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Ceramics International 39 (2013) 475–481

CERAMICS INTERNATIONAL

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# Comparative study on effect of oxide thickness on stress distribution of traditional and nanostructured zirconia coating systems

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Received 24 April 2012; received in revised form 17 June 2012; accepted 17 June 2012

Available online 23 June 2012

## Abstract

Numerical based assessment of traditional and nanostructured yttria stabilized zirconia (YSZ) thermal barrier coating systems (TBCs) has been carried out with varying thickness of thermally grown oxide (TGO). Radial, axial and shear stresses are determined for both coatings and are presented in comparison with few novel and interesting results. Elastic strain energy for TGO failure assessment is determined from calculated stress within TGO for varying thickness. Radial stresses at TGO/bond coat interface and maximum axial stresses in nanostructured zirconia coatings are found to be lower than in traditional YSZ up to a critical TGO thickness of 6 –7 μm, after which stresses in nanostructured zirconia coatings increase considerably. However, radial compressive stresses in nanostructured TBCs are lower in all TGO thickness cases and shear stresses are slightly higher with relatively more prominent difference at high oxide thickness.



*Keywords:* Thermal barrier coatings (TBCs); Thermally grown oxides (TGO); Interfaces; Residual stress

## 1. Introduction

Thermal barrier coatings (TBCs) are layer systems deposited on thermally highly loaded metallic components, as for instance in gas turbine engine blades and vanes to allow higher operating temperatures and thus to increase their efficiency and durability [1–5]. Demand for enhanced jet engine efficiencies has led to significant increase in combustion temperatures and operating pressures. These requirements have proved to be a big driving force to improve the thermal barrier coating technology, such as novel compositions, production techniques and improvement in microstructure, and physical and mechanical properties of TBCs. TBCs have typical duplex type configuration with an outer layer of compliant, porous zirconia, a film of dense aluminum oxide that grows at high temperature, a metal alloy bond coat layer from which the oxide film grows, and a thick superalloy substrate [6]. Preparation of nanostructured zirconia coating has become an active field in thermal spray industry in the last decade [7–10]. Nanostructured coatings are attractive because of their potential superior mechanical and physical properties over traditional coatings [11, 12]. The durability of thermal barrier systems is governed by a sequence of crack nucleation, propagation and coalescence events that depends on the stress state within TBC with the growth of thermally grown oxides (TGO) [6]. Thickness of TGO that is a function of thermal cycling is an important consideration to analyze the stress state in TBCs and thus plays an important role in failure studies consequent to TBC's structural integrity assessment [6,13–17]. Different studies on durability of nanostructured YSZ as compared to traditional YSZ have been reported [18–20] that describe the effect of exposure time on TGO thickness in traditional and nanostructured zirconia coatings. However, the scope of these studies is limited to the experimentally recorded data in each particular study and it still needs some quantitative comparative analysis in some methodological way, paying special attention to TGO

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http://dx.doi.org/10.1016/j.ceramint.2012.06.051

growth. Moreover, to identify the potential use of nanostructured YSZ in comparison with traditional zirconia coatings with TGO growth, change in stress state during oxide growth, its relation with durability and determination of critical thickness in case of nanostructured zirconia coatings are focused in this study. To cope with these arising queries in a time permissive manner, a finite element based numerical study has been carried out for traditional and nanostructured TBCs over a range of TGO thicknesses (1–12 μm). By a sequential simulation scheme with about 24 formulations for varying TGO thickness in both types of coatings, stress state at the TGO/bond coat interface, within TGO and in overall TBC system is determined, summarized graphically and compared with some novel observations.

## 2. Finite element model

### 2.1. Geometric model and FEM mesh

A circular disc specimen is considered having four layers; topcoat 200 μm, TGO 1–12 μm (varying parameter), bond coat 150 μm and substrate with thickness of 2 mm. Axisymmetric case is taken into account in the radial and through thickness directions allowing the problem to be reduced to a two-dimensional case for easy computation. A schematic illustration of the model is shown in Fig. 1. A coupled thermo-mechanical finite element solution has been employed using 2-D coupled field element PLANE223 that has eight nodes with up to four degrees of freedom per node. Due to the regular shape of the sample a mapped grid is selected for mesh construction and the geometry consists of approximately 20,000 elements. Due to the relatively small area of TGO, the regions neighboring the TGO and TGO itself are finely meshed to enhance the sensitivity to the rigorous change of stress distribution in this region.

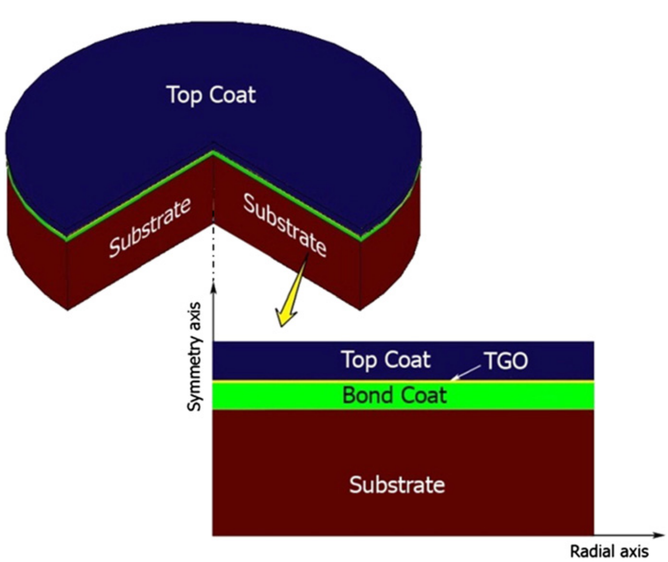


Fig. 1. Schematic illustration of coating specimen.

### 2.2. Materials parameters

The model has four layers: Ni-based superalloy substrate, NiCrAlY bond-coating, $Al_2O_3$ thermally grown oxide (TGO) and ceramic top coat. Thermal, mechanical and physical parameters of the materials used in the analysis are given in Table 1 [21,22,23].

### 2.3. Boundary condition

Symmetric boundary conditions are used due to the axisymmetric configuration. All layers are considered homogeneous and isotropic. The specimen is cooled from temperature 1050 °C to room temperature (25 °C) in 300 s time. Heat convection is imposed on the top and side of the sample while bottom of the specimen is assumed thermally insulated. The mechanical stress is induced during the cooling period of the thermal cycles. Phase transformation and creep mechanisms which result in stress-relieving and can effect stress state in TBCs are assumed inactive during the simulation. Peak radial tensile and compressive stresses that exist at the TGO/bondcoat interface and within TGO respectively, maximum axial stress and shear stresses within TBCs for both types of coatings are determined.

## 3. Results and discussion

### 3.1. Radial stress variation

Fig. 2 shows the variation of maximum tensile radial stress with varying TGO thickness. This stress exists at the bondcoat/TGO interface near the edge of the specimen and is important as it may propagate any pre-existing defect at the interface to increase its extent and eventually may result in TBCs failure [24]. As illustrated in Fig. 2, the interfacial stress in nanostructured TBCs remains low up to a critical TGO thickness which in this case is 6 μm. After the critical thickness of 6 μm, stress in nanostructured TBCs starts changing and keeps on increasing up to a maximum TGO thickness of 12 μm considered in this study. Higher stresses in nanostructured TBCs after a critical thickness is a novel finding that may be an important consideration for future studies on structural analysis and failure assessment of nanostructured TBCs. This finding also does not contradict to the high durability of nanostructured TBCs reported by many other researchers as nanostructured TBCs are more resistant to TGO growth [19] and it seldom exceeds the critical limit of TGO thickness found in this study. It has also been reported that the nanostructured zirconia coating has larger adhesion strength than traditional zirconia coating [22] thus having more capability to withstand high stress state. Moreover, these maximum radial stresses exist at the bondcoat/TGO interface where these two phases are more exposed to described stress state than the top coat. Thus the approximation of the thermal cycle lifetime of nanostructured TBCs needs a good estimation of stress state development