Surface & Coatings Technology 251 (2014) 98–105

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Evolution of residual stress in air plasma sprayed yttria stabilised zirconia thermal barrier coatings after isothermal treatment

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ARTICLE INFO

Article history:
Received 5 November 2013
Accepted in revised form 4 April 2014
Available online 13 April 2014

Keywords:
Thermal barrier coatings (TBCs)
Stress
Air plasma spray
Raman spectrascopy
Phase transformation

ABSTRACT

The evolution of residual stresses in yttria stabilised zirconia (YSZ) thermal barrier coatings (TBCs) produced by air plasma-spray technique after thermal treatments at 1150 °C was investigated. The residual stresses in YSZ layer were measured using the Raman spectroscopy and curvature method, respectively. Generally, the YSZ layer was under compressive stress in as-deposited condition, but changed to tensile after thermal treatment for 30 hours partly due to the monoclinic to tetragonal phase transformation in YSZ layer. With prolonged thermal treatment, the residual stress gradually transformed from tensile to compressive, which can be attributed to the sintering in the YSZ layer. In addition, the β-NiAl to γ/γ′-Ni_3Al phase transformation in the bond coat also plays an important role on the stress in the YSZ layer.

1. Introduction

Air plasma-sprayed (APS) yttria stabilised zirconia (YSZ) thermal barrier coatings (TBCs) have been widely used in the hot-section of gas turbine to increase the inlet temperature and to protect the engine components. Failure of TBCs under isothermal treatment typically occurs within the YSZ layer, i.e., several micrometres above the thermally grown oxide (TGO) [1]. The failure driven by the residual stress in the YSZ layer developed during cooling after high-temperature treatment [2], through a sequence of crack nucleation, propagation and coalescence process [3]. Therefore, determination of the residual stresses in the YSZ layer is of great importance to understand the failure mechanisms of APS TBCs. Due to the complicated microstructures and various thermal treatment conditions, the stress values of the APS YSZ coatings from different researchers/techniques show a significant scatter. For example, Teixeira and Andritschky [2,4] reported there is a compressive stress of about −70 to −300 MPa of the APS YSZ layer after thermal cycling. Portinha et al. [5] reported a compressive stress of −404 MPa measured by X-ray diffraction (XRD), −22 MPa investigated by XRD-$\sin^2\Psi$ method and −594 MPa by Raman spectroscopy for the APS YSZ layer after isothermal treatment. To date, there has been no systematic research to study the evolution of the residual stresses. Thus, it is necessary to know the stress state evolution in YSZ layer due to isothermal treatment, which is important for understanding the degradation and failure of TBCs.

Various methods have been employed to study the residual stresses in TBCs, such as neutron diffraction [6,7], XRD [8], luminescence spectroscopy [9–11], curvature measurement [12,13] and Raman spectroscopy [4,14–16]. The limitation of neutron diffraction is the large depth of penetration which will not reveal the stresses within the YSZ layer. XRD has a small penetration depth which limits the stress measurement close to the surface of the YSZ layer. Luminescence spectroscopy, on the other hand, has been used for measuring the residual stresses in the TGO, but not applicable to the YSZ layer. Amongst those, Raman spectroscopy is an easy and non-destructive technique to study the stresses in YSZ layer. It is able to provide localized information of the residual stresses for its high spatial resolution (of the order of 1 μm). Meanwhile, curvature method is considered as one of the simplest methods. This method can obtain the overall stress information in the TBCs. To understand the crack nucleation behaviour, the local stress should be known, whilst the failure of TBCs is related to the overall stress. Therefore, Raman spectroscopy and curvature method are both applied to obtain local and overall information.

The aim of this study is to investigate the evolution of residual stresses in the APS YSZ layer with isothermal treatment time at 1150 °C by Raman spectroscopy and curvature method. These are related to SEM, XRD and micro-indentation to study the effect of the microstructure, phase transformation and mechanical properties aspects on the stress in the YSZ layer. Then the results from Raman spectroscopy and curvature method were compared and their limitations discussed.

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http://dx.doi.org/10.1016/j.surfcoat.2014.04.009
0257-8972/

2. Experimental procedure

2.1. Specimen preparation

Both the bond coat consisted of NiCoCrAlY (23Co17Cr12Al0.5Y, in wt%, balanced by Ni) about 140 μm thick and 7–8 wt% YSZ top coat of about 400 μm thick was applied to a Hastelloy substrate with a thickness of 2 mm using APS technique.

The specimen was cut into 10 mm × 10 mm plates and 85 mm × 2 mm beams for Raman and curvature measurement. The thermal treatment test was carried out at 1150 °C in ambient air with dwelling times of 0, 30, 60, 90, 120 and 150 hours. After thermal treatment to the designed time, the specimens were taken out and cooled in air to the room temperature. At least two samples were used for each condition.

2.2. Elastic modulus measurement

The elastic modulus was measured by micro-indentation (CSM Instruments, Switzerland) with a Berkovich indenter. The measurement was carried out on the polished cross section of the TBCs. At least 6 indents were made on each layer. The interval between indents was more than 100 μm in order to avoid the influence from adjacent indents. The Poisson's ratio was taken as 0.2 for the YSZ layer, 0.3 for the bond coat and the substrate [17]. The maximum load was 1 N and the dwelling time was 10 s for all of the measurements.

2.3. Phase composition and microstructure characterisation

XRD (Rigaku, Japan) with a Cu-Kα radiation was used to identify the phase of the YSZ layer. Region from 5° to 85° 2θ range was recorded with a scanning speed of 0.5° min^{-1}.

The volume fraction of the m phase, f_m, was quantified from the intensity of the monoclinic peaks m (111), m $\left(11\bar{1}\right)$ and tetragonal peak t (101) by [18]:

$$f_m = \frac{1.311X_m}{1 + 0.311X_m} \quad (1)$$

where X_m is the integrated intensity ratio obtained by [18]:

$$X_m = \frac{I_m\left(11\bar{1}\right) + I_m(111)}{I_m\left(11\bar{1}\right) + I_m(111) + I_t(101)} \quad (2)$$

where the subscripts m and t refer to the monoclinic and tetragonal phases, respectively. In this study, the t (101), m $\left(11\bar{1}\right)$ and m (111) peaks in a range of 2θ between 27° and 33° were used to obtain the volume fraction of the m phase, and both t' and c phases were considered as the t phase.

The microstructures and thicknesses of the YSZ layer, bond coat and TGO layer were examined by scanning electron microscopy (SEM, FEI Quanta 200).

2.4. Raman spectroscopy

Raman spectroscopy was performed using a Raman Microscope (Jovin Yvon LabRAM HR800) with an excitation of 488 nm (Ar laser). The peak position of each band was obtained by curve fitting (NGSLabspec 5 software), assuming a mixed Lorentzian and Gaussian function.

A typical Raman spectrum of tetragonal YSZ is shown in Fig. 1(a). For the stress measurement, the peak at 465 cm^{-1} is chosen because it has a larger pizeospectroscopy coefficient (2.01 cm^{-1}/GPa [19]), which is well separated from other peaks.

The YSZ layer mainly consists of the meta-stable tetragonal-prime phase. Due to thermal treatment, the Y^{3+} ions diffuse to their equilibrium positions and the meta-stable phase slowly transforms to a mixture of tetragonal and cubic phase [20]. Thus, the stress-free lattice parameter varies with thermal treatment time, leading to a stress-free Raman peak displacement. Therefore, Raman measurement was carried out on both supported (with substrate) and freestanding coatings (without substrate). The freestanding coatings were obtained by dissolving the substrate using acids (HCl and HNO_3). The HCl-to-HNO_3 ratio was 3:1. For thermally treated samples, freestanding coatings were firstly obtained by thermal treatment followed by dissolving. The peak positions of freestanding coatings were used as stress-free reference positions to compare with supported coatings. The peak shift difference was used to estimate the residual stress in the YSZ layer. Each sample had undergone at least 20 measurements from the top surface (at least 500 μm far from the edge, random position) to ensure the reproducibility of the results.

The Raman mapping was employed to study the monoclinic phase distribution in the YSZ layer. Areas of about 125 × 145 μm were carried out. Each map involved about 100 single point measurements. These spectrums were analysed using the LabSpec 5 software. Characteristic Raman bands of at 182 and 191 cm^{-1} were selected for the mapping monoclinic zirconia [20], as shown in Fig. 1(b).

2.5. Curvature measurement

Residual stresses were evaluated through the changes in curvature of the specimen before and after isothermal treatment. Before deposition, the substrate was flat. After deposition of the bond coat and YSZ layer or thermal treatment, the curvatures changed and were recorded using

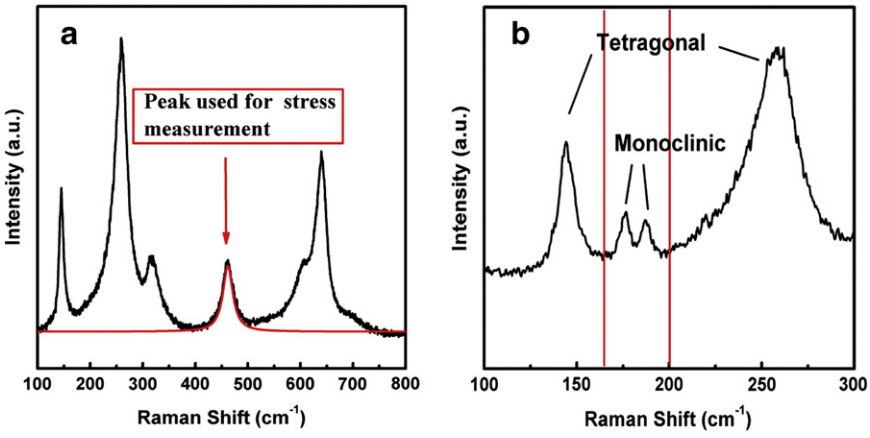

Fig. 1. (a) Typical Raman spectra of tetragonal 7–8 wt% YSZ. Residual stresses in YSZ layer are determined by evaluating the peak shift at 465 cm^{-1}. (b) Example of spectrum showing the monoclinic and tetragonal phases from the 100 cm^{-1} to the 300 cm^{-1}. The spectral range used for the phase mapping calculations is also marked.