Surface & Coatings Technology 206 (2012) 2751–2758

Contents lists available at SciVerse ScienceDirect

Surface & Coatings Technology

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

Stress measurements via photoluminescence piezospectroscopy on engine run thermal barrier coatings[☆]

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ARTICLE INFO

Article history:
Received 15 June 2011
Accepted in revised form 17 November 2011
Available online 26 November 2011

Keywords:
Photoluminescence Piezospectroscopy
Thermal Barrier Coatings
Thermally Grown Oxide
Remaining Life Prediction
CMAS

ABSTRACT

Optical measurements of stress in a thermally grown oxide (TGO) layer that has formed between a metallic bond coat and thermal barrier coating (TBC) have been previously demonstrated and shown useful in understanding aspects of TBC failure. These measurements have promise for nondestructive evaluation of coated turbine components. However, engine-run turbine parts collect significant surface contamination consisting of calcium-magnesium-alumina-silicate (CMAS). The deposited CMAS both blocks optical measurement of stress in the TGO and produces false stress signals. A recently developed laser ablation technique has enabled contaminant removal with minimal TBC damage. The locally cleaned engine run parts can then have their TGO stresses optically determined. In the present paper, it is shown that sporadic signals from contamination are still present due to CMAS infiltration into the TBC and due to local regions that cannot be cleaned without damaging the TBC. Methods for separating the contamination signal from the TBC signals are presented as needed for successful use of optical stress measurement on engine run turbine components. The stress measurements censored for false signals are compared to other destructive approaches and the methods are shown to provide robust nondestructive evaluation of the coating stress.

1. Introduction

Engine components, such as turbine blades, can be subjected to high temperature gas streams above the melting temperatures of the metal parts. Thermal barrier coatings (TBCs) are ceramic layers added to the top of these metals to insulate them from the high gas temperatures. The temperature reduction allows for increased part life and/or increased engine efficiency via higher gas path temperatures and reduced use of cooling air. TBC systems consist of an oxidation resistant bond coat (BC) applied to the component substrate and a ceramic top coat, the TBC itself, as shown in Fig. 1. A thermally grown oxide (TGO) region forms during engine operation at the boundary of the TBC and BC. At elevated temperatures, oxygen penetrates the top ceramic layer and reacts with alumina within the bond coat, creating growth in the TGO over time that leads to increased strain, decreased TGO to BC bond strength (stress) due to growth of microcracks, and subsequent TBC system failure as the coating eventually delaminates. Therefore, it is of considerable interest to develop techniques for accurate stress measurements within the TGO, which can then be correlated with the remaining lifetime of the coating.

Photoluminescence piezospectroscopy (PLPS) is a diagnostic technique that allows for nonintrusive stress measurements of TGO. The technique was first developed by Grabner [1] and Christensen *et al.* [2]. PLPS measurements are made by exciting chromium ions in the TGO and monitoring the fluorescence spectrum. The development of a nondestructive evaluation (NDE) method for TBC systems based on PLPS has been under investigation for a number of years [2–6]. Until recently, such methods had only been applied to clean TBC sample coupons that had been thermally cycled in furnaces. Hansen [7] attempted to apply this technique to turbine blades run in an engine and found that contaminant deposited onto the TBC surface provided false PLPS signals that overwhelmed the desired signals for NDE. These contaminant deposits are nonuniform in thickness and interfere by either blocking the desired signal from the TGO or providing a competing non-TGO fluorescence signal.

Engine components are subject to various environmental contaminants during normal use. These contaminants have been extensively studied and are known to consist primarily of calcium-magnesium-alumina-silicates (CMAS) [8–11], and trace amounts of iron oxide and sulfates [12]. In a recent paper, a method of removing the nonuniform thickness contaminant surface using laser ablation was described. Ablation of only the CMAS was achieved by using laser induced breakdown spectroscopy (LIBS) to identify the elements being ablated and to stop ablation when the first evidence of TBC materials was found [13].

[☆] This work was supported by the National Science Foundation (CTS-0553623) and Rolls-Royce Corporation.

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doi:10.1016/j.surfcoat.2011.11.026

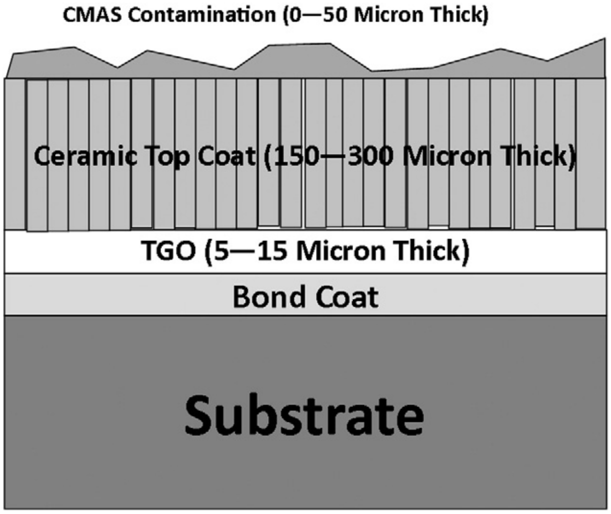

Fig. 1. Schematic of a contaminated TBC coated material with CMAS surface contamination.

In the present work, efforts are discussed to apply PLPS through the LIBS-cleaned areas of the engine run hardware. The surface CMAS removal allows the creation of a window for PLPS to successfully obtain a TGO signal and an accurate stress measurement within the TGO. Because some CMAS was found to remain embedded in the TBC, occasional measurements of fluorescence signals originating in the CMAS are collected even with ablation. In order to determine an average stress value representative of the TGO, the CMAS based signals must be separated or censored from the TGO based signals. Here we describe the data collection from engine run parts and a necessary method of separating the remaining non-TGO originating fluorescence signals from the collected data. The resulting data censoring approach, when combined with LIBS for CMAS removal, provides a robust method for NDE of engine-run coated hardware.

1.1. TBCs

TBC systems are applied to bond coated super alloy substrates to provide insulation and reduce the metal surface temperature. In the present study, TBC coated turbine blades taken from aircraft engines used in actual flight service are examined. As shown in Fig. 1, the TBC system's top ceramic coat is typically between 150 and 300 μm thick and provides thermal protection due to its low thermal conductivity.

The TGO forms as oxygen permeates the TBC and reaches the BC. Aluminum oxide then develops in the form of alpha alumina (α-Al_2O_3). Natural Cr^{+3} impurities are always present in the α-Al_2O_3 and it is this chromium ion that is excited during PLPS to monitor two very distinct and well known (R1 and R2) fluorescence peaks. On engine run blades containing contaminants that arise from normal use, Cr^{+3} doped α-Al_2O_3 is also usually found in the CMAS on the surface, resulting in competing fluorescence signals [7]. Additionally, the CMAS may block the excitation laser from reaching the thermally grown oxide, preventing diagnostic fluorescent emission from the TGO. CMAS containing iron oxide is especially capable of blocking the excitation process [12].

1.2. PLPS

Fluorescence from the Cr^{+3} impurities have distinct visible energy peaks at about 14,432 cm^{-1} and 14,400 cm^{-1} corresponding to the R2 and R1 lines, respectively from the 2E level [14]. Under strain of the surrounding lattice, the spectral position of these peaks shift to lower wavenumbers (higher compressive stress) and these shifts of the R1 and R2 peaks can be used to calculate stress in the TGO using a piezospectrographic tensor. The change in frequency, $\Delta\nu$, of the R1 and R2 fluorescence peaks is related to the internal stress by a general Π_{ij} tensor [15]

$$\Delta\nu = \Pi_{ij}\sigma^{c}_{ij} \tag{1}$$

The average spectral shift can be shown as

$$\overline{\Delta\nu} = \tfrac{2}{3}\,\Pi_{ii}\overline{\sigma} \tag{2}$$

due to the fact that the TGO is a flat scale and under biaxial stress. The mathematics of these tensors representing TGO stresses is discussed in more detail by Lipkin and Clarke [15] and Clarke *et al.* [16]. In this work, the value used for Π_{ii} is equal to 7.61 cm^{-1}/GPa [15]; thus, the shift in frequency is directly related to a change in stress within the TGO. Prior work has also shown that these measured stresses can be directly related to the remaining lifetime of the part for several important TBC systems [3,4].

1.3. CMAS Complications and Removal

On sample coupons which have undergone thermal loading in the laboratory, the PLPS method for measuring TGO stress has proved successful and repeatable [4]. However, the presence of surface CMAS from engine-run hardware gives erroneous results. The α-alumina of the surface CMAS creates a very strong, weakly shifted and therefore nearly unstressed signal when collected using standard PLPS procedures. While the R1 and R2 peak signals from the TGO could still provide the component's remaining lifetime, the surface contaminant effectively blocks this TGO signal and presents a false CMAS based signal that suggests eminent failure [7]. Eliminating the CMAS signal by physically removing the surface contaminant allows a region of the TBC to be probed for true TGO fluorescence signals.

A laser ablation method was designed and implemented [13] for the purpose of contaminant removal. This method determines when the CMAS is exactly removed based on LIBS to look for TBC material being removed in the ablative plume. The presence of yttrium or zirconium signals is used to stop the ablation. This method leaves the ceramic top coat largely unharmed, as shown in Fig. 2a, which is a cross sectional micrograph of the edge of an ablated region. As shown in the micrograph, the top layer of contaminant is removed from an area the size of the LIBS laser spot, providing a sufficient window for PLPS measurements.

Unfortunately, the CMAS particles not completely ejected from the surface can redeposit during the ablation process. This causes crater like CMAS structures to appear around the ablation area, redeposition