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ASSESSING THE PERFORMANCE OF CERAMIC COATINGS IN THERMAL BARRIER SYSTEMS

BY

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Abstract: Ceramic coatings with thermal barrier function (TBC) are widely used in extreme thermal environments, such as gas turbines, aero-engines and automotive high-performance systems, where metallic components require protection against oxidation and overheating. This paper reviews the main deposition techniques of thermal barrier coatings, with emphasis on atmospheric plasma spray (APS), vacuum plasma spray (VPS), low-pressure plasma spray (LPPS), and electron beam physical vapor deposition (EB-PVD). The microstructural characteristics, porosity, adhesion mechanisms and functional behavior of yttria-stabilized zirconia (YSZ) layers are analyzed in correlation with their deposition method. Moreover, the role of bond coats (MCrAlY alloys and NiAl) and thermally grown oxides (TGO) is highlighted as critical for durability under cyclic thermal loading. Applications in aerospace, energy and automotive fields are discussed, along with emerging plasma spray techniques such as Suspension Plasma Spray (SPS), which offer potential improvements in thermal insulation and lifetime extension. The study emphasizes the relationship between processing parameters, structural features and the performance of TBCs in service conditions.

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Keywords: thermal barrier coatings; atmospheric plasma spray; vacuum plasma spray; low-pressure plasma spray; suspension plasma spray; yttria-stabilized zirconia.

1. Introduction

Thermal Barrier Coatings (TBC - Thermal Barrier Coatings) are systems of functional coatings applied to the surface of metal components in areas subject to extreme temperatures, with the aim of reducing heat flux and protecting the substrate against oxidation and thermal degradation (Sezavar and Sajjadi, 2025; Todirică *et al.*, 2024). These are generally bilayer or multilayer systems consisting of a metallic bonding layer (usually based on NiCrAlY or MCrAlY) and a thermally insulating ceramic layer, frequently based on YSZ (yttria-stabilized zirconia).

The thermal barrier provides a significant temperature difference between the surface exposed to the combustion medium and the surface of the substrate, thus protecting the structural components of turbines, engines or combustion chambers (Stanciu *et al.*, 2024). Typically, the temperature at the outer surface of the ceramic layer can exceed 1200°C, while the metallic substrate is maintained at significantly lower values (700-900°C) (Li *et al.*, 2021; Luțcanu *et al.*, 2022).

2. General methods for obtaining TBs

The deposition methods of TBC coatings significantly influence their microstructure, porosity, adhesion and functional performance.

The most commonly used technologies are (Fig. 1):

- Atmospheric Plasma Spray (APS - Atmospheric Plasma Spray): a widely used method based on the projection of molten or semi-molten particles onto the substrate by means of an electrically generated plasma jet. It produces ceramic layers with layered (lamellar) microstructure, controllable porosity and thickness in the order of hundreds of microns (Ashofteha *et al.*, 2017).
- Vacuum plasma spraying (VPS) and controlled chamber plasma spraying (LPPS): allow better control of oxidative reactions and produce higher density layers.
- Electron-beam deposition - physical vapor deposition (EB-PVD): generates colloidal coatings with controlled vertical porosity, providing better thermal conformability and thermal shock resistance, but at a significantly higher cost (Teng *et al.*, 2023).
- Emerging techniques: such as Solution Precursor Plasma Spray (SPPS) or Suspension Plasma Spray (SPS), allow to obtain fine microstructures

with potential for thermal conductivity and superior performance compared to traditional methods.

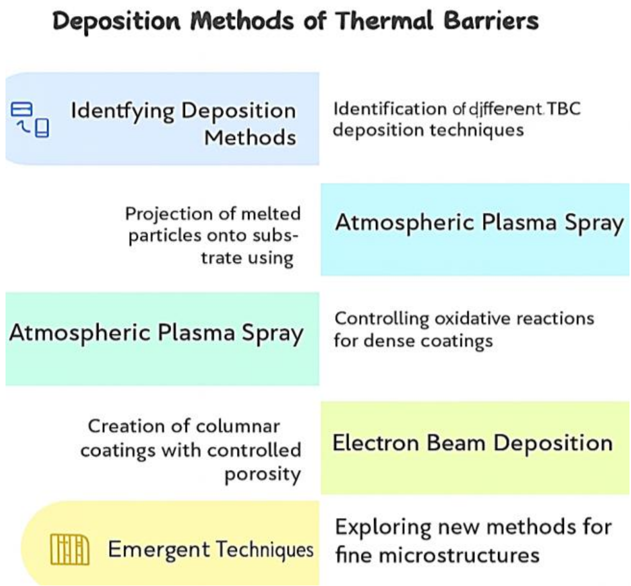

Fig. 1 – Methods of obtaining thermal barriers.

Each method has advantages and limitations in terms of cost, microstructure control, deposition rate and performance under real-world operating conditions.

3. Thermal barriers applications

Thermal barriers are essential in industries where materials are exposed to extreme thermal stresses and the performance of components is directly influenced by their resistance to high temperatures. Relevant applications include (Fig. 2):

- Gas turbines used in power generation and the aviation industry - protecting rotor blades and stator components. TBCs allow operation at temperatures above the melting limit of the metal superalloys used (Padture *et al*., 2002).
- Aviation engines (turbojets, turbofans): increasing combustion efficiency and reducing internal component wear (Ramesh *et al*., 2022).
- High-performance automotive engines (e.g. Formula 1): protection of valves, pistons and exhaust manifolds (Barbero *et al*., 2024).
- Components of nuclear reactors or hypersonic systems: where resistance to severe thermal cycling and oxidation is crucial (Bogdan *et al*., 2024).

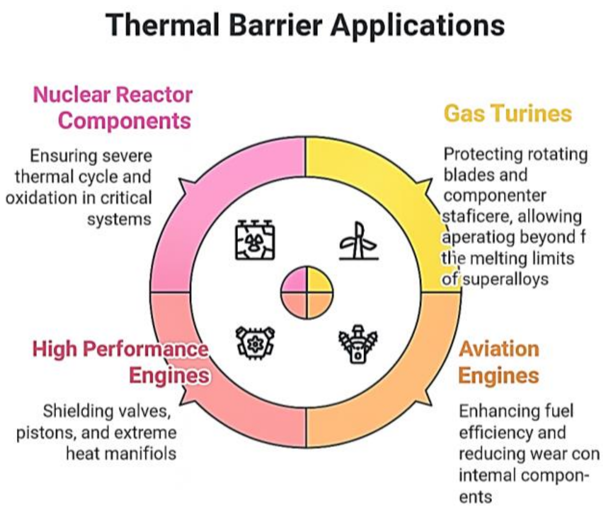

Fig. 2 – Examples of thermal barrier applications.

The application of TBCs contributes directly to extending component life, reducing fuel consumption and increasing the overall efficiency of energy systems.

4. Typical structure of a ceramic thermal barrier coating (TBC) system

A complete TBC system is composed of the following functional layers (Fig. 3):

- The metallic substrate, usually a nickel-based superalloy (e.g. Inconel 718, René 80), which gives mechanical and thermal resistance to the entire structure.
- The bond coat, made of MCrAlY alloys (where M = Ni, Co or combinations) or by aluminization (NiAl), is intended to ensure the adhesion of the ceramic layer and to form a controlled protective oxide (TGO - Thermally Grown Oxide) between the substrate and the insulating layer (Huang *et al*., 2021; Luțcanu *et al*., 2023a).
- Insulating ceramic layer, most commonly made of YSZ, which provides thermal protection, with low thermal conductivity and adequate stability at high temperatures.
- Thermally grown oxide (TGO), particularly Al_2O_3, which forms naturally at the bond coat-ceramic layer interface during exposure to high temperatures. The evolution of this layer critically influences the durability of the system, as its expansion or decohesion can lead to cracking and peeling (Shu *et al*., 2024; Luțcanu *et al*., 2023b; Luțcanu *et al*., 2023c).

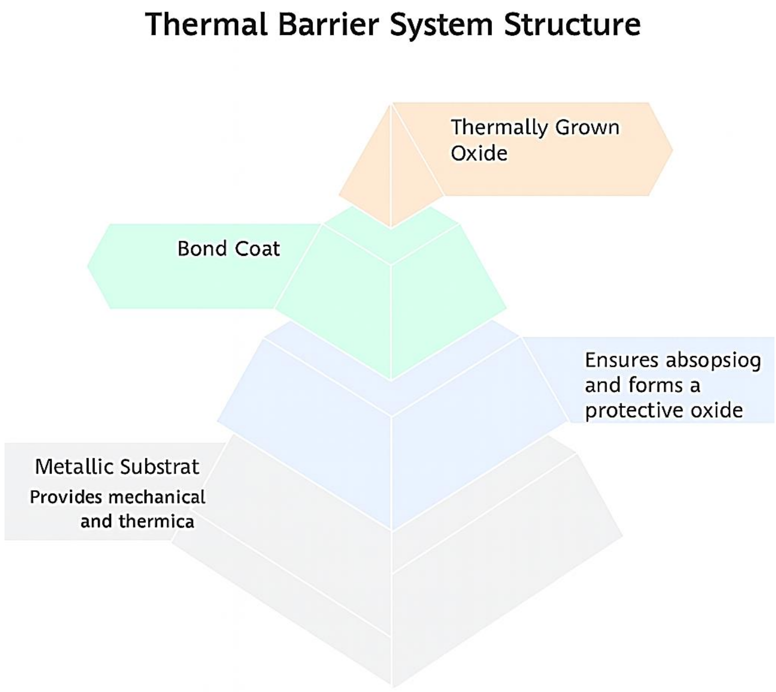

Fig. 3 – Structure of a typical ceramic coating system.

5. Conclusions

YSZ-based thermal barriers are the reference solution for the protection of metal components subject to extreme temperatures due to their low thermal conductivity and high temperature stability.

The bond coat (MCrAlY or NiAl) and the thermally grown oxide (TGO) layer play a determining role in the adhesion and durability of coatings, influencing the occurrence of cracking and delamination phenomena.

The deposition technology directly controls the microstructure of the layer: APS provides a lamellar microstructure with controlled porosity, while EB-PVD produces more flexible columnar structures under thermal shock.

Industrial applications for TBCs include gas turbines, performance aircraft and automotive engines, but also nuclear or hypersonic systems, where increased efficiency and extended component life are essential.

Emerging technologies, such as SPS and SPPS, open perspectives for optimizing thickness, porosity and thermal conductivity, with the potential to replace classical methods in future applications.

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EVALUAREA PERFORMANȚELOR ACOPERIRILOR CERAMICE ÎN SISTEMELE DE BARIERĂ TERMICĂ

(Rezumat)

Acoperirile ceramice cu funcție de barieră termică (TBC) sunt utilizate pe scară largă în medii termice extreme, cum ar fi turbine cu gaz, motoare aeronautice și sisteme auto de înaltă performanță, unde componentele metalice necesită protecție împotriva oxidării şi supraîncălzirii. Acest articol trece în revistă principalele tehnici de depunere a acoperirilor cu barieră termică, cu accent pe pulverizarea cu plasmă atmosferică (APS), pulverizarea cu plasmă în vid (VPS), pulverizarea cu plasmă la presiune scăzută (LPPS) şi depunerea fizică din vapori cu fascicul de electroni (EB-PVD). Caracteristicile microstructurale, porozitatea, mecanismele de aderență și comportamentul funcțional al straturilor de zirconiu stabilizat cu oxid de ytriu (YSZ) sunt analizate în corelație cu metoda de depunere a acestora. Mai mult, rolul straturilor de legătură (aliaje MCrAlY și NiAl) și al oxizilor crescuți termic (TGO) este evidențiat ca fiind esențial pentru durabilitate în condiții de încărcare termică ciclică. Sunt discutate aplicațiile în domeniile aerospațial, energetic și auto, împreună cu tehnicile emergente de pulverizare cu plasmă, cum ar fi pulverizarea cu plasmă în suspensie (SPS), care oferă îmbunătățiri potențiale în ceea ce privește izolația termică și prelungirea duratei de viață. Studiul subliniază relația dintre parametrii de procesare, caracteristicile structurale și performanța TBC-urilor în condiții de funcționare.