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On the propagation and coalescence of delamination cracks in compressed coatings: with application to thermal barrier systems

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Abstract

Coatings subject to residual compression eventually fail by buckle-driven delamination. The phenomenon is most vivid in thermal barrier coatings (TBCs) used in gas turbines. The failure evolution commences with the formation of a large number of small cracks at geometric imperfections near the interface. These cracks spread upon thermal exposure, particularly upon thermal cycling, because of the formation of a thermally grown oxide (TGO) beneath the TBC, which introduces normal and shear stress near the interface. Experimental observations indicate that some of these cracks coalesce to form large-scale delaminations susceptible to buckling. The mechanics governing crack coalescence and the consequent failure are addressed in the present analysis.

A model is introduced that simulates stresses induced in the TBC by spatial variations in TGO growth. Energy release rates for cracks evolving in this stress field are determined. Two related scenarios are considered, which differ in the way the TGO shape evolves. In both, contact between the crack faces and the consequent wedging action is responsible for ultimate coalescence. The wedging force induces a mode I stress intensity that becomes infinite as the cracks coalesce. The consequence is that, for some TGO shapes, the energy release rate is always non-zero, with a minimum at a characteristic crack length. This minimum establishes a criterion for crack coalescence and failure.

Based on these insights, finite element simulations have been used to predict cyclic crack growth rates in a TBC system that correlate well with experimental observations.

Keywords: Coalescence; Crack; Delamination; Thermal barrier coating; Toughness

1. Introduction

Multi-layer thermal barrier systems (Fig. 1) fail by the propagation and coalescence of micro-cracks within the outer layer of yttria stabilized zirconia (YSZ) [1–19]. The micro-cracks are motivated by localized tensile stresses in the thermal barrier that arise because of the strain misfit between the thermally grown oxide (TGO) and the other layers [4,6,8,9,11,12]. While the specifics are system dependent, there are commonalities (Fig. 1). The micro-cracks initiate at multiple sites,

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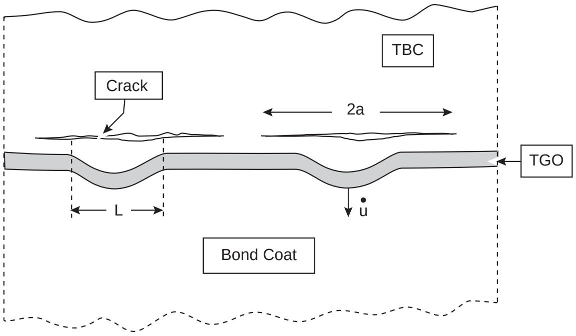

Fig. 1. A schematic of a crack configuration that arises in thermal barrier systems (see Fig. 2).

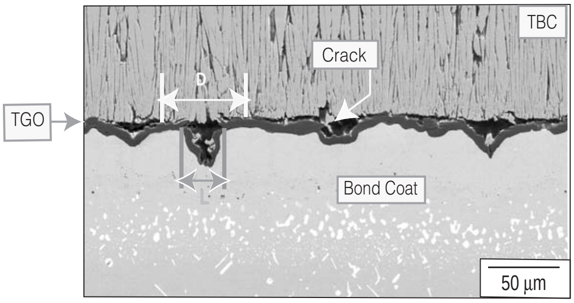

Fig. 2. A scanning electron image of a cross section of TBC system similar to Fig. 1 that has experienced 75% of its cyclic durability [9]. Note the undulations in the TGO and the cracks in the TBC just above the interface with the TGO.

either at or above the interface with the TGO [4,5,7,9,11,13]. They extend laterally from these sites as the system cycles. Eventually, a few adjacent micro-cracks coalesce into a crack large enough to exhibit large-scale buckling and spallation [4]. An example is illustrated in Figs. 1 and 2 [9]. In systems consisting of a Pt–aluminide bond coat and a columnar thermal barrier coating (TBC) made by electron beam physical vapor deposition (EB-PVD), the TGO exhibits a displacement instability directed into the bond coat. This displacement induces tensile stresses in the TBC above the instabilities (Figs. 1 and 2) [4–6,8–11], which cause cracks. Eventually, some of the cracks coalesce to cause failure.

In all cases, in the absence of cracks the TBC experiences an oscillating stress field with tension above the imperfections and compression outside. Accordingly, cracks that form have an energy release rate, G, that varies with micro-crack half-length, a, relative to imperfection wavelength, L. The objective is to determine the evolution of the energy release rate. Above the imperfection, where the stress is tensile, there is a rapid rise in G to a maximum [15]. This is followed by a decrease as the micro-crack front spreads into a region of compression and reverse shear. As neighboring cracks converge and coalesce, G attains a minimum, G_{min}. As the system cycles, the thickness distribution of the TGO evolves and G_{min} increases. This increase is promoted by a wedging force that arises where the crack faces are in contact. The cracks coalesce and cause failure when G_{min} reaches the fracture toughness of the TBC, $\mathrm{I}_{\mathrm{tbc}}$, at the appropriate mode mixity. The challenge is to gain a fundamental understanding of G_{min} sufficient to ascertain its dependence on the stresses and dimensions. The intent of the present study is to establish basic mechanics principles governing crack coalescence and to apply these to problems of the type indicated in Fig. 1.

The problems reside within the broad mechanics category of cracks extending within oscillating residual stress fields [15,20,21]. The special feature is that the cracks are parallel to a free surface and consequently no net force acts across the putative crack plane. This unusual situation requires a careful analysis of the crack tip intensities because the minimum energy release rates as the cracks approach coalescence are small relative to the peak. Contact between portions of the crack faces, which arises as the cracks spread, plays an essential role. It promotes mode I behavior in a situation wherein, otherwise, the energy release rate would vanish as the cracks coalesce. The mechanics problem for generating the pre-cracking stresses is as follows. Matter is inserted along a plane parallel to the surface with a thickness distribution that enables the ensuing residual stress to vary in a periodic manner (Fig. 3). This approach for creating stress closely duplicates that experienced by thermal barrier systems, which may be attributed to the periodic displacements caused by growth of the TGO [4].