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Mechanisms controlling the durability of thermal barrier coatings

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Abstract

The durability of thermal barrier coatings is governed by a sequence of crack nucleation, propagation and coalescence events that accumulate prior to final failure by large scale buckling and spalling. Because of differing manufacturing approaches and operating scenarios, several specific mechanisms are involved. These mechanisms have begun to be understood. This article reviews this understanding and presents relationships between the durability, the governing material properties and the salient morphological features. The failure is ultimately connected to the large residual compression in the thermally grown oxide through its roles in amplifying imperfections near the interface. This amplification induces an energy release rate at cracks emanating from the imperfections that eventually buckle and spall the TBC. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Background

1.1. The system

Thermal barrier coatings (TBCs) are widely used in turbines for propulsion and power generation [1–9]. They comprise thermally insulating materials having sufficient thickness and durability that they can sustain an appreciable temperature difference between the load bearing alloy and the coating surface. The benefit of these coatings results from their ability to sustain high thermal gradients in the presence of adequate back-side cooling. Lowering the temperature of the metal substrate prolongs the life of the component: whether from environmental attack, creep rupture, or fatigue. In addition, by reducing the thermal gradients in the metal, the coating diminishes the driving force for thermal fatigue. Both of these benefits can be traded off in design for greater component durability, or for reduced cooling air or for higher gas temperature/improved system efficiency. As a result, TBCs have been increasingly used in turbine engines. Successful implementation has required comprehensive testing protocols, facilitated by engineering models [9–12]. Expanded application to more demanding scenarios (Fig. 1) requires that their basic thermo-mechanical characteristics be understood and quantified. This need provides the opportunities and challenges discussed in this article.

There are *four primary constituents* in a thermal protection system (Fig. 2). They comprise (i) the TBC itself, (ii) the superalloy substrate, (iii) an aluminum containing bond coat (BC) between the substrate and the TBC, and (iv) a thermally grown oxide (TGO), predominantly alumina, that forms between the TBC and the BC. The TBC is the insulator, the TGO on the BC provides the oxidation protection and the alloy sustains the structural loads. The TGO is a reaction product. Each of these elements is dynamic and all interact to control the performance and durability.

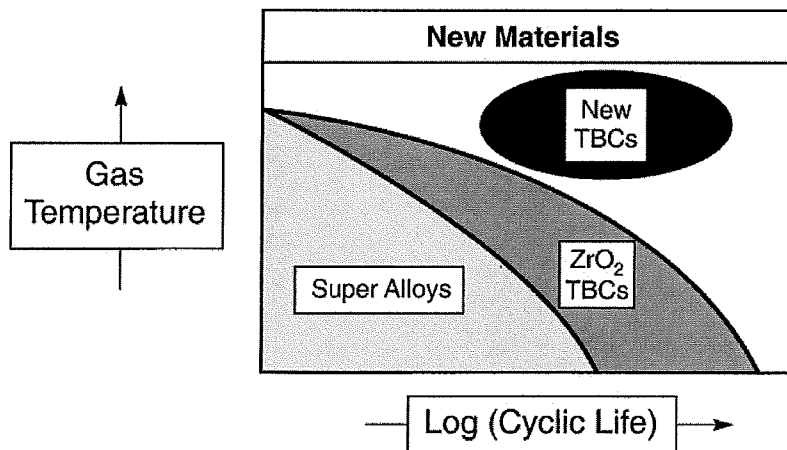


Fig. 1. Schematic indicating the operating domain for TBCs and the challenge for a new generation of materials.

The thermal barrier coating is a thermally insulating, “strain tolerant” oxide. Zirconia has emerged as the preferred material, stabilized into its cubic/tetragonal forms by the addition of yttria in solid solution. This material has low thermal conductivity ($\sim 1 \text{ W/m}^2 \text{ K}$) with minimal temperature sensitivity (Fig. 3) [13,83]. The thermal resistance at lower temperatures corresponds to a phonon mean free path governed by structural vacancy scattering. Complex oxides having even lower conduction are being investigated, but there is no affirmation of their viability as TBCs. Strain tolerance is designed into the material to avoid instantaneous delamination from the thermal expansion misfit. Two methods are used to deposit strain-tolerant TBCs. Electron beam physical vapor deposition (EB-PVD) evaporates the oxide from an ingot and directs the vapor onto the preheated component [2,5,14]. The deposition conditions are designed to create a columnar grain structure with multiscale porosity (Fig. 2) that provides the strain tolerance and also reduces the thermal conductivity (to about 0.5 W/m K , Fig. 3). Air plasma spray (APS) deposition is a lower cost alternative [15–17]. The deposition is designed to incorporate intersplat porosity and a network of crack-like voids that again provides some strain tolerance, while lowering the thermal conductivity.

The thermally grown oxide has a major influence on TBC durability [8–12,18–20]. The bond coat alloy is designed as a local Al reservoir (Fig. 2), enabling α -alumina to form in preference to other oxides, as oxygen ingresses through the TBC (which is

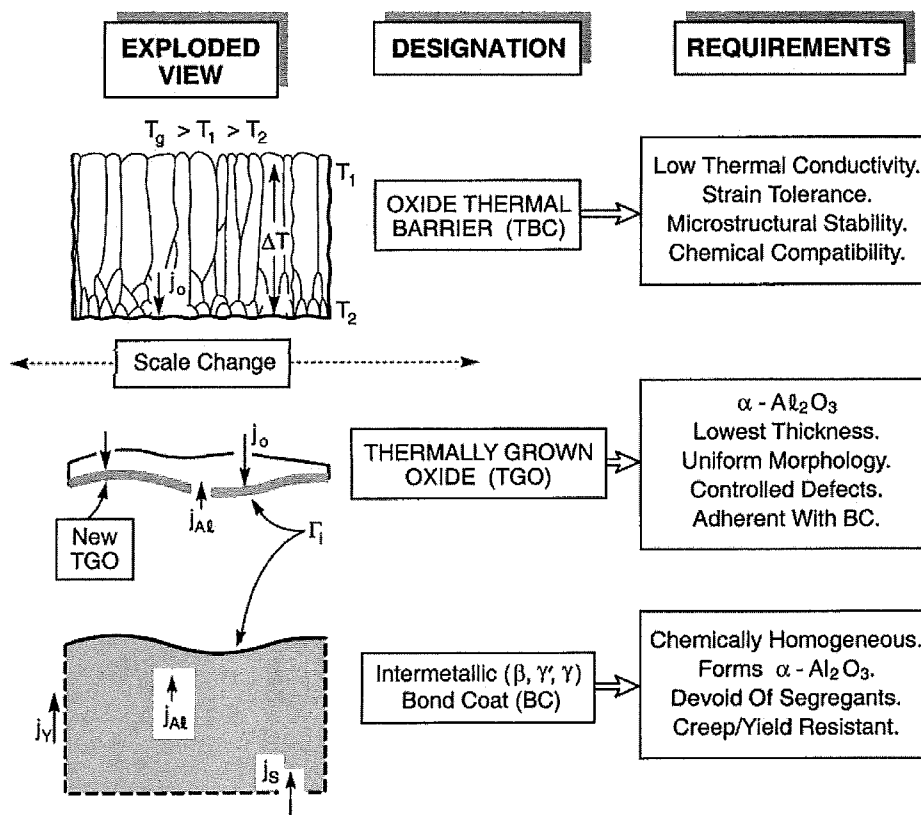


Fig. 2. The four major elements of a thermal barrier system: each element changes with exposure/cycling.

transparent to oxygen). Alumina is the preferred oxide because of its low oxygen diffusivity and superior adherence. This layer develops extremely large residual compressions (3–6 GPa, Fig. 4), as the system cools to ambient, primarily because of its thermal expansion misfit with the substrate (Fig. 5, Table 1) [21–27]. Stresses also arise during TGO growth [19,21]. They are much smaller (generally less than 1 GPa),

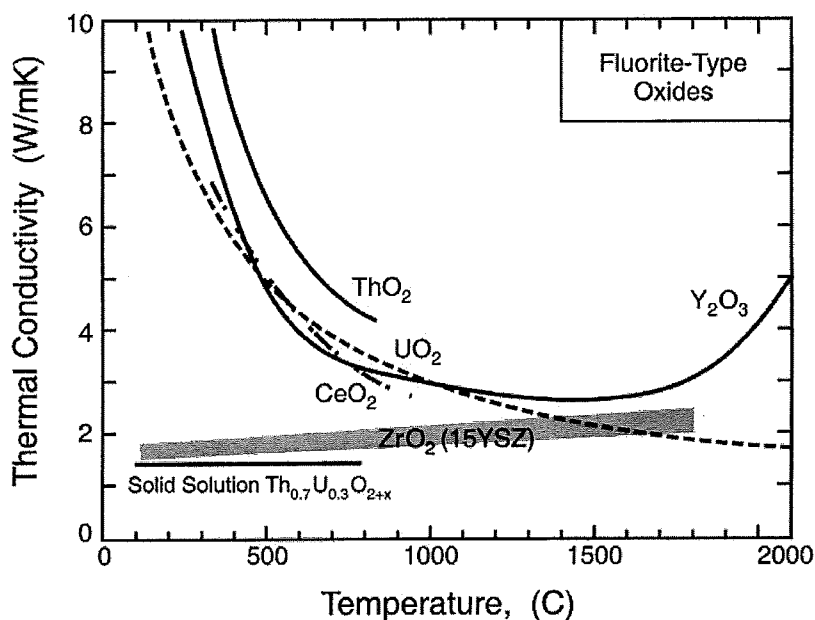


Fig. 3. The thermal conductivity of several insulating oxides illustrating the major role of solid solutions in affecting phonon transport.

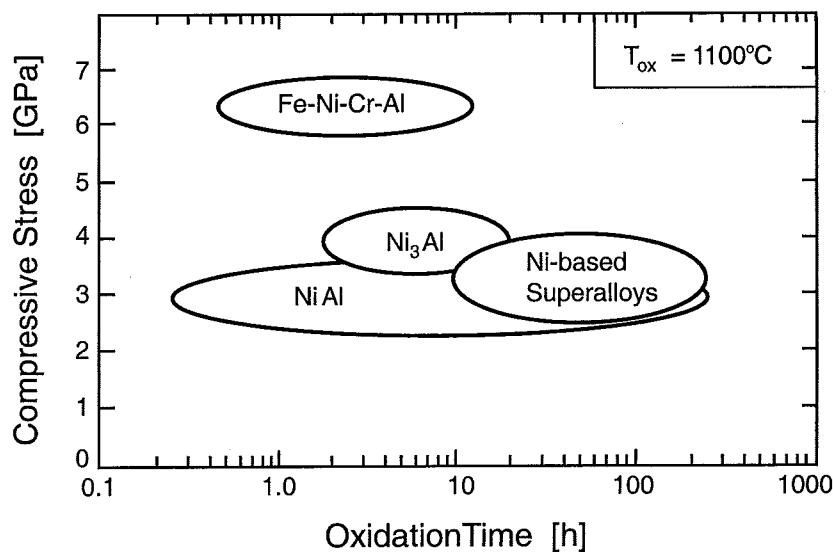


Fig. 4. Ambient residual compressions measured in the TGO developed on several alloy systems (after [21]).

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