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Influence of isothermal and cyclic oxidation on the apparent interfacial toughness in thermal barrier coating systems

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ABSTRACT

In thermal barrier coatings (TBCs), the toughness relative to the interface lying either between the bond coat (BC) and the Thermal Grown Oxide (TGO) or between the TGO and the yttria stabilized zirconia topcoat (TP) is a critical parameter regarding TBCs durability. In this paper, the influence of aging conditions on the apparent interfacial toughness in Electron Beam-Physical Vapor Deposition (EB-PVD) TBCs is investigated using a specifically dedicated approach based on Interfacial Vickers Indentation (IVI), coupled with Scanning Electron Microscopy (SEM) observations to create interfacial cracks and measure the extent of crack propagation, respectively.

1. Introduction

Thermal barrier coatings (TBCs) are typically used in key industrial components operating at elevated temperature under severe conditions such as gas turbines or aero-engines, to effectively protect and isolate the superalloy metal parts, for instance turbine blades, against high temperature gases. Even though TBCs allow drastic improvement of component performance and efficiency [1,2], thermal strains and stresses resulting from transient thermal gradients developed during in-service exposure limit the durability of the multi-material system. TBCs exhibit complex structure and morphology consisting of three successive layers, deposited or formed on the superalloy substrate (Fig. 1), i.e. (i) the bond coat standing as a mechanical bond between the substrate and the topcoat; (ii) the Thermally Grown Oxide (TGO), an Al_2O_3 scale that forms initially by pre-oxidation of the alumina-forming bond coat then slowly grows upon thermal exposure to protect the substrate from further high temperature oxidation and corrosion; (iii) The ceramic topcoat (TC), made of yttria-stabilized-zirconia (YSZ), the so-called thermal barrier coating itself whose role is mainly to insulate the superalloy substrate from high temperatures.

Electron Beam Physical Vapor Deposition (EB-PVD) and Air Plasma Spray (APS) are the two major coating processes implemented industrially for depositing YSZ. They generate different morphologies and microstructures and consequently different thermal and mechanical properties. The columnar structure, typical of the EB-PVD deposition, shows an optimal thermal-mechanical accommodation of cyclic stress resulting in high lateral strength. However, elongated (high aspect ratio) inter-columnar spaces roughly normal to the TBC, assist thermal flux conduction and penetration through the top-coat, which detrimentally increases the thermal conductivity of the system which can reach 1.6 W/m·K. APS TBCs are characterized by a lamellar structure, intrinsically much more efficient in terms of thermal insulation (conductivity as low as 0.8 W/m·K) but less resistant to in-plane cyclic mechanical loading.

Regardless of the coating process, TBCs can suffer in-service damage as a consequence of the synergetic effect related to mechanical stress, high temperature and thermally activated growth of interfacial alumina. Failure can either occur cohesively within the top coat for APS TBCs or adhesively at interfaces between successive layers in EBPVD TBCs. Degradation of such systems usually occurs through the spallation of the topcoat resulting from severe delamination either at the BC/TGO or the TGO/TC interface. The resistance to spallation is intimately related to the capacity of interfaces of the complex TBC system to sustain crack initiation and propagation, which can be evaluated by measuring the interfacial

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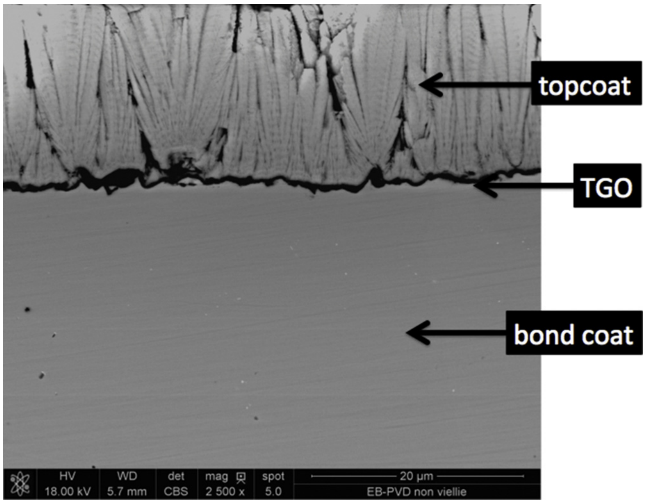

Fig. 1. SEM micrographs in cross-section of an EB-PVD TBC specimen.

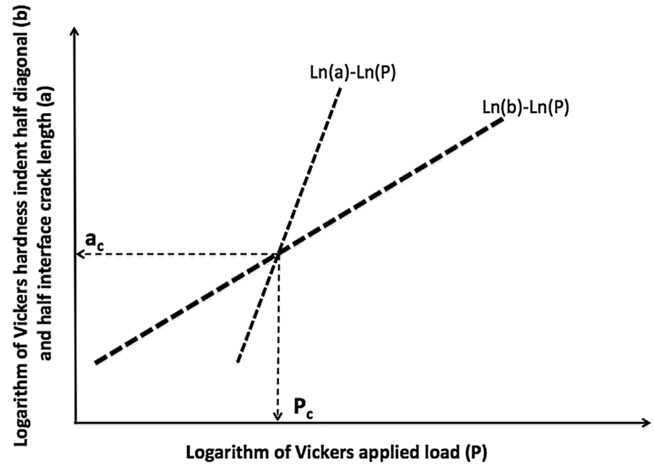

Fig. 2. Schematic representation of the intercept graphical method to determine the critical load required to generate interfacial crack [Ln(a) and Ln(b) are, respectively, plotted versus Ln(P)].

toughness. Several methods have been proposed to achieve interfacial fracture toughness measurement for various substrate/coating systems, including "four point bending test" [3], "barb test" [4], "buckling test" [5], "micro-bending test" [6] and various indentation techniques [7–11]. This paper proposes to implement the Vickers hardness technique to estimate the interfacial toughness in EB-PVD TBCs as well as its evolution upon various isothermal and cyclic aging conditions. As a matter of fact, aging may provoke microstructural changes and residual stress development prone to enhance crack initiation and propagation. A tentative correlation between the conditions of aging, the induced microstructural changes and the concomitant evolution of toughness, necessary to understand and predict the durability of TBC systems, is detailed.

2. Materials and testing conditions

TBC systems processed by EB-PVD (150 µm thick), are provided by SNECMA-SAFRAN. Topcoats and bond-coats are industrial standards, respectively made of yttria stabilised zirconia (namely ZrO_2-8 wt.% Y_2O_3) and β-(Ni,Pt)Al. Substrates are AM1 single crystal Ni-base superalloy disks, with a diameter of 25 mm and a thickness of 2 mm. All specimens are initially pre-oxidised to promote the growth of a thin protective Al_2O_3 scale. Samples are cut, polished and subsequently aged using various oxidation conditions prior to interfacial indentation. In addition to the as-deposited condition, two series of results are analyzed separately. The first series is relative to isothermal oxidation, following 100 h exposure at 1050 °C, 1100 °C and 1150 °C respectively. As the exposure time is kept constant, the influence of the oxidation temperature can be specifically analysed. The second series, performed at a given temperature, (1100 °C) is dedicated to compare isothermal and cyclic oxidation behavior. Here again, the hot time at 1100 °C (i.e., 100 h), is the same for both tests. Fig. 1 shows the typical cross-sectional microstructure of an initial as-deposited EB-PVD TBC. Note that, after aging, a slight additional grinding is often required to prepare thoroughly the surface for interfacial indentation.

3. Interfacial indentation test

Various types of interfacial or surface indentation tests exist. They are performed either on the top surface of specimens, normal to the coating [12], or on cross-section, either within the substrate close to the interface [13] or at the interface between the substrate and the coating [9]. The latter, further developed in [14], employs a pyramidal Vickers indenter and can be applied for a large range of coating thicknesses (greater than ~100 µm). Typically, it is specifically used for investigating adhesion of TBC systems [7,8,14,15]. The principle of interfacial indentation is to accurately align one diagonal of the Vickers pyramid with the interface between the substrate and the coating while loading the system to hopefully generate the local delamination of the coating. In this case, resulting from the application of a high enough indentation force, an induced crack with roughly semi-circular shape instantaneously propagates. For a given aging condition, each indentation force P greater than a critical force P_c that must be estimated, generates a crack with radius a and an indent imprint with radius b. P_c and correlatively the critical crack length a_c can not be determined using straightforward measurements but graphically correspond to the coordinates of the intercept between the apparent hardness line Ln(b)–Ln(P) showing the evolution of the imprint size versus the indentation force (master curve), and the Ln(a)–Ln(P) line giving the evolution of the crack size versus the indentation force (Fig. 2). The apparent interfacial toughness (K_{ca}) is calculated as a function of the critical values according to the following relationship:

$$K_{ca} = 0.015\frac{P_c}{a_c^{3/2}}\left(\frac{\left(\frac{E}{H}\right)_B^{1/2}}{1+\left(\frac{H_B}{H_T}\right)^{1/2}}+\frac{\left(\frac{E}{H}\right)_T^{1/2}}{1+\left(\frac{H_T}{H_B}\right)^{1/2}}\right) \quad (1)$$

where B and T stand, respectively, for the bondcoat and the topcoat.

In standard TBC systems, the thickness of the TGO is generally low, typically ranging from 0.7 µm (after initial pre-oxidation) to 7 µm (after long term exposure at high temperature), and is in any case much lower than the imprint of the indent resulting from the force range used for coating delamination purpose (Fig. 3). As a consequence, the influence of the TGO in terms of mechanistic issue is deliberately neglected [7]. However, it will be shown later that the thickness of the TGO has an influence on the location of the crack initiation and subsequently the propagation path.

4. Determination of Young's modulus and hardness

Young modulus E and hardness H strongly depend on the chemical composition and the process-induced microstructure of materials. In multi-materials such as TBCs, those mechanical characteristics change as composition changes throughout the entire thickness of the multi-layered system. If the nature of the single crystal substrate is essentially not affected by the overall deposition process, the morphology and microstructure of the top coat and to a lesser extent of the bond coat are strongly related to processing