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Piezospectroscopic evaluation and damage identification for thermal barrier coatings subjected to simulated engine environments

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ABSTRACT

The application of high temperature ceramic coatings has enabled aircraft and power generation turbines to run at higher inlet temperatures for greater efficiency. Their use extends the lifetime of the superalloy blades that bear thermal gradients and mechanical loads during operation. In this work, ex-situ photoluminescence spectroscopy was conducted to investigate the stresses within the thermally grown oxide of a thermal barrier coated tubular sample following complex realistic conditions, such as induced thermal gradients, and long duration aging. The resulting high spatial resolution stress contour maps highlight the development of the thermally grown oxide in response to the complex conditions. The outcomes highlight both the role of the aging process and the oxide growth's influence on the stress profile which varies spatially across the specimen. The results further provide early detection of micro-damaged zones in the oxide layer nondestructively. Improving the understanding of the coating system's response to loading conditions will allow for more accurate system modeling and early detection and monitoring of damage zones, which is critical for improving efficiency and longevity of aircraft and power generation turbines.

1. Introduction

As turbine inlet temperatures have increased the overall efficiency of engines, thermal barrier coatings (TBC) have been utilized to protect the load bearing superalloy substrate from the high temperatures in aircraft and power generation turbines in an effort to extend its lifetime [1–3]. It is therefore paramount to understand the mechanisms that govern the durability of these coatings, which play a critical role in increasing engine reliability and longevity [4,5].

The coating system typically comprises a ceramic top coat, adhered to the superalloy substrate via a metallic bond coat. Between the bond coat and ceramic top coat an oxide layer begins to develop, which grows rapidly due to thermal loads. For aircraft jet engines, the ceramic top coat is deposited via Electron Beam Physical Vapor Deposition (EB-PVD), whereas power generation turbines often utilize coatings applied by atmospheric plasma spraying. These techniques produce microstructures that influence the coatings' thermal conductivity, porosity, and strain tolerance [4,6]. Coatings deposited via EB-PVD feature a columnar structure that has excellent strain tolerance and durability [7,8]. The oxide layer, commonly referred to as the thermally grown oxide (TGO) is comprised primarily of α phase alumina and has a central role in the failure mechanics of the system [9,10]. Considerable research has been conducted to identify how the thermally grown oxide behaves under cycling throughout its lifetime and eventual failure [11,12]. While much of the studies have been conducted under isothermal conditions, recent efforts to combine thermal gradients, mechanical loads, and in-situ measurements provide the ability to explore the resulting strain evolution under realistic loading conditions [13–15]. High resolution spatial mapping of stress within layers could improve our understanding of mechanisms leading to failure.

Piezospectroscopy is a viable and effective method for investigating the ceramic top coat and oxide layer of TBC's deposited via EB-PVD. It is a non-destructive technique which examines spectral response of the material under stress via laser excitation. The ceramic top coat's columnar structure and translucence to the laser excitation allows for the excitation laser light to penetrate to the oxide layer below. The excitation and subsequent relaxation of the Cr^{3+} impurity in the material results in photon emission, which can provide insight as to the mechanical behavior and material

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properties of the material [16–20]. This technique has been utilized to probe the behavior of the interfaces of the oxide scale, where many failure mechanisms are observed [15,21,22]. In these efforts, the technique has contributed to both identifying damage to the TGO, and some efforts to assess its degree of severity [10,23]. As the coating ages, micro-cracking and micro-delamination occurs. Through their growth and merging, macro scale damage begins to propagate which can lead to the failure of the system [23–27]. Modeling the life expectancy for the coating structure remains an arduous process, as the complexity of the service conditions may lead to a variety of failure mechanisms.

Our growing efforts to enable high-resolution spatial measurements with this technique has expanded its capabilities for stress distribution and damage mapping [28–30]. Monitoring the stress evolution in the TGO, with high spatial resolution, identifying initiation of damage to the coating under realistic loading conditions could provide a powerful advantage for understanding its response to complex loading conditions and its longevity. The ability to observe the initial onset of damage and to capture its progression will shed light on the long term evolution of the coating system, allowing for the refinement and validation of numerical models with the aim of advancing the efficiency and longevity of these high temperature coating systems.

In this study, representative specimens were held under cyclic thermal gradient mechanical loading conditions. The tubular geometry of the specimens was designed for investigations of the strain response with internal forced cooling for in-situ synchrotron X-ray diffraction measurements described elsewhere [15,31,32]. The as-processed samples were cyclically aged with this complex loading and then investigated via piezospectroscopy to determine how the loading conditions develop the oxide layer (Dataset 1). Following a long duration aging under isothermal loading conditions of 1000 ° C, the piezospectroscopic measurements were re-conducted to investigate the response due to thermal aging and to identify any zones of preliminary micro-damage on the tubular geometry (Dataset 2). Further cyclic aging was then conducted, and a final set of piezospectroscopic measurements was evaluated for comparison (Dataset 3).

2. Experimental procedure

2.1. Experimental setup and test protocol

The investigation was conducted on a TBC system deposited on an Inconel 100 superalloy substrate. The TBC was comprised of a 7 wt.% Yttria partially stabilized Zirconia (YSZ) top coat and a NiCoCrAlY bond coat (BC), both deposited via EB-PVD. The deposition method provides a columnar structure of the YSZ top coat, resulting in strain tolerant behaviors [33,34]. The specimens were designed to incorporate the application of internal coolant, thermal loads, and mechanical loads and used for in-situ synchrotron X-ray diffraction measurements described elsewhere [15,31]. As such, the sample was designed with a tubular geometry with a substrate inner diameter 4 mm and outer diameter 8 mm. The YSZ ceramic top coat and NiCoCrAlY metallic bond coat had an as-coated thickness of 240 μm and 80 μm, respectively. The coated length was 102 mm of the full length of 160 mm. The design and manufacturing of specimens was conducted at the German Aerospace Center (DLR) in Cologne, Germany. A schematic of the loading conditions and diffraction measurements is presented in Fig. 1a. Specimens were heated to an exterior temperature of 1000 °C with simultaneous internal cooling to impose a thermal gradient across the coating while a 30 μm beam passed through the coating. This is illustrated in Fig. 1b and c. A combination of the focusing of the heater lamps over the sample length, the internal cooling and heat flux to the specimen's clamping grips, results in a thermal gradient which also evolves with the highest temperatures in the central section of the sample where X-ray data was collected. This is likely to create a variation in TGO development within and outside the central heating zone. The thermal condition of external heating and internal cooling over the cross-section and length of the layers is represented in a schematic in Fig. 1d. The measurements have revealed in-situ strain evolution for the bond coat and YSZ layers. The current study compliments and extends the synchrotron measurements [15,32] by providing valuable information on the TGO layer, identifying any variations indicating non-uniform thermal gradient mechanical loading, and to prove the location of the X-ray diffraction measurements was uniform and viable for study.

The stress state was influenced by the prior complex thermal loads for a high temperature duration of 17 h and the mechanical loading. Photoluminescence spectroscopy measurements were then taken to map the stress state spatially over the cylinder. To conduct the photoluminescence measurements, a green 532 nm diode laser with 19 mW of power was utilized to excite a piezospectroscopic response. An exposure time of 4 s was used to optimize the collection, and the calibration was conducted with a Neon–Argon source lamp. The expected uncertainty was ±0.030 nm root mean squared (RMS) with the calibration. A Princeton Instrument Acton Series 2150 spectrometer with a 1200 grating/mm grating was utilized in conjunction with a fiber optic probe to collect the piezospectroscopic data. A schematic of this can be seen in Fig. 2a. For the early developing oxide, four horizontal snake scans of 2000 points each were collected to produce a high resolution map. The resolution in the vertical and horizontal scan direction measured 400 μm, with 100 vertical scan rows and 20 horizontal scan columns. This covered an area of 40 mm by 8 mm and spanned the entire diameter of the sample. After each scan, the sample was turned 90°, which provided complete 360 ° of measurements plus overlap of two faces. It has been reported in literature that small spot sizes below 2 μm fall within the range of individual crystallites and can therefore result in variances due to the anisotropy of mechanical and thermal properties of α alumina [35] at that scale. In this study, the laser spot size was large enough to average the crystal grains effectively.

The scan was focused on the midsection of the primary heated zone and upward to the top of sample outside of this zone. This was designed to measure the regions of variation induced by slight changes in thermal loading and interactions with the induced cooling flow on the inner wall of the tubular sample [36]. The scan was broken into four scanning face segments with overlap to reduce the error associated with the extremities of the map. After the analysis revealed that the 90 ° scan procedure's overlapping data did not have significant variations in the stress profile's mean or standard deviation due to laser incidence angle, the presented scans feature only two faces 180° apart which assist in clearly showing the spacial stress profile variations. For clarity, the comparison of the statistical difference between the inclusion of the overlapping spacial data and the presented circumferential axis images is provided in Fig. S1.

Fig. 2b schematically illustrates the characteristic peaks R1 and R2 from Cr^{3+} doped alumina [37] and how they shift due to compressive stresses. To ensure that the influence of depth of focus was not significant, a separate experiment was designed by varying the depth of focus over a distance of 2400 μm at a spatial resolution of 10 μm. The measurements from this test are plotted in Fig. 2c which revealed small variation of approximately 13 MPa over the varying focus distance. This confirmed that the geometry of the sample in conjunction with the YSZ top coat does not significantly alter the alumina emissions with respect to focusing distance. As such, high resolution spectral contour maps could be produced for each loading history condition. Table 1 presents the full cycling history and when the three datasets were collected. Following piezospectroscopic measurements of the early TGO with thermal gradient and mechanical fatigue (TGMF) loading (Dataset 1), the specimen was placed in a furnace for long duration isothermal aging. The isothermal aging was

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