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Calcium–magnesium–alumina–silicate (CMAS) delamination mechanisms in EB-PVD thermal barrier coatings

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Abstract

Thermal barrier coatings (TBCs) 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. TBC exhibit multiple failure modes. Among them, in-service erosion caused by the deposition of significant amount of calcium–magnesium–alumina–silicate (CMAS) at high temperature was found to be one of the most prevalent failure modes. The large thermal expansion mismatch between the CMAS and TBC and the extra strain energy stored in the CMAS layer can lead to delamination cracks between the TBC and bond coat (BC). In this study, the energy release rate and mode mixity of a propagating delamination crack are calculated by using the finite element analysis. The columnar microstructure of EB-PVD TBC is factored into the approach. The effects of CMAS layer thickness, mechanical and thermal properties are examined, and the steady-state energy release rates are compared with a theoretical model. Two failure mechanisms associated with CMAS deposition are analyzed: cracking within individual columns and spallation of a large TBC layer. It is believed that both mechanisms have contributed to the CMAS delamination failure. Failure criterions are derived which provide useful insights on how to improve the resistance of CMAS delamination.

Keywords: Thermal barrier coating; CMAS; Delamination; Energy release rate; Fracture toughness

1. Introduction

Thermal barrier coatings (TBCs) are widely used in turbine engines. They are regarded as one of the most successful innovations and applications of coatings in industry. Thermal barrier systems consist of a tri-layer (Fig. 1): the prevalent outer layer is yttria-stabilized-zirconia (YSZ), acting as the thermal barrier coating (TBC). A thermally grown oxide (TGO) exists between the TBC and a bond coat (BC) [1–4]. TBC exhibit multiple failure modes [1–3,5]. Prior assessments have focused primarily on modes governed by the energy density in the thermally grown oxide associated with thermal cycling, which causes failure by either large-scale buckling or edge delamination [1,5–9]; as well as modes related with foreign object damage (FOD) [10,11] and erosion [12,13] at high temperature, which causes material removal due to the ingestion of foreign particles during turbine operation. Among other failure modes that have not been widely documented, spallation caused by environmental surface deposits at working temperature is particularly important [13–15].

The study emphasizes TBCs produced using electron beam physical vapor deposition (EB-PVD), which have a strain tolerant columnar microstructure and the gaps are filled with high-porosity oxides (Fig. 1) [1]. At temperature in excess of 1150 °C, sand particles and debris ingested during operation become molten and adhere to TBC surfaces. During this process, calcium, magnesium, alumina, and silicate (CMAS) are incorporated in the molten phase, and the excellent wetting characteristics of CMAS enable the deposition to infiltrate the TBC microstructure. The addition of the CMAS layer changes the near-surface mechanical properties. Thereafter, upon cooling, the CMAS layer solidifies into a fully dense stiff domain (Fig. 2a)

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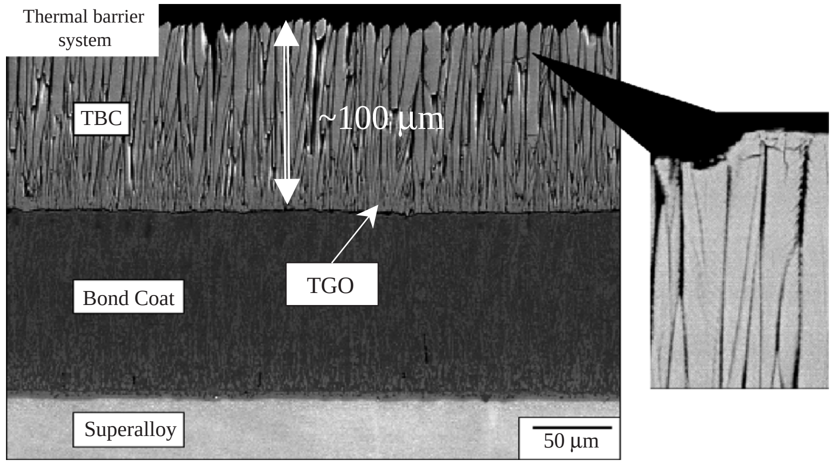

Fig. 1. The thermal barrier system consisting of several layers: the Thermal Barrier Coating (TBC), Thermally Grown Oxide (TGO), Bond Coat (BC), and the superalloy substrate [1]. Note the columnar microstructure of EB-PVD TBC and the gaps are filled with high porous materials.

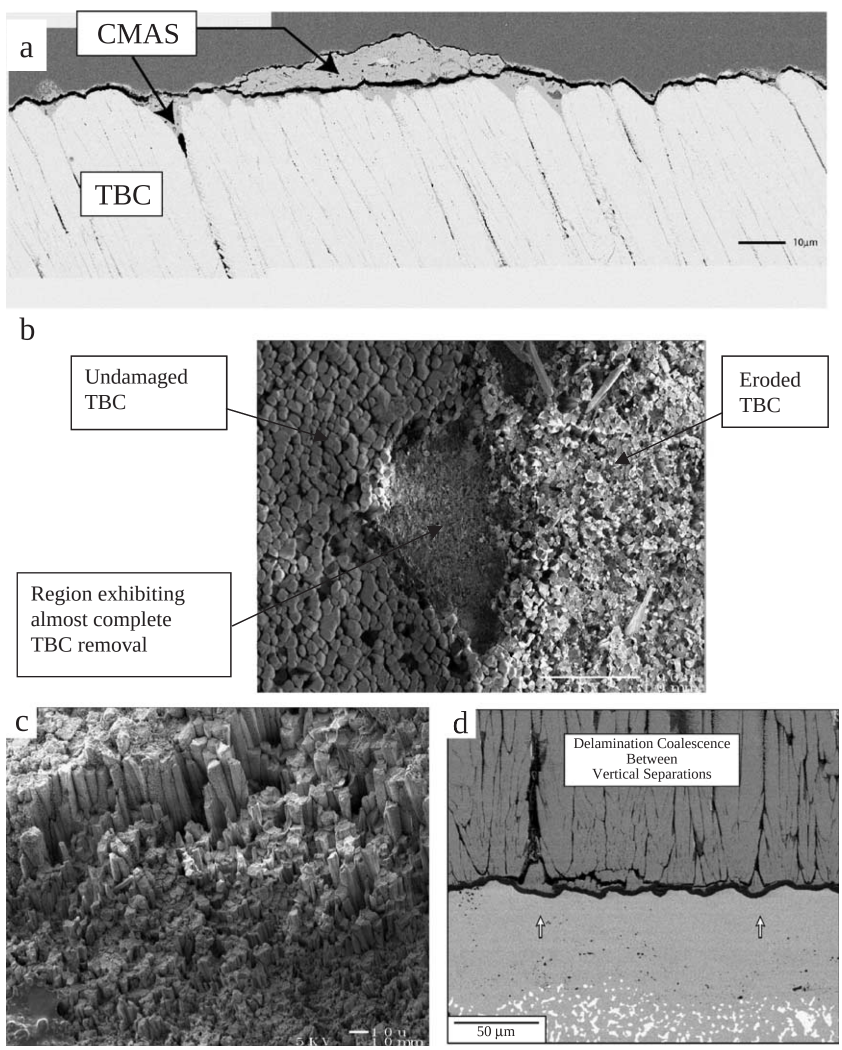

Fig. 2. Recent experimental observations [13]: a) CMAS deposits that penetrate between intact TBC columns; b) Center regions showing almost complete TBC removal caused by CMAS deposition (the right half of the specimen are eroded where the TBC columns are not completely removed); c) Side view of the spallation of TBC by CMAS deposition: in some regions the TBC columns are completely removed, whereas in other regions the eroded TBC columns show "terracing" effect; d) Vertical separations that form in the TBC due to sintering, which serve as internal edges to initiate delamination.