Surface & Coatings Technology 302 (2016) 359–367

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Remote temperature sensing on and beneath atmospheric plasma sprayed thermal barrier coatings using thermographic phosphors

Fahed Abou Nada [a,*], Andreas Lantz [b], Jenny Larfeldt [b], Nicolaie Markocsan [c], Marcus Aldén [a], Mattias Richter [a]

[a] Department of Physics, Division of Combustion Physics, Lund University, Box 118, SE-221 00 Lund, Sweden
[b] Siemens Industrial Turbomachinery AB, SE-612 83 Finspång, Sweden
[c] University West, SE-461 86 Trollhättan, Sweden

ARTICLE INFO

Article history:
Received 12 April 2016
Revised 14 June 2016
Accepted in revised form 15 June 2016
Available online 16 June 2016

Keywords:
Thermal barrier coatings
Thermographic phosphors
Remote temperature sensing
Laser-induced phosphorescence
Phosphor thermometry

ABSTRACT

Investigations on remote temperature sensing of yttria stabilized zirconia (YSZ) thermal barrier coatings (TBCs) at the surface and at the bond-coat/top-coat interface were carried out. Using Y_2O_3:Eu thermographic phosphor as an embedded temperature sensing layer, sub-surface temperature probing through 300 μm of atmospheric plasma sprayed YSZ is demonstrated. The Y_2O_3:Eu thermographic phosphor displays a temperature sensitivity ranging between 400 °C up to a maximum of 900 °C when utilizing the luminescence originating from the 611 nm emission band. Dysprosium stabilized zirconia (10 wt.% DySZ), a TBC material, is also investigated and established as a temperature sensor from 400 °C up to a temperature of 1000 °C using both the intensity decay time and emission intensity ratio methods. In addition, the luminescence of presumed optically inactive YSZ materials was spectroscopically investigated in terms of optical interferences caused by impurities. A validation temperature probing measurement through 300 μm of YSZ top-coat was successfully performed in a SGT-800 Siemens burner running at six different operating conditions in an atmospheric combustion rig.

1. Introduction

The efficiency of gas turbines is directly related to the turbine inlet temperature. Higher gas temperature at the inlet of the turbine yields higher overall efficiency. Currently, gas turbines operate at temperatures that are very close to or even exceeding the melting temperature of the high performance nickel-based alloy substrates used to manufacture the different engine components. The introduction of thermal barrier coatings (TBCs) contributed to a substantial increase in gas turbine efficiency due to their oxidation resistance and thermal insulating properties. Thermal barrier coatings are a multilayered system that is mainly composed of a ceramic coating that is deposited upon a thin layer of metallic binder known as the bond-coat.

The strong reliance on TBCs for increasing the operating temperature of gas turbines means that the integrity of such coatings is crucial for the lifetime of the engine components. Different degradation mechanisms of the ceramic coatings are directly related to the temperatures that the TBC system experience during operation, especially the temperature registered at the metallic substrate/TBC interface. An increase of temperature of 50 °C at the substrate/TBC interface can lead to as much as six folds decrease in the lifespan of the TBC [1]. Thus, in situ monitoring of the temperature at the substrate/TBC interface is of high significance to evaluate the performance of the coatings and investigate the potential for further advancement in engine efficiency.

Conventionally, the temperature of different elements of the gas turbine is monitored using pyrometry or thermocouples. Both methods have their limitations in their application to measure the coating temperature. Reflections from the very hot combustion environment and variations in emissivity of the coating can severely distort the measured temperatures in the case of pyrometry. The intrusiveness of the thermocouples and their difficulty to be implemented to rotating engine components is a drawback for their temperature measuring capability in gas turbines. During the last decade, an alternative method of temperature sensing, known as phosphor thermometry, has been studied and applied to different applications for remote temperature probing [2,3]. Phosphor thermometry utilizes the luminescence originating from optically active materials. These sensors are known as thermographic phosphors (TP) and have been developed and implemented as temperature sensors in thermal barrier coatings [4–10]. Phosphor thermometry provides multiple advantages such as remote probing capability, non-intrusiveness and high endurance when applied to harsh experimental environments such as those present in gas turbines.

TBCs can be optically activated and transformed into a thermographic phosphor by doping them with an activator ion, usually a rare-earth element such as europium, erbium, dysprosium, samarium, and terbium to name few. The doping process renders inert TBCs into temperature sensing thermographic phosphors that can be integrated as a

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[*] Corresponding author.

http://dx.doi.org/10.1016/j.surfcoat.2016.06.038

layer within the applied TBC system. For example, in zirconia, yttria ions are used to stabilize the composition of the zirconia, forming yttria stabilized zirconia (YSZ) which is the most applied TBC in gas turbines. Rare-earth ions can also be incorporated in YSZ or zirconia to act both as a stabilizing ion and as a luminescence center within the coating material. The concentration of the rare-earth ions can affect the stabilization and luminescence properties of the doped zirconia coatings [10].

The difficulty of probing temperature of sensor coatings embedded underneath the TBC rises from the severe attenuation of the incident excitation radiation and emitted luminescence. Thermographic phosphors are usually excited using ultraviolet (UV) radiation, most often from lasers sources such as Nd:YAG lasers producing 355 nm laser pulses. YSZ TBC coatings are opaque to ultraviolet (UV) radiation which makes the excitation of the embedded TP sensing layer inefficient and limited to penetration depths of around 50 μm [11]. However, it has been demonstrated that by judicious selection of the excitation wavelength to match the translucency window of YSZ materials in the visible range of the spectrum, depth-penetrating temperature sensing at the bond-coat/top-coat interface is feasible for Atmospheric plasma spray (APS) applied TBCs [5]. A study presented by Eldridge el al. on YSZ coatings deposited using electron beam physical vapor deposition (EB-PVD) and APS methods, showed that EB-PVD coatings have superior transmission properties compared to APS coatings of the same thickness [12]. Coatings applied using EB-PVD had transmission starting from 300 nm and increased with increasing wavelength. On the other hand, APS coatings were opaque to radiation with a wavelength shorter than 450 nm. The enhanced transmission characteristics of EB-PVD deposited YSZ coatings are due to their vertically columnar structure facilitating the propagation of light by acting as a channel to guide the excitation and emission radiations through the thickness of the top-coat. Hence, most of the studies reporting temperature measurement beneath the surface of the TBC, utilized EB-PVD coatings. Few studies [5,11], however, illustrated the feasibility of conducting a depth-penetrating temperature measurements with APS applied coatings. The study by Eldridge et al. [5], reported successful temperature measurements from beneath a 100 μm thick YSZ coating using Y_2O_3:Eu as the sensor of choice. Chen et al. [11], however used Dysprosium doped YSZ as a sensor layer and successfully illustrated temperature measurement from beneath a 50 μm thick YSZ top-coat. Typical thicknesses of APS applied top coats in gas turbines well exceed 100 μm, thus there is a necessity for extending the capability of performing bond-coat/top-coat interface temperature probing beneath thicker APS coatings.

This study, for the first time, demonstrates the feasibility of conducting depth-penetrating temperature measurements beneath 300 μm thick APS coated YSZ using Y_2O_3:Eu (75 mol.% Eu) thermographic phosphor as the embedded temperature sensing layer. The spectral characterization of the luminescence emitted and the decay time of Y_2O_3:Eu is reported as function of temperature. In addition, dysprosium partially stabilized zirconia (DySZ) was also characterized and established as a potential temperature sensor. DySZ was implemented for TBC on-surface temperature monitoring for the first time. Furthermore, spectroscopic studies were conducted on YSZ top-coats to investigate the presence and possible interference from impurities present in presumed optically inactive YSZ material. An optimal YSZ material was identified for spectroscopic applications, in particular for monitoring of TBC temperature.

2. Thermal barrier coating systems

Thermal barrier coatings are ceramic materials that supplies thermal insulation to critical engine components; such as combustion liners, guiding vanes, heat shields, turbine blades and afterburners, which are subjected to high thermal loads. They are typically zirconia based materials (usually stabilized with oxides of rare earth elements). The most used material is Y_2O_3-stabilized ZrO_2 ceramic (YSZ) where the portion of the Y_2O_3 ranges between 6 and 8% by weight. Thermal barrier coatings can be considered as a complex and interrelated system that is composed of multiple layers and not solely from (top-coat) oxide ceramic coating. This system is composed of the underlying super-alloy engine part then followed by a metallic bond-coat layer, a thin thermally grown oxide layer (TGO) that is created by bond-coat oxidation and the zirconia top coat. Fig. 1 illustrates the multilayer structure in a typical TBC system.

Electron beam physical vapor deposition (EB-PVD) and atmospheric plasma spray (APS) are the two most commonly used techniques for the deposition of TBCs on different engine components. Each of the two techniques produces different top-coat microstructure and consequently thermal conductivity characteristics. The EB-PVD method produces coatings with vertical columnar structures that have high strain tolerance but with increased thermal conductivity compared to APS produced coatings. On the other hand, the APS method produces coatings that have a splat like structure with pores that are of different size and shape, uniformly distributed through the coating. Plasma sprayed thermal barrier coatings have a high level of porosity which is a desired feature. The high level of porosity in APS coatings leads to improved reduction in thermal conductivity compared to coatings produced by the EB-PVD method. APS produced coatings are relatively cheaper than those produced with the EB-PVD method. The choice of the suitable coating method depends on the engine component, the desired performance characteristics and the cost. In this study, the APS process has been implemented to apply the metallic bond-coat, the YSZ top-coat and the DySZ top-layer.

3. Temperature sensing

3.1. Thermographic phosphor principles

Temperature sensing on/in and beneath the TBC can be accomplished either by the utilization of commonly available thermographic phosphors or by doping the YSZ TBC with a rare-earth element, for example with dysprosium, and thus converting it into a sensor material similar in its temperature sensing characteristics to thermographic phosphors. For both materials, the principle of temperature sensing is the same and there are two major methods of extracting temperature information from the emitted luminescence of such sensors. The first method utilizes the change in the emission spectrum of the phosphor as function of temperature, while the second method implements the measurement of the rate of decay of the delayed luminescence.

The change of emission is usually displayed as an intensity variation where one spectral band displays a relative increase in intensity while another band displays a counter behavior. Then, by simultaneous measurement of the intensity of both spectral bands, one can deduce a relation of their ratio as function of temperature. This method is known as the intensity ratio method. At a specific temperature, by using a

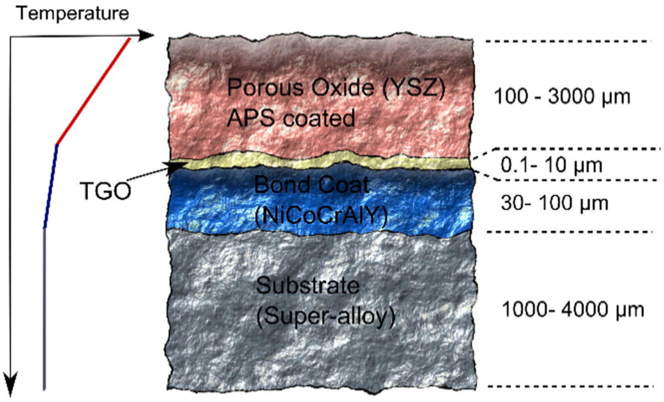

Fig. 1. Schematic drawing of thermal barrier coating system composed of a substrate, bond-coat, thermally grown oxide layer, and top-coat.