Surface & Coatings Technology 232 (2013) 116–122

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

High resolution erosion detection in thermal barrier coatings using photoluminescent layers

C.C. Pilgrim [a,b], S. Berthier [a], J.P. Feist [a], A.L. Heyes [b,*]

[a] Sensor Coating Systems, Imperial Incubator, Bessemer Building, Level 1&2, Imperial College London, London SW7 2AZ, UK
[b] Imperial College London, London, London SW7 2AZ, UK

ARTICLE INFO

Article history:
Received 5 March 2013
Accepted in revised form 27 April 2013
Available online 4 May 2013

Keywords:
Thermal barrier coating
Erosion
Phosphor
Yttria stabilised zirconia

ABSTRACT

Accurate life prediction of thermal barrier coatings (TBCs) becomes increasingly important as they progress towards prime reliant status. Quantitative non-destructive evaluation techniques, which can enable remaining life assessments, are integral to achieving this goal. Although not the primary failure mechanism, in certain operating conditions, degradation to the TBC occurs by gradual erosion from the surface. The introduction of rare earth ions in discrete layers in the ceramic coating enables this form of degradation to be detected by analysis of the inherent phosphorescence. It has been shown that this technique can quantify thickness reductions with a resolution greater than the thickness of the doped layers and estimated to be ±5 μm. A model has been developed to predict the relationship between coating thickness and emission intensity based on absorption and scattering coefficients derived from the literature. The model suggests that the relationship is linear and this has been validated using the experimental data. Sample TBCs, largely comprised of YSZ with europia and dysprosia doped layers, were eroded using a particle laden jet and the phosphorescent emission was imaged. Through bespoke image processing the data was reconstructed into a three-dimensional coating profile that correlates well with that expected for the applied erosion method. Further validation was achieved by comparing the surface profile with data taken using a confocal microscope. A protrusion approximately 0.3 mm wide from the erosion crater was identified by both techniques and is indicative of the fidelity of the technique. Secondly, the profile over the erosion crater derived from the phosphorescence image is within the error range, ±5 μm, of the reconstructed confocal microscope data.

1. Introduction

The drive towards 'prime reliant' thermal barrier coatings (TBCs) dictates the need for a greater accuracy in life prediction methods. This, in turn, requires information to be gathered using suitable non-destructive evaluation (NDE) techniques on the condition of coatings in different operating regimes to validate lifing models. Ideally, this technique should assess condition and degradation whilst the component is in-situ, to avoid the costly operation of disassembly, and to allow cost-effective utilisation of the indicated remaining coating life.

Degradation of the TBC system can occur through a variety of different mechanisms. Failure is often attributed to the growth of the thermally grown oxide layer, beneath the ceramic top coat [1]. However, TBCs sometimes operate in conditions that cause degradation through thinning of the ceramic top coat from the surface, where ingested air can be contaminated with particulate matter for example. Some ingested particles can be transported through the engine to impact on the coating surface causing compaction damage or material removal [2]. Other contaminants, for example volcanic ash, can melt in the combustor and deposit on the coating surface as in calcium-magnesium-alumino-silicate (CMAS) attack [3]. The deposits penetrate into the porous ceramic, locally reducing the strain tolerance and eventually causing partial or total spallation [4]. Alternatively, when the coating surface temperature approaches or exceeds 1250 °C, in very high temperature operation, local volumetric changes leading to high strain levels can occur through phase transformation (tetragonal to monoclinic [5,6] in TBCs made from yttria stabilised zirconia) again resulting in spallation. The reduction in the ceramic thickness, through any of the failure mechanisms outlined, will reduce the thermal protection offered by the ceramic and hence promote premature failure of the complete TBC system.

Although there are several NDE methods that have been proposed for the detection of TBC thinning, the demand for an in-situ technique limits those which are practically viable. One method to detect erosion of TBCs [7] that does have the potential to provide accurate measurements in-situ consists of a TBC wherein the ceramic outermost layer is rendered phosphorescent by the substitution of optically active rare earth ions into the crystal lattice with different dopant ions introduced in discrete layers. As the coating is gradually thinned the

* Corresponding author at: Mechanical Engineering, Imperial College London, London SW7 2AZ, UK. Tel./fax: +44 20 7594 3519.
E-mail address: a.heyes@imperial.ac.uk (A.L. Heyes).

0257-8972/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.surfcoat.2013.04.061

phosphorescent characteristics of the multi-layered coating change. With suitable image processing techniques it should be possible to remotely observe (using a boroscope for example) these changes in the optical properties of the coating and calculate the extent of any erosion. The production of suitable coatings has been demonstrated [8] and, more recently, it has been shown that they can be used to make quantitative measurements of erosion damage [9]. Using bespoke but simple image processing, the extent of the damage was indicated by detecting the presence or absence of emission from each layer thereby indicating if they were present or if erosion had removed them. The present contribution, however, presents a more refined method wherein the erosion can be detected and quantified before it breaches given layers and as such could provide a technique to measure erosion rates more accurately, identify critical areas and enable remaining coating life assessment.

2. Theory

The addition of optically active ions into a ceramic crystal can induce photoluminescence in the material. Rare earth ions are widely used as the dopant because their luminescence is primarily generated by electron transitions between states in the partially filled 4f shell [10]. The outer 5d and 6s shells provide the bonding with the host material and, as such, the transitions in 4f shell are largely unaffected by the host material whose influence on the optical properties is, therefore, minimal. Different rare earth ions can be introduced to the same host allowing layers to be produced with distinctly different optical characteristics, such that they are discernible by their photoluminescence. When the coating is damaged causing thinning from the surface, material is removed and the thickness of the doped layers change, altering the luminescence from the coating. The luminescent emission can, therefore, indicate how much material has been removed and thereby the remaining coating thickness.

Yttria stabilised zirconia (YSZ), the industrial standard material for the ceramic top coat in TBC systems, is known to be translucent from the near-ultraviolet to the infrared range of the spectrum [11]. As a result, the excitation and emission light in this range can be transported through the material. A thick layer of luminescent material will, therefore, produce intense emission as more material is excited and more emission observed. A widely used theory for describing the light transport through a coating layer is the Kulbelka–Munk (KM) theory [12]. It was originally devised to describe paint layers but has been applied across a variety of different applications [13]. The benefit of the theory over others is that it relies on coefficients which can be derived from relatively simple experimentation and it has been previously adapted to describe phosphorescent coatings [14,15]. In this paper a similar model has been implemented to describe the light transport through a YSZ coating with dopant ions present in discrete layers. This two-flux radiative transfer model is one-dimensional so that light is considered to travel only in the direction perpendicular to the coating surface, as illustrated in Fig. 1.

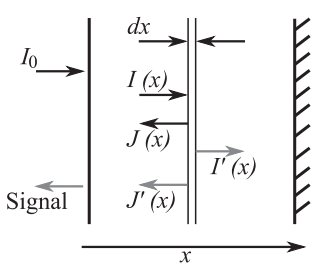

Fig. 1. An example phosphorescent coating showing how KM theory models the light transport.

The light propagating in the positive x direction, i.e. towards the substrate is labelled $I(x)$ and the light travelling in the opposite direction is termed $J(x)$ and either may be absorbed, transmitted or scattered as they pass through the coating. Therefore light propagating in each direction can be described by:

$$\frac{dI(x)}{dx} = -(s+k)I(x) + sJ(x) \tag{1a}$$

$$\frac{dJ(x)}{dx} = (s+k)J(x) - sI(x) \tag{1b}$$

where s and k are scattering and absorption coefficients respectively.

It has been shown that these equations can be generalised to cover light from all directions by modification of the scattering and absorption coefficients, such that S = 2 s and K = 2 k [16]. The general solutions of Eqs. (1a) and (1b) are then:

$$I(x) = A(1-\beta)e^{\alpha x} + B(1+\beta)e^{-\alpha x} \tag{2a}$$

$$J(x) = A(1+\beta)e^{\alpha x} + B(1-\beta)e^{-\alpha x} \tag{2b}$$

where A and B are constants and $\alpha = \sqrt{K(K+2S)}$ and $\beta = \sqrt{K/(K+2S)}$. Eqs. (2a) and (2b) can be used to describe the transport of excitation light through the phosphorescent coating. Provided the subsequent phosphorescence is generated equally in both the positive and negative x directions then the behaviour of the emission light can be described by:

$$\frac{dI'(x)}{dx} = -\left(K' + S'\right)I'(x) + S'J'(x) + qK\left(Ae^{\alpha x} + Be^{-\alpha x}\right) \tag{3a}$$

$$\frac{dJ'(x)}{dx} = \left(K' + S'\right)J'(x) - S'I'(x) - qK\left(Ae^{\alpha x} + Be^{-\alpha x}\right) \tag{3b}$$

where the prime refers to the light at the emission wavelength and q is the quantum efficiency of the phosphorescence. These equations have the general solutions:

$$I'(x) = \frac{qKA}{\beta'}\frac{\alpha\beta' - \alpha'}{\alpha^2 - \alpha'^2}e^{\alpha x} - \frac{qKB}{\beta'}\frac{\alpha\beta' + \alpha'}{\alpha^2 - \alpha'^2}e^{-\alpha x} + A'(1-\beta)e^{\alpha' x} + B'(1+\beta')e^{-\alpha' x} \tag{4a}$$

$$J'(x) = -\frac{qKA}{\beta'}\frac{\alpha\beta' + \alpha'}{\alpha^2 - \alpha'^2}e^{\alpha x} + \frac{qKB}{\beta'}\frac{\alpha\beta' - \alpha'}{\alpha^2 - \alpha'^2}e^{-\alpha x} + A'(1+\beta)e^{\alpha' x} + B'(1-\beta')e^{-\alpha' x} \tag{4b}$$

This set of equations was used to implement a model using Matlab software to simulate the response of a multi-layered phosphorescent coating.

3. Experimental procedure

Sample TBCs were designed and produced with distinct doped layers. The samples were eroded and imaged using a bespoke optical and signal processing system to investigate whether the coating thickness could be determined using the phosphorescence emission.

3.1. Coating specification and production

The coating architecture was designed so that there were only minor modifications relative to an industrial standard TBC system. The ceramic layer was primarily unmodified YSZ with two distinct layers, one doped with europium, the other with dysprosium. These dopants were chosen because they are known to produce sufficiently bright luminescence at distinctly different wavelengths [17].