represent the contours of the out-of-plane slope of a reflective surface [16,17]. The shape of the surface can be obtained by

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* Corresponding author.
E-mail address: xiehm@mail.tsinghua.edu.cn (H. Xie).

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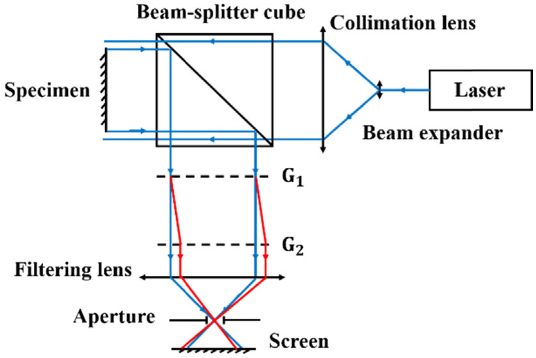

Fig. 1. The principle of reflective CGS method.

numerical integration method. In this study, 8 wt% yttria partially stabilized zirconia (8YSZ) powders and NiCoCrAlY powders were directly sprayed onto a Ni-based alloy substrate by plasma flame deposition to obtain two kinds of film–substrate specimens. The specimens were then heated with an oxy-acetylene flame, and the resulting thermal stress caused out-of-plane deformation of the specimen. This deformation was measured by reflective CGS, and the thermal stress field of the system was finally obtained by calibration with the help of finite element analysis.

Figure 1 shows the principle of the reflective CGS method, where G_1 and G_2 are two identical Ronchi gratings. A laser beam is passed through a beam expander and collimation lens to become a collimated beam with a diameter of 30 mm. A beam-splitter cube is used to split the collimated beam. The transmitted beam comes into contact with the specimen surface and is reflected back into the beam-splitter cube. The reflected beam passes through two gratings and the interference fringes can be seen behind the second grating G_2. As shown in Fig. 1, the light beam is diffracted when it travels through the first grating G_1. Only the diffraction beams with the diffraction order of 0 and +1 are shown in Fig. 1. The grating pitch (p) is 40 lines/mm, the laser wavelength (λ) is 532 nm, and the distance between the two gratings (Δ) is 30–50 mm. Therefore, the separation between the two diffracted beams at G_2 is:

$$s = \Delta \cdot \tan\left(\sin^{-1}\frac{\lambda}{p}\right) \approx \Delta \cdot \frac{\lambda}{p}. \tag{1}$$

Therefore, the interference fringes behind G_2 originate from two superimposed light beams with a separation of s. Moreover, the gray level of any point on the interferogram depends on the light path difference between two beams reflected from the corresponding point and its contiguous point with a distance of s. For the reflective CGS method, the governing equation is:

$$\frac{\partial w}{\partial X} = \frac{np}{2\Delta}, \tag{2}$$

where w is the out-of-plane displacement of the specimen, X represents the principal direction of the two gratings, and n is the fringe order [16,17]. As can be seen from Eq. (2), the interference fringes represent the contours of an out-of-plane slope. Because many diffraction beams are superimposed on G_2, a filtering lens and an aperture are used to remove all other orders of interference beams except those of +1 order. A screen or a camera is placed behind the aperture to capture the interferogram.

The specimens used in this study are shown in Fig. 2(a). There were two groups of specimens. For #1, a polished Ni-based alloy substrate of 5.0 mm in thickness was coated with a plasma sprayed 8YSZ layer (TC layer) of about 1.0 mm in thickness. For #2, a polished Ni-based alloy substrate of 3.0 mm in thickness was coated with a plasma sprayed NiCoCrAlY layer (BC layer) of about 0.5 mm in thickness. The diameter of the #1 specimens was 20 mm, while the diameter of the #2 specimens was 25 mm.

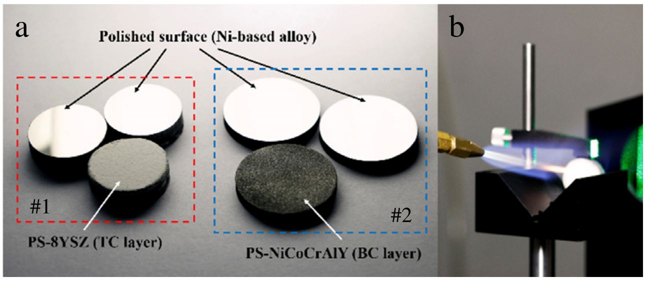

Fig. 2. (a) Specimens used in this study, (b) thermal shock experiment.

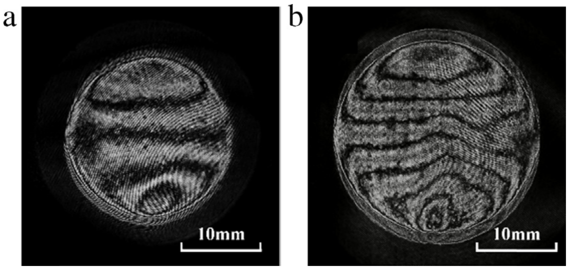

Fig. 3. Interferograms obtained at stable temperature: (a) #1 specimen with a TC layer surface temperature of 631 °C, (b) #2 specimen with a BC layer surface temperature of 437 °C.

All substrate surfaces were precisely polished to obtain a mirror like surface and high quality null field. In this study, the surface roughness was $Ra \leqslant 0.04\ \mu\text{m}$ and the surface flatness tolerance was $0.3\ \mu\text{m}$, as optimized by the authors in a previous study [18]. During the experiment, the specimens were fixed on a metal table and heated with an oxy-acetylene flame as shown in Fig. 2(b). The temperature of the TC/BC layer surface was measured with a thermocouple. Because of the limited heating power and the room temperature environment, the temperature field tended to be stable in the entire specimen. Then, the interferogram, which represented the slope of the substrate surface at the corresponding temperature, was captured using a camera.

Figure 3(a) shows the interferogram of a #1 specimen at a TC layer surface temperature of 631 °C, while Fig. 3(b) shows the interferogram of a #2 specimen at a BC layer surface temperature of 437 °C. The principal direction of the two gratings used in this study was vertical, therefore, the homogeneous horizontal fringe pattern means that the surface slope was linear and the surface shape was quadratic. It should be noted that the distortion of the fringes in the images was caused by the unstable flame.

Once the interferograms and the corresponding temperatures were obtained, the surface slopes were calculated via Eq. (2). To obtain the thermal stress field in the entire specimen, two finite element models were implemented. The surface temperature of the TC/BC layer was the same as that measured in the experiment, and the size of the model was the same as that of the specimen. The mechanical and thermal parameters of the three kinds of material are listed in Table 1 [19], where E is the elastic modulus (in GPa), ν is the Poisson's ratio, α is the thermal expansion coefficient (in units of $\times 10^{-6}\ {}^\circ\text{C}^{-1}$), and λ is the thermal conductivity (in $\text{W} \cdot \text{cm}^{-1} \cdot \text{K}$).

The finite element method software ANSYS was used in this study and an axisymmetric model was implemented. The initial residual stress of the model was supposed to be zero, which means that the residual stress caused by the plasma spraying and cooling procedure was neglected. The TC surface temperature was set