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Review

Processing and design methodologies for advanced and novel thermal barrier coatings for engineering applications

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A B S T R A C T

Thermal barrier coating is a crucial thermal insulation technology that enables the underlying substrate to operate near or above its melting temperature. Such coatings bolster engineers' perpetual desire to increase the power and efficiency of gas turbine engines through increasing the turbine inlet temperature. Advances in recent years have made them suitable for wider engineering and defense applications, and hence they are currently attracting considerable attention. A thermal barrier coating system is itself dynamic; its components undergo recurrent changes in their composition, microstructure and crystalline phases during its service life. Nevertheless, the performance of multi-layered and multi-material systems tailored for high temperature applications is closely linked to the deposition process. The process improvements achieved so far are the outcome of increased understanding of the relationship between the coating morphology and the operating service conditions, as well as developments in characterization techniques. This article presents a comprehensive review of various processing techniques and design methodologies for thermal barrier coatings. The emphasis of this review is on the particle technology; the interrelationship between particle preparation, modification and the resulting properties, to assist developments in advanced and novel thermal barrier coatings for engineering applications.

Contents

Abbreviations: AALD, aerosol-assisted liquid delivery; ANOVA, analysis of variance; APS, air plasma spray; BC, bond coat; CVD, chemical vapor deposition; DCL, double ceramic layer; DVC, dense vertically cracked; DVD, directed vapor deposition; EBC, environmental barrier coating; EB-PVD, electron beam-physical vapor deposition; EOH, equivalent operating hour; FA, fly ash; FAC, fly ash cenospheres; FEM, finite element method; FG, functionally graded; FGM, functionally graded material; FS, flame spraying; HPCVD, hybrid physical-chemical vapor deposition; HPT, high pressure turbine; HVOF, high velocity oxy-fuel; LPPS, low pressure plasma spraying; LSPPS, liquid solution precursor plasma spray; LZ, lanthanum zirconate; MOCVD, metal-organic chemical vapor deposition; NLPM, normal liters per minute; OP-POSS, octaphenol-polyhedral oligomeric silsesquioxane; PLD, pulsed laser deposition; POSS, polyhedral oligomeric silsesquioxane; PS, plasma spraying; PS-PVD, plasma spraying-physical vapor deposition; PVD, physical vapor deposition; SANS, small-angle neutron scattering; SEM, scanning electron microscopy; SI, spark ignition; SPPS, solution precursor plasma spray; SPS, suspension plasma spray; TBC, thermal barrier coating; TC, top coat; TEC, thermal expansion coefficient; TEM, transmission electron microscopy; TGO, thermally grown oxide; TIT, turbine inlet temperature; TTBC, thick thermal barrier coating; USAXS, ultra-small-angle X-ray scattering; VPS, vacuum plasma spraying; XMT, X-ray microtomography; XRD, X-ray diffraction; YDZ, yttrium-doped zirconia; YSZ, yttria-stabilized zirconia.

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Introduction

Background

The challenges in a gas turbine relate to the protection of its two main parts, the combustor and turbine, against degradation because they operate within an extremely demanding high temperature environment (Belmonte, 2006; Bose, 2007; Davis, 2004; DeMasi-Marcin & Gupta, 1994; Nelson & Orenstein, 1997; Ray & Goswami, 2004; Sims, Stoloff, & Hagel, 1987). The increasing of gas turbine operating temperatures is inevitable because any increase in efficiency would result in increased combustion temperature (Belmonte, 2006; Comassar, 1991; DeMasi-Marcin & Gupta, 1994; Miller, 1997; Stöver & Funke, 1999). The temperature of the gas is highest just before the turbine, and the ability of the turbine to withstand this higher turbine inlet temperature (TIT, T_1) is a critical limiting operating parameter in jet engines. Higher TIT allows for increased power and improved efficiency. The motivation for achieving higher TIT is evident from the basic efficiency (ε) equation of a heat engine (Moore, 1972):

$$\varepsilon = \frac{(T_2 - T_1)}{T_1}, \tag{1}$$

where T_2 and T_1 are the operating temperature and the sink temperature, respectively.

As combustion temperature is increased to achieve higher efficiencies, material issues such as corrosion, oxidation, creep, and micro-structural degradation become more pronounced. Superalloys, which are tailored for high temperature applications, are currently operated at their peak capacity. When they are subjected to even higher temperatures, typical in a gas turbine combustor, their tensile strength drops. The combustion temperatures in gas turbines are already in the range of the melting temperatures of the base elements used in superalloy substrates (Ni, Co, Fe) (Eriksson, 2011). Thus, well performing thermal barrier coatings (TBCs) are needed to support superalloys to allow higher turbine inlet temperatures that may even exceed the melting temperature of the superalloy substrate.

Along with internal air cooling, TBCs can provide a surface temperature reduction of up to 300 °C for superalloy substrates (Myoung et al., 2013), which surpasses all other achievements in materials technologies over the last three decades. The continuous effort to improve gas turbine efficiency have raised operating temperatures to above 1300 °C, which necessitates thicker, chemically modified TBCs as well as new cooling systems (Ahmaniemi et al., 2005; Amagasa et al., 1994; Schwingel, Persson, Taylor, Johanesson, & Wigren, 1995). The surface temperature of the TBC protected components decreases at a rate of 4–9 °C per 25 μm increase in the thickness of the top ceramic coat (Bhatia et al., 2002; Khan & Lu, 2003; Kumar & Balasubramanian, 2016; Padture, Gell, & Jordan, 2002; Rabiei & Evans, 2000; Schlichting, Padture, Jordan, & Gell, 2003; Xie et al., 2003).

Applications of TBCs

The use of TBCs to enhance the thermal stability of the internal metallic components of gas turbines is increasing for commercial and military applications in the fields of power generation and aircraft and marine propulsion (Evans, Mumm, Hutchinson, Meier, & Pettit, 2001; Kim, Shin, Lee, & Cho, 2011; Padture et al., 2002). Improved turbine engine efficiency eventually leads to a significant boost in the performance and fuel efficiency of commercial and military air vehicles, enabling them to carry increased payloads and fly further. Fig. 1 shows a schematic of a jet engine with TBC applied to the turbine blades (Hille, Nijdam, Suiker, Turteltaub, & Sloof, 2009).

Higher thermal efficiency is achieved in advanced diesel engines by insulating combustion system components such as pistons, piston rings, cylinder heads, the cylinder block, intake and exhaust valves, and exhaust manifolds. The addition of a TBC to the piston

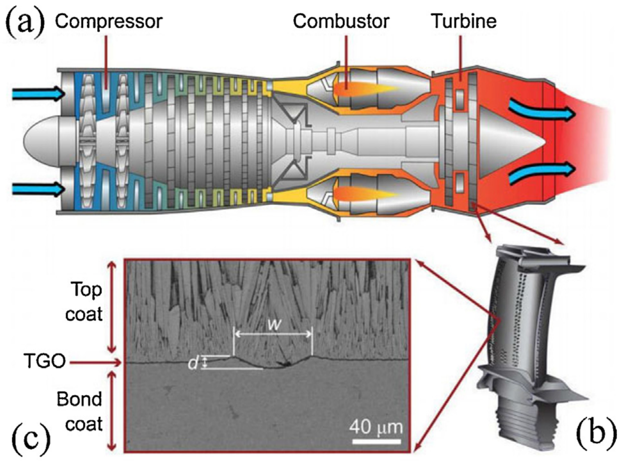

Fig. 1. (a) Schematic diagram of a jet engine; (b) a turbine blade; (c) a cross-section of a TBC system with bond coat deposited by vacuum plasma spraying and top coat deposited by electron beam-physical vapor deposition (Hille et al., 2009).