Scripta Materialia 115 (2016) 100–103

Contents lists available at ScienceDirect

Scripta Materialia

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

Three-dimensional displacement mapping of diffused Pt thermal barrier coatings via synchrotron X-ray computed tomography and digital volume correlation

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ARTICLE INFO

Article history:
Received 17 September 2015
Received in revised form 18 October 2015
Accepted 19 October 2015
Available online 25 January 2016

Keywords:
Thermal barrier coating
Three-dimensional tomography
Synchrotron radiation
Cyclic oxidation
Digital volume correlation

ABSTRACT

A progressive study of the three-dimensional deformation field within a γ/γ′ thermal barrier coating following cyclic oxidation at 1200 °C is presented, observed using synchrotron X-ray micro-computed tomography and analysed by digital volume correlation. Oxide thickening and bond coat creep displacements are quantified as a function of exposure time at temperature. Linear gradients of these displacements are measured both in-plane and normal to the oxide layer. The first thermal cycle shows the most displacement changes; destructive sectioning confirms the DVC-calculated displacement magnitudes.

Thermal barrier coatings (TBCs) applied to gas turbine components in both aerospace and land-based applications allow increased turbine inlet temperatures and fuel efficiency. Full exploitation of TBCs and prediction of the remaining useful life is limited by an incomplete understanding of TBC failure mechanisms. Typical current-generation diffusion coating systems consist of an yttria partially-stabilised zirconia topcoat, an alumina thermally grown oxide (TGO) and an aluminium-rich metallic bond coat. At operating temperatures, oxidation-induced growth stresses and mismatches in thermal expansions of these constituents generate residual strains [1], which may eventually lead to spallation of the thermally protective topcoat and/or the TGO.

The most commonly used technique, to date, for monitoring the evolution of TGO residual stresses is photo-luminescence piezospectroscopy (PLPS) [2]. Although PLPS allows imaging of production and in-service TBCs, the key limitations of the technique are an inability to resolve out-of-plane strains and a limited spatial resolution (on the order of 20–50 μm) due to beam scattering within the topcoat. Other approaches utilising synchrotron X-ray diffraction (XRD) [3–5] have recently been used to measure elastic strains within TBC layers. The through thickness averaging characteristic of this 2-dimensional (2-D) method however, does not allow identification of local out-of-plane strains. Other attempts to measure local strains in TBCs have involved the use of neutron [6] diffraction that restricts mapping in 3-dimensional (3-D) space. The importance of out-of-plane strains and total deformation, either neglected or only partially explored by the aforementioned techniques has been underscored by failure prediction models [7]. One approach to obtaining full-field 3-D displacement and strain fields, as pursued in this contribution, is to combine a 3-D volumetric imaging technique such as X-ray computed tomography [8] or laminography [9] with a high precision measurement technique such as digital image correlation [10].

Digital image and digital volume correlation (DIC and DVC, respectively) are 2-D and 3-D image analysis techniques that map relative displacements across a time-dependent sequence of images. DIC and DVC divide each data set (i.e., images) into smaller subsets, commonly known as interrogation windows. By maximising the correlation coefficient for each interrogation window between successive images, the relative displacement and deformation of each interrogation window is calculated. The computed displacement field can be used to derive total strain fields, from which the position of strain-influencing features such as cracks [11], for instance, may be inferred. It is noteworthy that

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http://dx.doi.org/10.1016/j.scriptamat.2015.10.033
1359-6462/

the inputs are digital images and the technique is consequently independent of the image acquisition technique and hence length scale [12]. Additionally, displacements can be computed beyond the resolution of the imaging technique (i.e., sub-pixel and sub-voxel, respectively) [13]. DIC techniques have previously been used to characterise the mechanical properties of TBCs [14] but were limited to 2-D surface imaging and lacked the capability of probing internal volumes.

In the present work, DVC was coupled with high resolution synchrotron X-ray absorption computed micro-tomography to study, in a near in-situ fashion, the progressive development of the oxidation induced displacement field within a TBC system undergoing cyclic oxidation. The TBC system examined was the second-generation single crystal nickel superalloy CMSX-4, with a diffused platinum γ/γ′ bond coat [15]. The ceramic topcoat was a 135 μm thick electron beam–physical vapour deposited (EB–PVD) yttria partially stabilised zirconia (7-YPSZ) coating. Cylindrical specimens, 500 μm in diameter, were prepared from turbine components. These samples were thermally exposed in a horizontal tube furnace in laboratory air for 20-hour cycles at 1200 °C from the as-received state. Following removal from the furnace at the end of each exposure period, the samples were allowed 20 min to reach the room temperature of 21 °C (without forced cooling) before imaging via synchrotron X-ray micro-tomography. Following completion of each scan, the samples were returned to the furnace for the next 20-hour exposure period. This experimental schema allowed a near in-situ imaging of the same specimen as a function of time at temperature.

The synchrotron X-ray micro-tomography was carried out at the I12 Joint Engineering, Environmental and Processing (JEEP) beamline [16] at the Diamond Light Source (UK). A monochromatic beam of 53 keV was used in absorption contrast configuration, with a camera to sample distance of 300 mm which provided some phase contrast; the PCO 4000 camera with a field of view of 3.6 × 2.4 mm delivered a nominal pixel resolution of 0.9 μm. Samples were positioned such that the beam was approximately parallel to the planar interface of the TBC layers. The cylindrical specimen geometry allowed uniform beam penetration to minimise reconstruction artefacts. The tomography scans were over 180° with 0.06° steps between radiographs, with an exposure time of 3.0 s per step. Back-filtered projection reconstruction was carried out using the in-house reconstruction algorithm at I12 [17]. Finally, the grey-scale distributions (down-sampled to 8 bits) of the reconstructed tomographs were normalised relative to the substrate bulk grey-level of the as-received condition, prior to image correlation analysis.

Reconstructed planar tomography sections (Fig. 1a and b) allowed direct observation of TBC microstructure evolution, at the same location within the sample, as a function of exposure time at temperature. The different TBC layers were discernible owing to the density-dominated differences in relative X-ray attenuation between the topcoat (3.960 cm^2/g), alumina TGO (0.276 cm^2/g), bond coat (4.422 cm^2/g in the as-received state), the substrate (2.417 cm^2/g) and air (0.201 cm^2/g); all attenuations calculated at 53 keV using WinXCom [18]. Some regions of the TGO were observed in the as-received case while other regions of the TGO (measured at 0.3–1.1 μm metallographically) fell below the detectable resolution limit at 0.9 μm voxel size. Within the bond coat, entrapped alumina particles attributable to the grit-blasting process during coating manufacture (grit line) were also observed. The boundary between the γ′ dominated lamellar regions of the bond coat was clearly visible against the more strongly attenuating (i.e., darker) γ phase of the bond coat.

Following 40 h of exposure (two 20-h periods) of the same specimen at 1200 °C (Fig. 2b), thickening of the TGO was observed; in independent samples treated identically, the TGO thickness was measured between 2.6 and 4 μm. Bond coat phase transformation was also

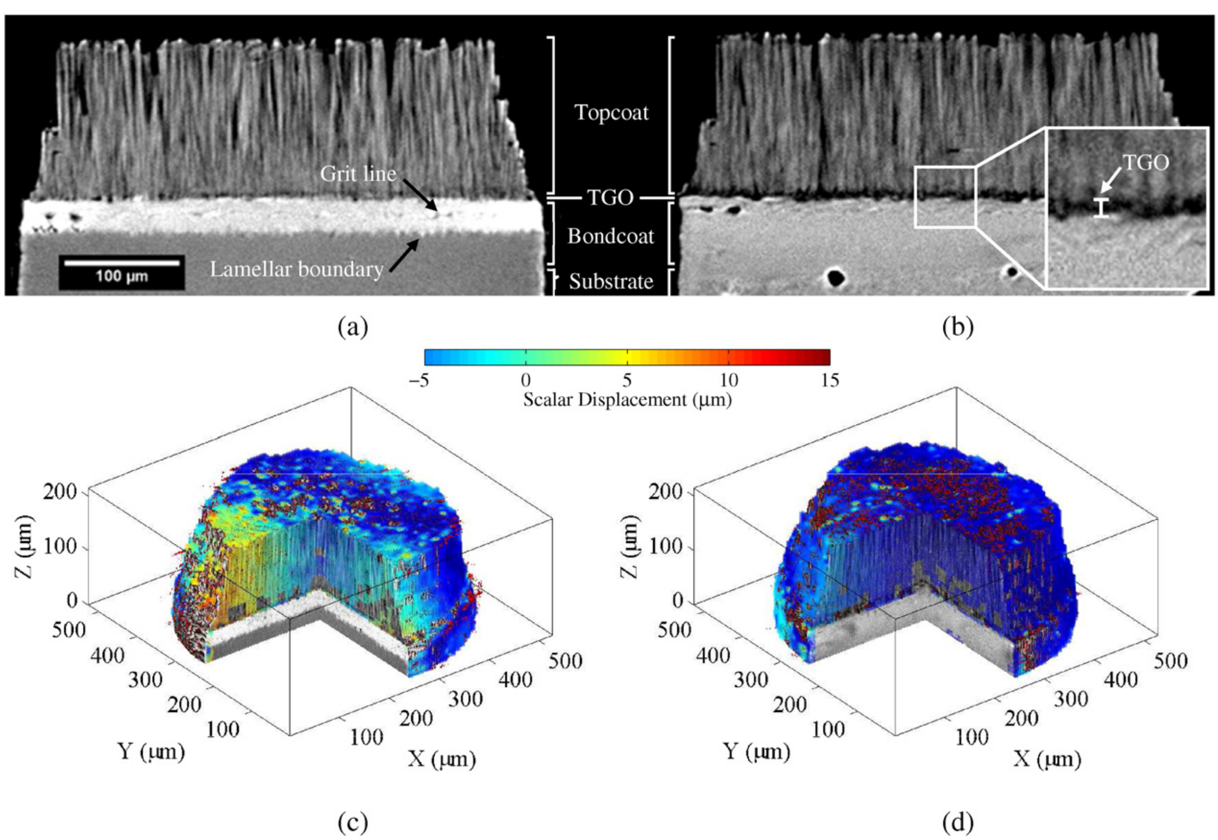

Fig. 1. Reconstructed sections of TBC samples in (a) as-received condition and (b) following 40 h at 1200 °C (note that the X-ray attenuation of the TGO is similar to air; both appear dark compared to the substrate); and three-dimensional DVC computed scalar displacement field showing the total magnitude of 3D displacements for (c) time-steps one and two (i.e., as-received and 20 h) overlaid onto as-received reconstruction and (d) 20 h and 40 h overlaid onto the reconstruction after 20 h at 1200 °C. Please note that 'scalar displacements' were calculated from magnitudes of 3-D Cartesian point displacements of combinatorial X-ray attenuation data.