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Review

Progress update on failure mechanisms of advanced thermal barrier coatings: A review

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ABSTRACT

Thermal barrier coatings (TBCs) have proved to be a key technology in thermal stability and their use to achieve surface temperature reduction of the underlying super alloys surpass all other achievements in the field of material technologies that have taken place in last three decades. The technological advances in TBCs also make them suitable for wider engineering and defense applications. The performance of these multi-layered and multi-material systems, tailored for high temperature applications is closely linked to their microstructure evolution. The article presents a comprehensive review of various degradation mechanisms to which the TBC system is subjected during service life viz. hot corrosion, CMAS attack, oxidation, erosion, foreign object damage, sintering and phase transformations. Strategies to mitigate the adverse impact of the degradation mechanisms and the recent advances toward reduction in the thermal conductivity of TBCs have also been discussed. The emphasis of this review is on the relationship between the properties and the microstructure of TBCs for better understanding of their life limiting mechanisms to assist developments in advanced and novel TBCs for engineering applications.

Contents

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1. Introduction

Thermal barrier coatings (TBCs) are multi-layered and multi-material coating system, used to lend thermal protection from hot gases in turbines and engines, hence lower the surface temperature of the substrate components [1,2]. The conventional TBC system consists of three layers over the super alloy substrate; the metallic bond coat (BC), the intermediate thermally grown oxide (TGO) and the ceramic top coat (TP). All these layers have distinct physical, mechanical and thermal properties, which are strongly affected by the processing conditions [3]. TBCs are being used on turbine engine components such as combustors, turbine blades and nozzles to achieve higher operating temperatures which consequently result into improved efficiency, increase in thrust to weight ratio, reduced emissions and reduction in air cooling needs.

TBCs have proven to be a crucial technology in thermal endurance and their use along with the internal air cooling for the super alloy substrates can provide surface temperature reduction up to 300 °C [4]. These temperature benefits using TBCs surpass all other achievements in the field of material technologies, including single crystal Ni base super alloys that have taken place in last three decades. Over the years, the TBCs have evolved from just insulating layers to complex designs. A number of factors such as heat flux, heat transfer coefficients, backside cooling, part geometry and location, coating thickness and its thermal conductivity, determine the magnitude of temperature reduction of the substrate. The continuous efforts to improve the efficiency of a gas turbine, have resulted into the operating temperatures to above 1300 °C, which necessitate thicker TBCs with its chemistry modification, along with a new cooling system [5–7]. The thickness of the top coat has progressively increased (in the range 600–2000 μm). With the increase in top ceramic coat thickness, the surface temperature of the TBC cooled components reduces at a rate of 4–9 °C per 25 μm [8–14].

Higher thermal efficiency is achieved in advanced diesel engines by insulating combustion system components. In SI engines, TBCs are typically deposited at the piston top surface near the crevice to lower knocking. TBCs are also used in the braking systems of automobiles to insulate the hydraulic components from heat. Though, the TBCs are typically applied to the metallic substrates, they can also be coated on composites, which has further stepped up their use for diverse defense applications. The extensive research work on TBCs undertaken for aerospace and defense applications also include the design of the rocket nozzles, nosecones, wings and stabilizers of hypersonic missiles. TBCs are also capable of playing a decisive role in enhancing the technological superiority of military tanks. They enable improvements in the cooling effectiveness of the components, which result in increased specific power and allow combustion at higher operating conditions, without the use of conventional cooling system in the turbine engine of a tank.

1.1. Scope of review

The article is aimed to review and summarize the technological advances on the vital aspects of TBCs, with emphasis on the relationship between their properties and the microstructure. The research work in this field is directed to improve the TBC atomic level properties to extend their survival under the hostile high temperature environment, to make them suitable for wider engineering applications. Various degradation mechanisms to which the TBC system is subjected during service life, in a gas turbine have been reviewed. The fallout of sintering with respect to the coating microstructure as well its properties at higher temperatures and the efficacy of nano-structured coatings to counter sintering has been discussed. Another degradation mechanism of TBCs is chemical attack such as oxidation, for which the selection of bond coat material plays a vital role. Oxidation behavior in the absence and presence of moisture and also the use of ultra-thin graphene protective coatings to counter oxidation has been discussed. Hot corrosion degradation mechanism and various approaches to enhance hot corrosion resistance of TBC system have been presented. Calcium–magnesium–alumina–silicate (CMAS) attack, wherein at temperatures greater than 1200 °C, the molten CMAS glass infiltrates into the porous TBC surface, is a major challenge to the material scientists. CMAS attack mechanics and the uses of alternative compositions to mitigate the damages are discussed. Evaluation of coatings with CMAS deposits infiltration and damage by impact and erosion have also been discussed. These degradation issues are examined independently in most of the research works, whereas during service life of TBCs, a number of degradation mechanisms occur simultaneously. The use of modulated TBC structures and ablative coatings for high temperature applications has been commented upon.

Failure modes of TBCs such as multiple surface cracking and interfacial delamination are discussed. Thermo-mechanical fatigue (TMF) methods for evaluation of service lifetime of TBC system, failure mechanism and lifetime modules of TBCs have also been discussed. Finally, the present challenges and the future research trends in this field are presented.

2. Sintering effects and residual stresses

2.1. Sintering effects on coating properties and microstructure

At high temperatures (>1000–1200 °C), additional mechanisms such as sintering and phase transformation, contribute to TBC failure. When deposited, the TBCs are porous. However, during their service life at higher temperatures, TBCs are subjected to sintering, thereby leading to densification and a rise in thermal conductivity [15]. At higher temperatures, sintering causes additional stresses in the coating due to mismatch of sintering rate and thermal expansion coefficient for the coating and the super alloy substrate. Appreciable microstructural changes accompany sintering, leading to changes in the coating properties [16–18]. Sintering of EB-PVD coatings occur in a manner similar to Rayleigh instability problem. However, the distance between the necks is shorter than the expected from Rayleigh theory [19]. The sintering of free standing ZrO_2 plasma sprayed coating has been characterized by measuring the shrinkage [20,21] and variations in the microstructural dependent properties like elastic modulus and bend strength [22].