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CHARACTERIZATION OF CERAMIC COATINGS WITH THERMAL BARRIER ROLE OBTAINED BY ATMOSPHERIC PLASMA JET SPRAYING

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Abstract

This paper presents the characterization of ceramic thermal barrier coatings (TBCs) obtained by atmospheric plasma spraying (APS), focusing on their functional, structural, and chemical performance under extreme thermal conditions. The study highlights the critical requirements of TBC systems, including low thermal conductivity, high phase stability above 1200 °C, resistance to thermal shock, and strong adhesion between the ceramic top coat, bond coat, and metallic substrate. Special attention is given to YSZ (zirconia stabilized with yttria) coatings with a high yttria content (38 wt% Y_2O_3), which ensure cubic phase stabilization and enhanced durability at elevated temperatures. Recent advances in TBC design are discussed, such as optimized ceramic compositions, controlled microstructures, and multifunctional architectures that integrate chemical protection and sensing capabilities. The advantages of ceramic TBCs compared to massive or non-ceramic barriers are also outlined, emphasizing their reduced weight, improved thermal insulation, chemical stability, and thermomechanical compatibility. These results confirm the potential of advanced YSZ-based coatings to provide reliable thermal protection in aerospace and energy applications, contributing to increased efficiency and reduced environmental impact.

Keywords: *ceramic coatings, TBC, YSZ, microstructure*

1. INTRODUCTION

In order to ensure effective and durable protection of components exposed to extreme temperatures, a Thermal Barrier Coating (TBC) system must simultaneously meet a rigorous set of functional and structural requirements, Figure 1. Firstly, the low thermal conductivity of the ceramic layer is fundamental in limiting the heat flow to the substrate, thus helping to keep the temperature below the thermal critical of the structural alloy and prolonging the lifetime of the whole assembly [1]. At the same time, it is essential that the ceramic material exhibits outstanding phasic stability at high temperatures (≥1200 °C) without spontaneous structural transformations (such as tetragonal-monoclinic transition in conventional YSZ), which can lead to internal stresses, cracking or exfoliation [2].

Another essential criterion is thermal shock resistance, which refers to the coating's ability to withstand sudden temperature variations without cracking or loss of adhesion. This implies a suitable microstructure (e.g. controlled porosity, vertical cracks), but also good thermomechanical compatibility between the ceramic layer, the bond coat and the substrate - in particular in terms of the coefficient of thermal expansion (CTE), which must be as close as possible to prevent the build-up of interfacial stresses during thermal cycling [3].

Also, interlayer adhesion is crucial: without good adhesion between the ceramic layer and the bonding layer (e.g. NiCrAlY), the coating is prone to delamination and spalling under operating conditions. Finally, the TBC system must resist oxidation and corrosion, especially in aggressive firing environments that may contain reactive gases such as SO_2 or H_2O, or contaminants such as Cl^- and Na^+, which may favor infiltration processes, phasic reactions or accelerated degradation [4].

Therefore, a high-performance TBC system must not only be an effective thermal insulator, but also a stable chemical barrier, a strong mechanical structure and a well-balanced interfacial layer - all of which are prerequisites for its operation in extreme environments, such as aircraft turbines or the combustion chambers of high-power engines.

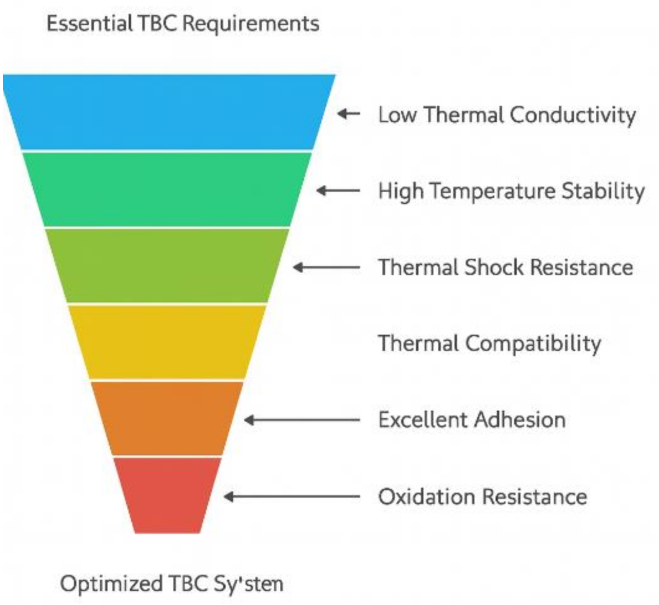

Figure 1. Main characteristics of a ceramic thermal barrier coating

Evaluation of these characteristics is done by standardized methods, such as cyclic thermal shock tests, adhesion tests, post-test morphological analysis (SEM, XRD), and conductivity and hardness measurements.

2. CURRENT TRENDS IN THE DEVELOPMENT OF TBC

Modern research in the field of Thermal Barrier Coatings aims to overcome the limitations of conventional systems by developing innovative solutions that combine thermal stability at extreme temperatures, microstructural adaptability and extended functionalities, Figure 2. A first condition for success is the optimization of the ceramic composition, where attention is focused on YSZ with high Y_2O_3 content (>20 mol%), able to stabilize the cubic phase (c-YSZ) even at temperatures above 1400 °C, thus preventing destructive phase transformations. In parallel, alternative oxides, such as $Gd_2Zr_2O_7$, $La_2Zr_2O_7$, CeO_2 or HfO_2, are being explored, which offer even lower thermal conductivity and improved resistance to chemical attack or accelerated sintering [1].

A second direction is advanced microstructure control, where columnar (EB-PVD) or layered porous microstructures (SPS) are being developed, offering high thermal flexibility, cyclic stress accommodation and superior durability in thermal shock. These architectures allow efficient stress dissipation through vertical intergranular openings and maintenance of low thermal conductivity even after prolonged exposure [5].

At the same time, the direction of multifunctional coatings is taking shape, where TBC coatings no longer only have a passive thermal insulation role, but also integrate chemical protection (oxidation, molten silicate deposits corrosion) or even smart functions such as embedded sensors (e.g. piezoelectric structures, optical or fluorescent markers) for real-time degradation monitoring [6]. These solutions bring added reliability and enable predictive maintenance in critical applications.

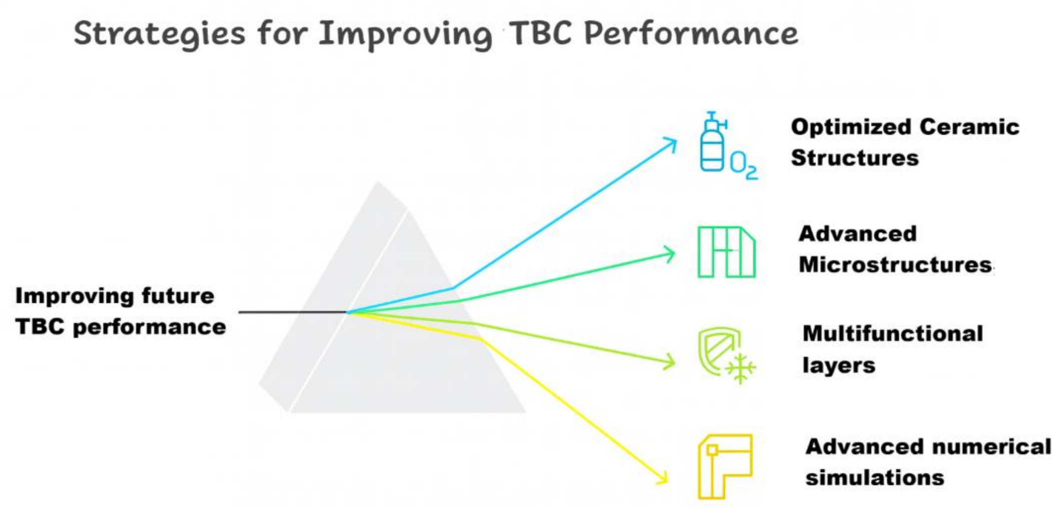

Figure 2. Main methods to improve the performance of ceramic thermal barrier coatings

Last but not least, an increasingly important role is played by advanced numerical modeling, through the integration of CFD (Computational Fluid Dynamics), FEM (Finite Element Method) and thermomechanical failure models, which allow the optimization of the design of TBC systems from the concept phase, thus reducing the time and costs associated with experimental testing. Through these synergistic directions - compositional, microstructural, functional and digital - new perspectives are opening up for the realization of resilient, intelligent and extreme conditions-adapted TBCs for future energy and aerospace technologies. In conclusion, modern TBC systems represent a complex and evolving interdisciplinary field with a direct impact on the efficiency and reliability of energy and aeronautical equipment. The investigation of alternative ceramic compositions, such as YSZ with 38% Y_2O_3, is a promising direction to overcome the limitations of current commercial systems.

3. MAIN ADVANTAGES OF CERAMIC THERMAL BARRIERS OVER OTHER TYPES OF SOLID OR NON-CERAMIC THERMAL BARRIERS

Ceramic thermal barriers in the form of thin coatings have a number of significant advantages over traditional methods of thermal protection, which involve either massive layers of refractory materials or metallic or composite solutions without a ceramic component. These advantages concern both functional properties and technological and economic efficiency.

Light weight and geometric adaptability: ceramic coatings have typical thicknesses in the order of 100-500 µm, compared to a few millimeters for solid refractory insulations. This makes them ideal for aero and automotive applications where weight is a critical parameter. They can be applied on components with complex geometries, including turbine blades, injectors, valves, etc., where solid materials are impossible to fit or would affect functionality.

Low thermal conductivity: YSZ-based ceramics have a thermal conductivity of 1-2 W/m^{-}K, compared to metals (>20-100 W/m^{-}K) or even some metal composites. This allows a high thermal gradient to be achieved at low thicknesses, providing superior thermal protection without requiring large volumes of material [6]. Chemical stability and corrosion resistance: YSZ ceramics are inherently stable at high temperatures and have high oxidation resistance, unlike metal alloys which oxidize rapidly at >1000 °C. It is resistant to aggressive environments (combustion gases, erosive particles), making it durable in severe industrial conditions.

Thermomechanical compatibility and thermal shock resistance: Modern ceramic coatings, due to their porous and layered microstructure, exhibit good thermal conformability, capable of absorbing cyclic expansion/contraction without generating critical cracks. In combination with a flexible bonding layer, they provide superior durability in cyclic conditions, where solid materials can crack or peel [2]. Easy technology integration: TBC coatings can be deposited directly onto finished metal components without requiring additional assemblies or major part design changes. They are compatible with automated industrial processes and have a lower overall cost than alternative volumetric thermal protection methods.

Increased overall thermal efficiency: thanks to their ability to increase the working temperature of components by up to 150-200 °C without degradation, TBCs contribute directly to the thermodynamic efficiency of engines or turbines. This translates into lower fuel consumption and reduced CO_2 emissions - major goals in aviation, energy and transportation . All in all, ceramic thermal barriers offer a performance-to-weight-to-cost ratio incomparably superior to other thermal protection solutions. Combining advanced insulation, stability and resistance properties, they are the reference solution for modern applications in extreme environments.

4. CONCLUSIONS

Plasma sprayed ceramic coatings exhibit low thermal conductivity (1-2 W/m^{-}K), which allows effective protection of the metal substrate even at low thicknesses (100-500 μm). The structural stability of YSZ with high Y_2O_3 content (≈ 38 wt%) ensures cubic phase maintenance and temperature resistance > 1200 °C, reducing the risk of destructive phase transformations. The porous and layered microstructure favors thermal shock resistance and thermomechanical compatibility between the ceramic layer, the bonding layer and the substrate. TBC coatings demonstrate good resistance to oxidation and corrosion, including in aggressive combustion environments, extending the service life of protected components. The major advantages of these coatings (low weight, applicability on complex geometries, high thermal efficiency) recommend them as the reference solution for aero, energy and automotive applications.

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