Minireview Article

A Short Review OfYttria-Stabilized Zirconia (YSZ) for Thermal barrier coatings: Recent Progress

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Abstract

According to some reports, yttria-stabilized zirconia has remained one of the most applied TBC materials due to its excellent thermal insulation properties and very high melting point, besides high resistance to thermal shock. In this paper, an overview of the most recent developments on YSZ-based TBCs is given, basically on the improvement of their thermal stability, sintering resistance, and phase stability. It further reviews very recent advances in fabrication techniques and deposition techniques and nanostructuring, which have been extremely useful in improving the performance and durability of YSZ coatings. Furthermore, in the review, the incorporation of new, novel dopants or alternative ceramic materials is given for further optimization of properties for TBCs. This paper finally concludes by giving the current challenges and future directions of YSZ-based TBC development, with the note that more R&D efforts need to be directed towards it, more so in view of the growing demands in the high-temperature applications domain for gas turbines and aero engines.

Keywords: Thermal Barrier Coatings, Gas Turbines,Aero Engines,**,Zirconia Ceramics**

INTRODUCTION

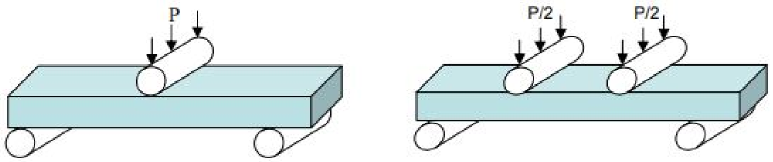
The use of tetragonal polycrystalline zirconia, which is stabilized with 3 mol% of all yttrium (3Y-TZP), has led to the development of bio-compatible ceramics with mechanical and translucent properties, particularly in the 1970s for dental and medical implant applications. Garvie et al . [1] and then Gupta et al.[2]found zirconia to possess a mechanism thatinhibits the propagation of cracks in its composition.
By increasing their volume and converting metastable tetragonal crystallites into the non reactive phase at each crack point, compression is caused by the stress-induced phase change. This family of hardened materials includes Y-TZP (yttriastabilized tetragonal zirconia poly-crystal) zirconia ceramics. They can have a flexural strength of over 1000 MPa and an elasticity of approximately 5-10 MPa√m. The exceptional qualities of oxide ceramics facilitated the development of novel structural elements and patterns that are not present in more fragile ceramic materials like alumina. Y-TZP was preferred over other zirconia ceramics because of its unique balance of durability and strength. The United States and Europe have the highest number of zirconia femoral heads implanted, totalingEurope . Recent advancements in CAD/CAM procedures have led to

the increasing use of zirconium in dental use, which includes endodontic posts brackets, and restorative dental inlays,Thermal barrier coating crowning, or bridges.[3] To enhance engine efficiency and protect metal parts from harsh environments, thermal barrier coatings (TBC) are commonly used to improve operating temperature.[4-9] These coatings are used to lower the temperature of the metal, which slows the onset of heat-induced failure mechanisms such as oxidation, creep rupture, thermal fatigue and hot corrosion, etc. The thickness of most thermal barrier coatings is between 100 m and 1 mm, with Y2 O3 serving as a partially stabilized ZrO2 (7YSZ) at 7 wt% (4 mol%A porous YSZ with micropores and numerous defects offers superior thermal insulation and has an exceptional voltage tolerance limit. There are two main types of TBCs in aircraft engines [10, 11,][12-14].

Mechanicalproperties

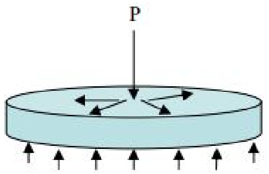
2.1 flextural strength

“Stress distributions caused by compressive, tensile, and shear stresses are present in most test specimens of flexural strength. However, brittle materials are much weaker in tension than in compression”(Ban and Anusavice 1990). “Therefore, tensile strength is generally considered the most important property of brittle materials in evaluating the fracture potential of dental fillings” (Ban and Anusavice 1990). Flexural strength is a mechanical property related to fracture because it measures the resistance of fillers to tensile forces.Sunnegrdh-Grönberg et al. suggest that materials with high flexural strength are more appropriate for filling cavities and minimize the risk of mass fractures. 2003). Various methods are available to evaluate the flexural strength of ceramic materials. These test methods included three-point bending, four-point bending, and biaxial bending tests.



(a) 3-point bending

(b) 4-point bending



(c) Biaxial flexure

Figure 1.flextural strength Test by PiyapannaPittayachawan et al

2.2 Fatigue test

Physical exertion leads to a loss of strength and energy, which is known as fatigue.To determine the performance of zirconium-based dental ceramics under repetitive vibration or stress, fatigue testing involves applying a constant load to inspected samples. This is known as fatigue analysis. How does this technology work? Clinically, the accumulation of micro-structural damage during occlusion can lead to catastrophic failure.

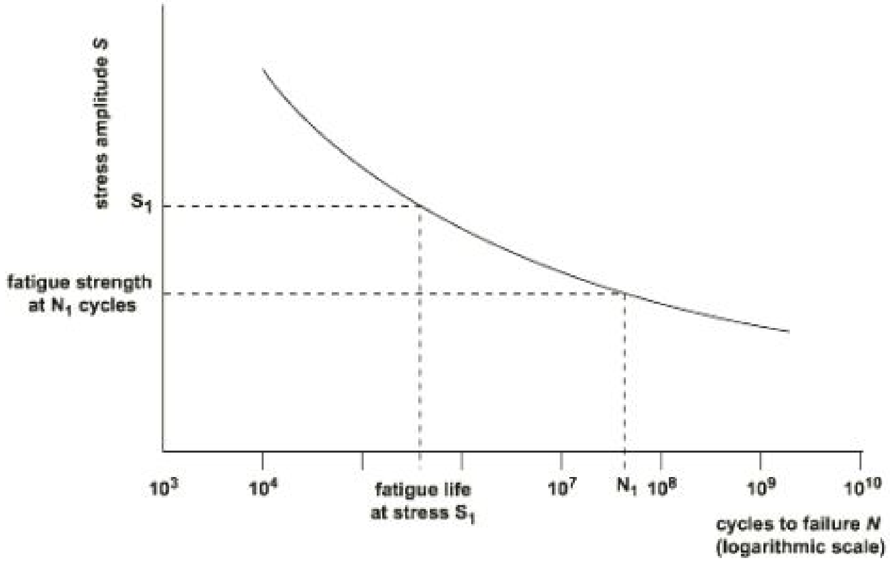


Figure 2Figure 2.4. S-N curve by PiyapannaPittayachawan et al

2.3 Hardness test

Hardness is a crucial aspect when comparing durable materials.The resistance to permanent surface depression or intrusion is gauged by Albacker and his colleagues.2003a). This is defined as penetration resistance. Comparative study of the physical properties of zirconium oxide exposed by a hard indenter of specified geometry and pressed on a test surface in the prescribed manner (BSI ENV 843-4:1994). Albakry et al. (2003a) recommended a force of 1.According to Albacker et al.'s ASTM C 1327-99, the use of 5 N in ceramics can prevent radial cracking.2003a)..

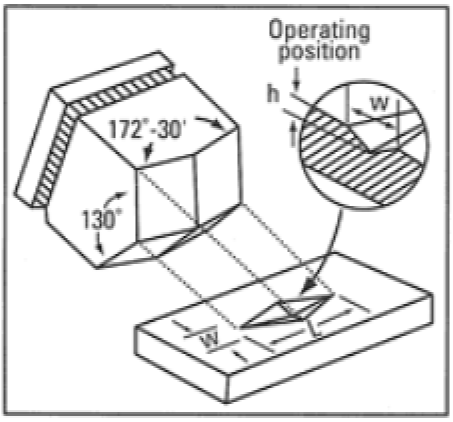


Figure 3 Knoop Hardnessref PiyapannaPittayachawan et al

2.4 Bond strength test

The strength of a material under sustained tensile stress is one of the most critical and widely measured properties in structural applications.Calculating the breaking strength of a material is done by using an average force per-unit area (Callister In the SI system, the units are newtons per square meter (N/m2) or pascals (Pa). The design of the tensile test consists of two bars with a uniform cross-section. A comparative study of the physical properties of zirconia-based dental ceramics bonded and unbonded on ceramic surfaces using a universal testing device (Della Bona and van Noort 1995)

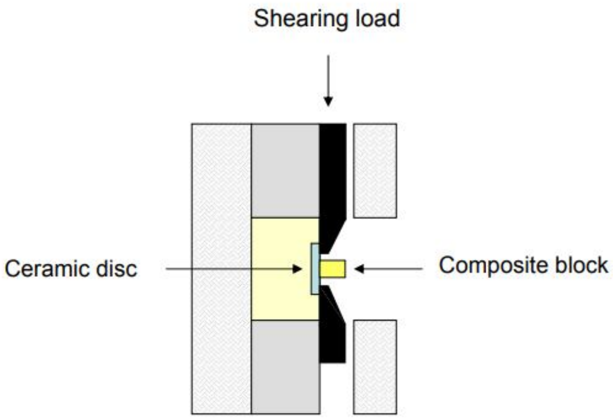


Figure 4 Assembly used for determination of shear test

Advances in YSZ Coating Techniques

3.1 Plasma spraying technology

“PS TBC was first invented in the 1960s.After being introduced into a plasma jet at high temperatures, the alized metal and ceramic powders are typically heated to fusion or melting point before being laid onto varying substrates. Due to its high speed, the molten drop hits the surface of the substrate, spreads like a disk, and finally the disk layers spread into a coating layer. During the last decades, several PS methods such as atmospheric plasma spraying (APS), low pressure plasma spraying (LPPS) and solution precursor plasma spraying (SPPS), vacuum plasma spraying (VPS) and shielded plasma spraying (PAPS) have been for for TBC to develop further to produce”[15-18]. “APS and LPPS are the two main layering methods for TBCs.The benefits of these include low cost, quick coating time, high efficiency, ease of administration, and more.TBCs obtained through APS or LPPS exhibit an ordinary spongy microstructure that appears to be a complicated laminated structure, with numerous pores and cavities that are randomly distributed across the surface area. In general, APS TBCs have a porosity between 3 and 20%, while the accepted porosity range for TBC is 10-15%” [19]. “The laminated PS coating is well-suited for TBC applications because of the pores within the laminates that connect to the lattice slit-like cavities, which can decrease thermal conductivity. However, interlayer pores, microcracks and interface-parallel microstructural defects also increase the potential for delamination and cracking. In addition, it causes a low elastic layer and poor adhesion of the lamella” [20].Thus, this approach is particularly suitable for parts with low-mechanical properties and high volume (combustion chambers, evaporators, stator shields).

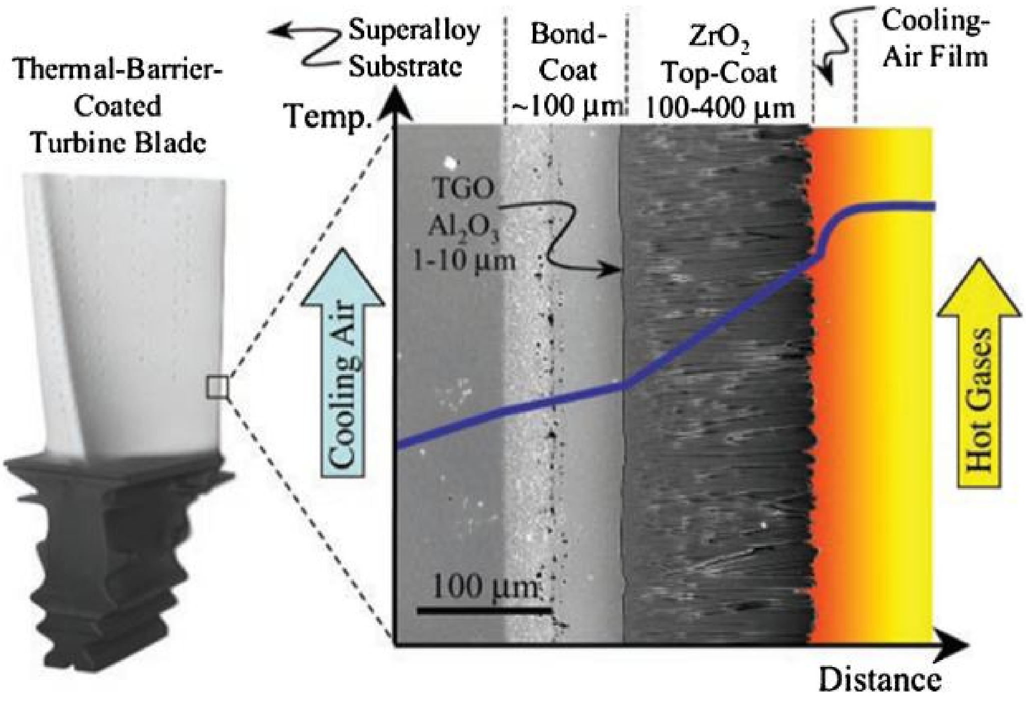


Figure 5 A cross-sectional image of a TBC system on an aero-turbine blade by ref [21]

3.2 Thermal conductivity of high-temperature materials

Despite the work of Kingery and others, the experimental investigation of thermal conductivity at high temperatures has been mostly ignored. This is not surprising. They measured the thermal conductivity of many oxides as a function of temperature and studied the effects of porosity and mixing of two different oxides.After accounting for the temperature dependence of thermal expansion, it was shown that the inelastic Umklapp phonon-phono scattering is responsible for a 1/T decrease in the thermal conductivity of almost all oxides. Most of their measurements (Fig. 6a) do not extend to temperatures of interest for future TBCs.

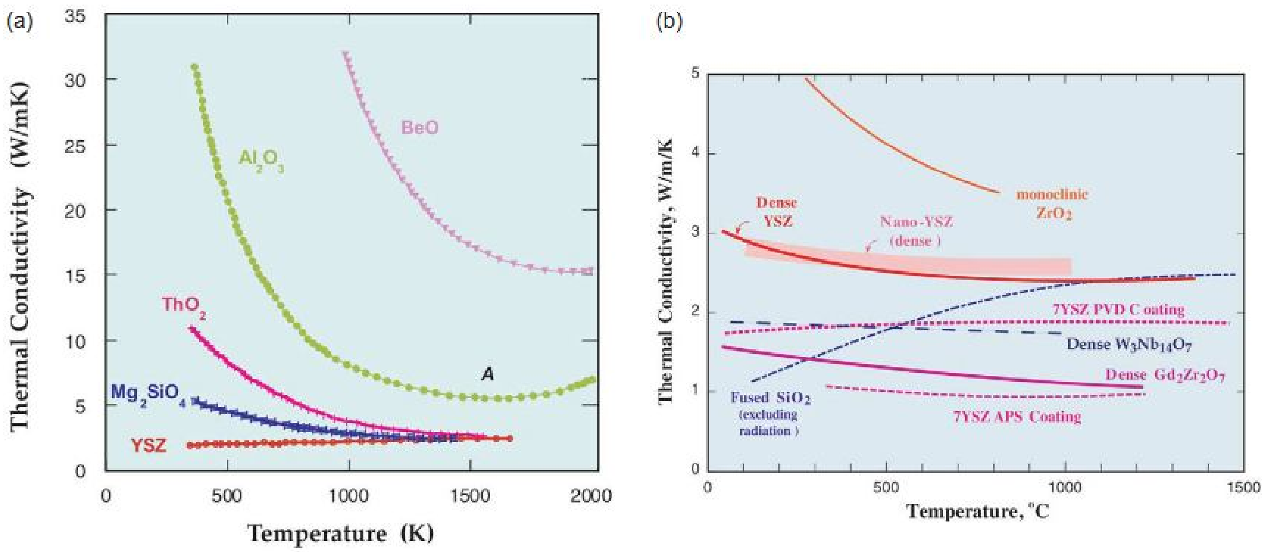


Fig. 6 (a) Thermal conductivity versus temperature for several refractory compounds (after 9). The upturn A at the highest temperatures is a result of radiative transport through the material during measurement. (b) Materials usually exhibiting low thermal conductivity.

3.3 Electron beam physical vapor deposition technology

“EB-PVD technology became prevalent in TBC production in the United States, Great Britain and Germany and the former Soviet Union during the 1980s. 1990. In the mid-1990s, the International Electron Beam Center in Paton, Ukraine invented a low-cost EB-PVD device that became popular worldwide, starting a new wave of EB-PVD TBC development. In the process, the electron gun emits electron beams in a vacuum chamber, thermal electrons are accelerated under high voltage. In addition, fast thermal electrons hit metal or ceramic target materials to melt and vaporize them, and then deposit on the substrate to form a coating” [22]. A typical structure of EB-PVD YSZ TBC is shown in Figure 7[23]. “EB-PVD TBCs have excellent aerodynamic properties. Their surface roughness is better than PS TBCs and does not cover the fine cooling holes” [24]. “EB-PVD-TBCs possess a distinct columnar microstructure that has randomly distributed multidimensional, and concentric grains form close proximity to the bonding and ceramic layers. The columnar grains are separated from each other by channels parallel to the direction of heat conduction. The columnar grains between the channels can improve the tensile strength, thermal shock resistance of the TBC system and alleviate their mismatch stresses due to thermal expansion” [25]. However, EB-PVD TBCs result in higher thermal conductivity and lower thermal insulation than APS-TBC**s**..

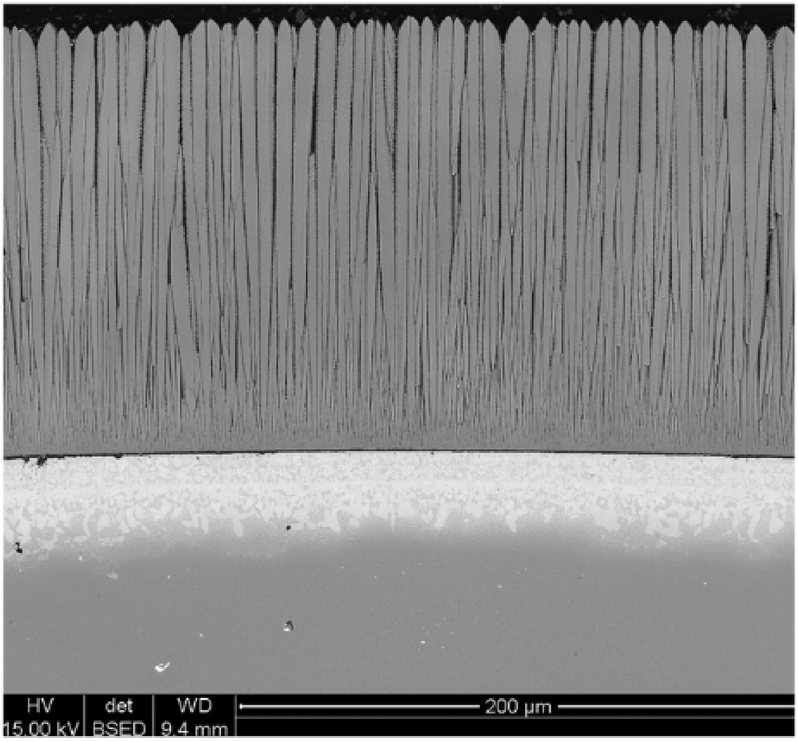


Fig 7 The cross-sectional morphology of EB-PVD YSZ TBCs

Failure and life prediction of TBCs

The properties of TBCs that are used to define their stability and durability include thermal cycling and thermal shock lifetime. TBC service environments are very complex, including high temperature oxidation, hot corrosion, wear and impact, environmental deposits ($CaO-MgO-Al_2O_3-SiO_2$, V_2O_5 and SO_2) deposits etc[26,27]. TBC service life is influenced by those operating environment factors, coating structure and coating materials characteristics, which made TBC failure modes difficult. As a result, accurately predicting the lifespan of TBC has become a focus of TBC research, and the failure mechanism of TBC is particularly important.YSZ， several rare earth alloys YSZ, e.g. A2 B2 O7 type rare earth zirconates contain many oxygen vacancies. When these materials act asTBC at high temperature, TGO is produced. Although the TGO film can effectively prevent the bonding coating from oxidizing , it causes thermal stress that can lead to cracking.The TGO film's formation is subjected to intense in-plane pressure because it is located between the ceramic coating and bonding layer. This is a cause for concern. Therefore, the TGO tends to expand in-plane to release lattice distortion energy. When confined by adjacent coatings, the TGO film tends to form a vertical interface to obtain a larger surface area, wrinkling occurs. The adhesive coating also synergistically changes its shape as the TGO film adheres to the adhesive coating.

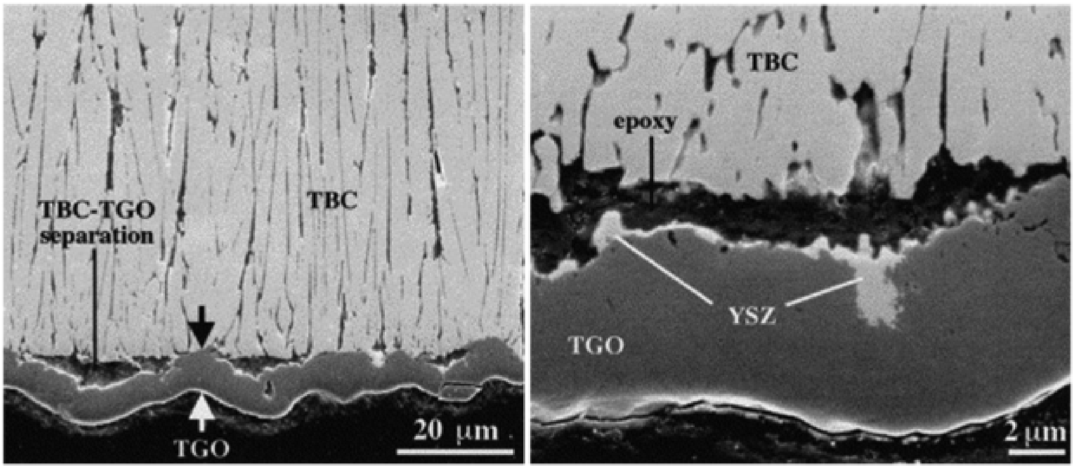


Fig 8 The coating failure caused by the cracking of the TGO film ref 28

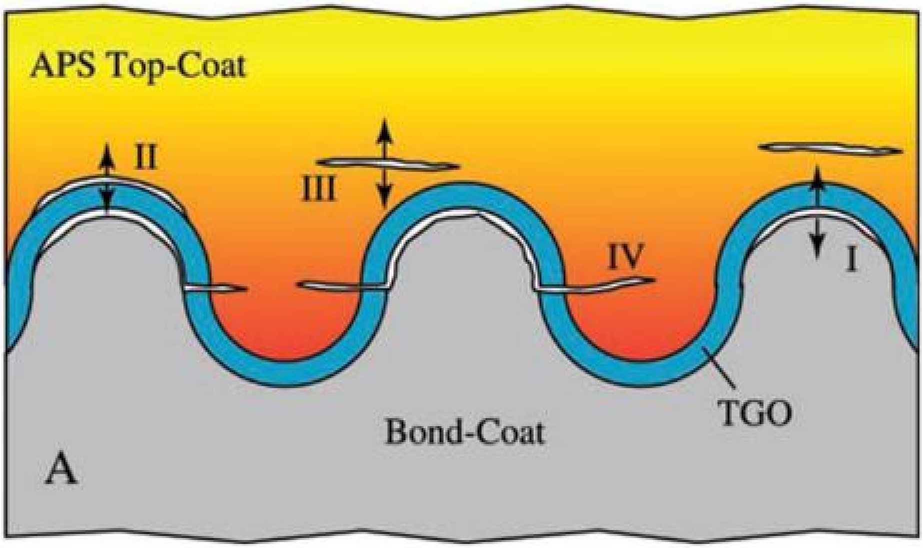


FIG 9 A schematic illustration showing the cracking mechanism in the APS TBC ref [30]

Fig. 10. (a) TBCs coated on the combustor tile and (b) the edge morphology of the cooling hole with TBCs.

Applications of TBCs

The use of TBC in aircraft engines has increased dramatically over the past decade.

The extended component life, increased engine durability, and lower operating costs are achieved through the widespread use of hot stator or rotor components such as combustion chambers, fuel vaporizers (in engines), wings, airfoils, etc.Consequently, the investigation and reaction methods concerning the disabling of cooling holes during TBC production are still being developed. Adjusting the route of the TBC process and drilling covered cooling holes is considered as one of the attractive methods. In addition, ultra-fast laser etching and laser micro-jet methods2019 have also been tested for drilling turbine blades and labels with coating.[29]

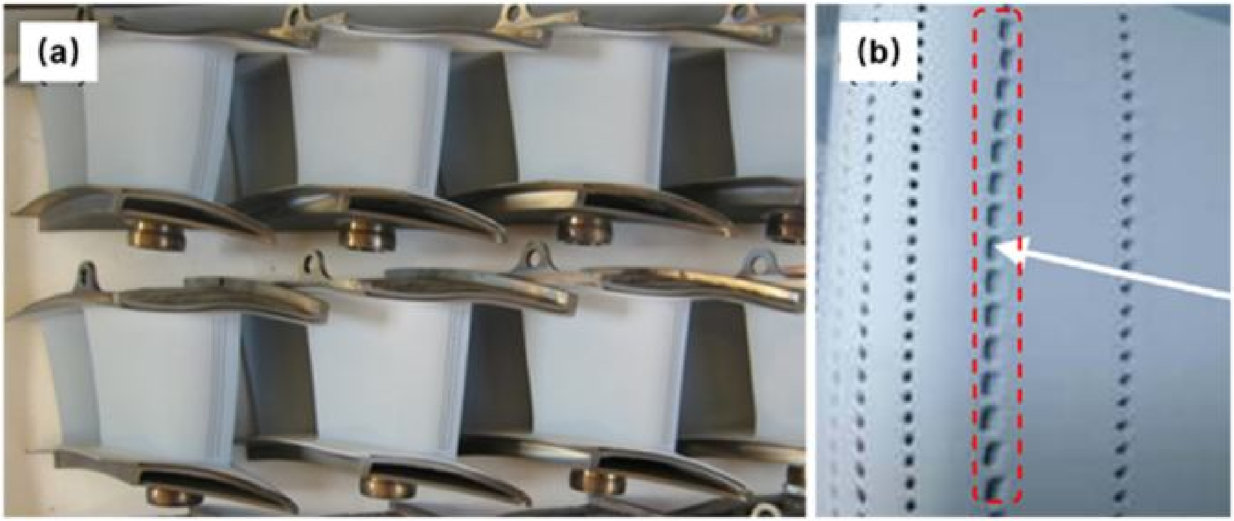


Figure 11 (a) HPT vanes with TBCs and (b) morphology of the cooling holes with TBCs

Conclusion

in summary, Yttria-Stabilized Zirconia remains at the heart of material development efforts aimed at advanced TBC technologies for high-temperature applications, including gas turbines and aero engines. The key areas of development that have come to the fore in recent progress in this field relate to improving the thermal stability and sinter resistance of YSZ and mitigating phase transformations. This has been partially caused by the developments in methods of fabrication, including novel deposition techniques and nanostructuring, while others improve the performance and durability of YSZ coating. Again, new dopants, as well as exploration of alternative ceramic materials, have opened new avenues toward the optimization of thermal and mechanical properties of TBCs.Further researchers will be needed to sort out remaining issues, such as spallation resistance and long-term behavior of YSZ during operation. Coupling computational modeling with experiments holds very great promise for accelerating design and optimization of next-generation TBCs. With the demand for higher efficiency and longer lifetimes from high-temperature applications continuing to increase, there is no doubt that YSZ-based thermal-barrier coatings will be at the cutting edge of protective coatings technology, driving innovation toward further extending service life and performance of mission-critical components taking on challenging environments.

Disclaimer (Artificial intelligence)

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