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A Comprehensive Study on Thermal Barrier Coating Techniques in High-Temperature Applications

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Abstract

High-temperature applications, such as gas turbines, aircraft engines, and industrial furnaces, require materials that can withstand extreme heat and thermal cycling. Thermal Barrier Coatings (TBCs) are commonly used to protect components in these applications from high-temperature degradation. TBCs are typically applied to the surface of components to provide thermal insulation and reduce heat transfer, thereby extending the service life of the components. This paper comprehensively studies different TBC techniques used in high-temperature applications. The methodology of this study involved a comprehensive review of existing literature on TBC techniques used in high-temperature applications. This review included studies on different types of TBC materials, deposition methods, and performance evaluations. In addition, data from relevant studies were analyzed to assess the effectiveness of different TBC techniques in protecting components from high-temperature degradation. The study revealed that several TBC techniques are commonly used in high-temperature applications. These techniques include Electron Beam Physical Vapour Deposition (EB-PVD), Atmospheric Plasma Spraying (APS), and sol-gel coating. Each technique has advantages and limitations regarding thermal insulation, adhesion strength, and durability. EB-PVD is known for its high thermal insulation properties and excellent adhesion strength, making it suitable for high-temperature applications. APS, on the other hand, is a cost-effective technique that can be used for large-scale production of TBCs. The sol-gel coating offers good thermal insulation and corrosion resistance but may have lower adhesion strength than other techniques. The study's findings suggest that the TBC technique should be based on specific requirements of the applications, such as temperature range, thermal cycling conditions, and component geometry, to protect components from high-temperature degradation. Further research is needed to optimize TBC techniques for specific high-temperature applications and improve their performance in harsh environments.

Keywords: Thermal barrier coating, Thermal insulation, Extreme heat, Thermal cycle, Heat transfer.

1 | Introduction

There is an important need to enhance the thermo-mechanical performance of systems operating in extremely hot and corrosive environments. Equipment's heat reduces its useful life if it is not removed promptly. Thermal Barrier Coatings (TBCs) are effective thermal resistance coatings that shield heat-affected systems from surface deterioration. TBCs have a high thermal resistance, which makes heat transfer difficult. Engine

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blades in power plants, commercial aviation engines, gas turbine flame tubes, rocket engine injectors, and semiconductor substrates are all treated with TBCs [1]. Gas turbine combustors and turbines, as well as components used to control exhaust heat in automobiles, are examples of components that frequently have metallic surfaces treated with TBCs, an advanced materials system. TBCs are multilayer coatings applied to the substrate of interest and consist of a metallic bond coat and a ceramic topcoat. As a result of its low thermal conductivity and strain-compliant ceramic structure, the ceramic topcoat offers thermal protection. The bond coat increases adhesion by matching thermal expansion. It forms an oxidation barrier, forming a Thermally Generated Oxide (TGO), a slow-growing oxide like Aluminum Oxide (Al2O3) [2]. The ceramic topcoat for TBCs has to match the substrate's coefficient of thermal expansion and have a low thermal conductivity (<2 W/m/K); however, other compositions may be used to make these coatings. Topcoat ceramics with 7% Yttria-Stabilized Zirconia (7YSZ) are the most popular choice for TBCs. Low thermal conductivity, phase stability, and erosion resistance are all qualities that 7YSZ possesses to a good degree [3]. Materials such as MCrAlY compositions and aluminides from the platinum group are commonly used as bond coats.

Ceramic topcoats are often applied using Electron Beam-Physical Vapour Deposition (EB-PVD) or plasma spray, whereas TBC bond coat layers can be produced using chemical or physical deposition processes. Either of these methods may produce coatings with microstructures adaptable to specific applications; they are erosion-resistant, have low thermal conductivity, and are strain-compliant [4], [5]. Coatings of thermally insulating materials, ranging in thickness from 100 μm to 2 mm, protect components from high and sustained heat loads and may withstand a significant temperature differential between the load-bearing metals and the coating surface. These coatings improve the life of parts by minimizing oxidation and thermal fatigue, allowing for greater operating temperatures while limiting the heat exposure of structural components. Working fluid temperatures greater than the melting point of the metal airfoil can be achieved in some turbine applications with the help of TBCs and active film cooling. There is a strong incentive to create new and improved TBCs since there is a growing need for more efficient engines that can run at higher temperatures, have longer lifespans, and thinner coatings to decrease parasitic mass for moving and rotating components. Heat shields and TBCs have comparable material requirements; emissivity is typically more important in the latter use. When tested in harsh thermo-mechanical conditions, an effective TBC must adhere to specific standards [6].

To handle stresses caused by thermal expansion when heated and cooled, a TBC coating must have sufficient porosity, and its thermal expansion coefficients must be properly matched to those of the metal surface. Phase stability is necessary to keep the coating from cracking or spalling due to the large volume changes during phase shifts. Parts that spin, move, or come in contact with air must have good mechanical qualities, and air-breathing engines must also have oxidation resistance. For this reason, a TBC needs to have a high melting point, not undergo phase transformation between room temperature and operating temperature, have a low thermal conductivity, be chemically inert, have a similar thermal expansion match with the substrate, adhere well to the substrate, and have a low sintering rate for a porous microstructure to be effective [7]. Ceramic materials often possess the necessary qualities, which significantly restricts the range of materials that may be utilized. When gas turbine engines reach their maximum working temperatures- 700 °C-a- a Thermally-Grown Oxide (TGO) layer is formed due to bond-coat oxidation. For many high-temperature uses, the TGO layer will inevitably occur; hence, TBCs are often engineered to promote uniform and gradual TGO layer growth [8], [9]. In this kind of TGO, the structure has a low oxygen diffusivity, which means that metal diffusion from the bond coat, not oxygen diffusion from the topcoat, controls continued developmentd.

2 | Historical Development of TBCs

The history of TBCs can be traced back to the early 20th century when researchers began exploring ways to improve the thermal resistance of materials used in high-temperature applications. One of the earliest developments in TBC technology can be attributed to the work of Robert C. Tucker, who, in the 1950s, pioneered ceramic coatings to protect turbine blades in gas turbine engines [10]. These early coatings were primarily made of alumina or Zirconia (ZrO2) and were applied using techniques such as plasma spraying or

Physical Vapour Deposition (PVD). Over the years, researchers continued to refine and improve TBCs, developing more advanced coatings with enhanced thermal and mechanical properties. Another critical historical development in TBCs can be traced back to the 1960s when researchers began exploring ceramic materials as thermal insulators. This led to the development the first generation of TBCs, primarily based on Yttria-Stabilized Zirconia (YSZ) coatings [11]. In the 1980s, the introduction of YSZ as a TBC material revolutionized the industry, as it offered superior thermal insulation and resistance to thermal cycling. This breakthrough paved the way for the widespread adoption of TBCs in gas turbine engines, where they are now used to protect components such as turbine blades, combustors, and exhaust systems [12].

In addition to aerospace applications, TBCs have also been found to be helpful in power generation, automotive, and other high-temperature industries. Researchers started investigating new materials and coating techniques as the demand for more efficient and durable TBCs grew. This led to the development of second-generation TBCs incorporating advanced ceramics such as rare earth oxides and pyrochlores. These materials offered improved thermal stability and resistance to thermal cycling, making them ideal for high-temperature applications in aerospace, power generation, and other industries [13].

In recent years, there has been a shift towards developing third-generation TBCs, which aim to enhance the performance and durability of coatings further. This has been achieved using novel materials such as TBCs with self-healing properties and advanced deposition techniques such as Electron Beam Physical Vapour Deposition (EB-PVD) and plasma spray processes. Overall, the evolution of TBCs has been driven by the need to address the challenges posed by high-temperature applications, such as thermal stress, oxidation, and corrosion. By continuously improving the materials and techniques used in TBCs, researchers have enhanced the efficiency and reliability of components operating in extreme heat environments [14]. Significant materials, techniques, and performance advancements have marked the history and evolution of TBCs. It is a testament to the ingenuity and innovation of researchers and engineers in materials science. From humble beginnings in the early 20th century to widespread use in modern industrial applications, TBCs have come a long way in enhancing the performance and efficiency of critical components [15]. As industries continue to push the boundaries of high-temperature applications, developing TBCs will play a crucial role in ensuring the reliability and efficiency of components operating under extreme heat conditions.

3|Advancements in the Field of TBCS

Over the years, significant advancements have been made in developing TBCs, leading to improved thermal insulation, durability, and reliability, as well as the emergence of new materials, coating techniques, and performance enhancements. These coatings protect the underlying components from extreme temperatures, corrosion, and wear, thereby extending their service life and reducing maintenance costs. The various advancements in the field of TBCS are highlighted as follows:

I. One of the critical ground-breaking advancements in TBCs is using novel materials with superior thermal and mechanical properties. For instance, the introduction of YSZ as a topcoat material has significantly enhanced the thermal resistance and thermal conductivity of TBCs. YSZ has a high melting point, excellent thermal shock resistance and thermal insulation properties, high-temperature stability, good adhesion to substrate materials and low thermal conductivity, making it an ideal choice for high-temperature applications. Additionally, incorporating rare earth oxides, such as gadolinium and cerium, into the YSZ matrix has further improved the thermal stability and erosion resistance of TBCs. The development of YSZ-based TBCs has significantly improved the thermal protection of components in gas turbines, diesel engines, jet engines, industrial furnaces and other high-temperature-based components [16], [17].

II. Another significant advancement in TBCs is the development of advanced deposition techniques, such as EB-PVD and Atmospheric Plasma Spraying (APS). These techniques allow for the precise control of coating thickness, microstructure, and composition, resulting in improved adhesion, thermal insulation, thermal barrier performance, durability and erosion resistance. EB-PVD, in particular, has been widely adopted in the aerospace industry for its ability to produce dense, columnar microstructures with low thermal conductivity and high thermal shock resistance, while APS is preferred for its cost-effectiveness and scalability in industrial applications [18], [19].

III. Incorporating novel materials such as rare earth oxides, ceramic composites, and nanomaterials has led to the development of TBCs with enhanced thermal and mechanical properties. For example, adding rare earth oxides like Gadolinium Zirconate (GZO) has improved the thermal stability and erosion resistance of TBCs, making them suitable for harsh operating conditions. Similarly, ceramic composites and nanomaterials have enabled the development of TBCs with superior thermal conductivity, oxidation resistance, and mechanical strength [20], [21].

IV. Integrating TBCs with other advanced materials, such as Environmental Barrier Coatings (EBCs) and bond coats, has led to synergistic effects in enhancing high-temperature components' overall performance and durability. EBCs are designed to protect TBCs from hot corrosion, oxidation, and thermal cycling, while bond coats provide a strong bond between the TBC and the substrate material. By optimizing the composition and microstructure of these coatings, researchers have achieved superior thermal protection and mechanical integrity in harsh operating conditions [22], [23].

The advancements in TBCs have revolutionized high-temperature applications by providing enhanced thermal protection, durability, and reliability. Using novel materials, advanced deposition techniques, and integrated coating systems has paved the way for improved performance and efficiency in high-temperature-based components. As research in this field continues to evolve, further innovations are expected to be made to address the challenges of higher operating temperatures, longer service life, and reduced environmental impact.

4 | Selection Criteria for TBCs in High-temperature Applications

The selection of appropriate TBCs is essential to ensure the longevity and performance of these components under extreme operating conditions. The critical selection criteria for TBCs in high-temperature applications and the importance of considering these factors in the decision-making process are as follows:

I. One of the primary considerations in selecting TBCs for high-temperature applications is the thermal stability of the coating material. TBCs must withstand the high temperatures and thermal cycling experienced in these environments without undergoing significant degradation. Materials with high melting points and low thermal conductivity, such as YSZ, are commonly used for TBCs due to their excellent thermal stability [24].

II. Another essential criterion for TBC selection is the adhesion strength between the coating and substrate. Poor adhesion can lead to delamination and spalling of the coating, compromising the protection of the underlying component. Various techniques, such as surface roughening and the use of bond coats, can be employed to improve the adhesion of TBCs to the substrate [25].

III. Furthermore, the mechanical properties of TBCs, such as hardness and toughness, are critical factors to consider in high-temperature applications. TBCs must withstand mechanical stresses, such as thermal expansion and contraction, without cracking or failing. Coating materials with high hardness and toughness, such as ceramic-metal composites, are often preferred for these applications [26].

IV. In addition to thermal stability, adhesion strength, and mechanical properties, the environmental resistance of TBCs is also an important consideration. TBCs must withstand corrosive gases, thermal shocks, and other environmental factors in high-temperature applications. Coating materials with good chemical resistance, such as alumina-based TBCs, are commonly used in these environments.

The selection of TBCs for high-temperature applications is a complex and critical process that requires careful consideration of various factors, including thermal stability, adhesion strength, mechanical properties, and environmental resistance. By evaluating these criteria and choosing TBCs that meet the application's specific requirements, engineers and designers can ensure the long-term performance and reliability of high-temperature components.

5 | Materials for the Fabrication of TBCs

TBCs are designed to provide thermal insulation, reduce heat transfer, and increase the lifespan of the components. Several vital materials are used to fabricate TBCs, each with unique properties and advantages.

I. One of the most commonly used materials for TBCs is YSZ. YSZ is known for its high thermal stability, low thermal conductivity, and excellent resistance to thermal shock. It is often used as the topcoat in TBC systems due to its ability to withstand high temperatures and provide effective thermal insulation. Additionally, YSZ can be quickly deposited using techniques such as plasma spraying or EB-PVD, making it a versatile material for TBC fabrication [27].

II. Another vital material for TBCs is a bond coat, which improves the adhesion between the substrate and the topcoat. Nickel-based superalloys are commonly used as bond coats due to their high-temperature strength, oxidation resistance, and compatibility with YSZ topcoats. These materials help to prevent delamination and spalling of the TBC system under thermal cycling conditions, ensuring the longevity and performance of the coated components [28].

III. Alumina, also known as Al2O3, is widely used in TBCs due to its high melting point, excellent thermal conductivity, and chemical stability. Alumina-based TBCs have been shown to provide adequate thermal insulation and protection against oxidation in high-temperature environments. Additionally, alumina can be easily processed into thin films, making it suitable for coating applications [29].

IV. Mullite, a compound of Alumina and Silica (Al6Si2O13), is another material that has gained attention for TBCs due to its low thermal conductivity and high-temperature stability. Mullite-based TBCs have been found to exhibit superior thermal insulation properties compared to other materials, making them ideal for use in demanding thermal environments. Furthermore, mullite has good mechanical strength and resistance to thermal shock, making it a reliable choice for TBC applications. Mullite-based materials provide high-temperature strength and resistance to thermal shock [30].

V. Rare earth oxides, such as Yttria (Y2O3) and Ceria (CeO2), have also been investigated for TBCs due to their unique properties, including high thermal expansion coefficients and excellent thermal stability. YSZ is a commonly used rare earth oxide material in TBCs, as it exhibits low thermal conductivity and high-temperature resistance. Ceria-based TBCs have also shown promise in providing adequate thermal insulation and protection against oxidation in high-temperature environments. Rare earth oxides, such as GZO, are known for their low thermal conductivity and excellent phase stability at high temperatures, making them suitable for TBC applications in extreme environments [31].

Overall, the selection of materials for TBC fabrication depends on the application's specific requirements, including temperature range, thermal cycling conditions, and performance expectations. By utilizing a combination of crucial materials such as YSZ, bond coats, and other ceramic compounds, engineers can design TBC systems that effectively protect components from high temperatures and extend their operational lifespan [32]. The continuous development and optimization of TBC materials will further enhance the performance and reliability of coated components in various industrial applications.

6 | Thermal Barrier Coating Layout

Modern materials known as TBCs can include numerous layers, each contributing to the overall system's improved performance and longevity. As seen in *Fig. 1*, TBCs consist of four main layers: the metal substrate, the metallic bond coating, the TGO layer, and the topcoat layer.

I. The metal substrate is the base material onto which the TBC is applied. It is typically made of nickel-based super-alloys or other high-temperature materials commonly used in aerospace and power generation industries. The substrate provides the structural support for the coating system and must have good mechanical properties to withstand the thermal and mechanical stresses experienced during operation [33].

II. The metallic bond coating is applied directly onto the metal substrate to improve the adhesion of the subsequent layers. This layer is typically made of nickel-chromium-aluminium alloys, which form a strong bond with the substrate and topcoat layer. The metallic bond coating also acts as a diffusion barrier, preventing oxidation of the metal and the migration of harmful elements from the substrate into the topcoat layer [15].

III. The thermally grown oxide layer is a unique feature of TBCs that forms during the initial exposure to high temperatures. This layer consists of oxides of the metallic elements in the bond coating, which grow and densify upon heating. The thermally grown oxide layer provides thermal insulation and protects the underlying layers from oxidation and corrosion. It also helps reduce the coating system's thermal conductivity, improving its overall thermal performance [34].

IV. The topcoat layer is the outermost layer of the TBC, designed to provide additional thermal protection and resistance to environmental degradation. This layer is typically made of ceramic materials such as YSZ, which have low thermal conductivity and high-temperature stability. The topcoat layer also acts as a thermal barrier, reducing the heat transfer between the hot gas environment and the metal substrate [35].

The metal substrate, metallic bond coating, thermally grown oxide layer, and topcoat layer are essential components of TBCs that protect metal substrates from high-temperature degradation. By understanding the role of each layer in the coating system, engineers can design and optimize TBCs for specific applications, improving the performance and longevity of critical components in demanding environments.

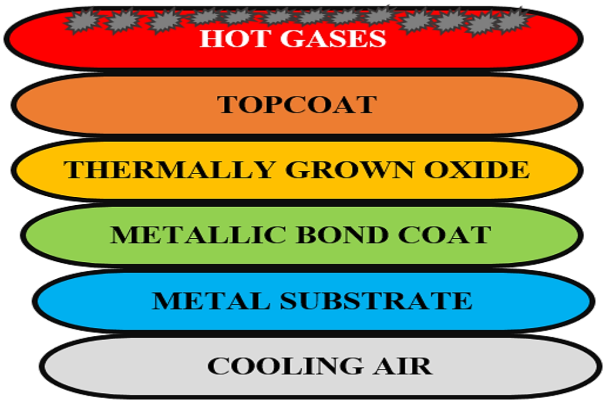

Fig. 1. Diagram of thermal barrier coating layout.

Topcoats made of YSZ are stable at the normal operating temperatures usually seen in TBC applications and have extremely low conductivity. By maintaining a lower temperature than the surface, this ceramic layer produces the TBC's biggest thermal gradient [36]. Unfortunately, YSZ undergoes unsavoury phase changes, going from t'-tetragonal to tetragonal to cubic to monoclinic, when heated over 1200 °C. The top layer becomes cracked as a result of these phase changes. In an attempt to find a replacement for the YSZ ceramic topcoat, researchers have recently discovered a number of other ceramics, such as rare earth zirconates, that perform better at temperatures beyond 1200 °C but have lower fracture toughness than YSZ [37]. The production of the TGO may be accelerated, and the large concentration of oxygen-ion vacancies in these zirconates may facilitate oxygen transport. Coating spalling, a disastrous form of failure for TBCs, is possible with sufficiently thick TGO. Coatings with excellent oxidation resistance, such as mullite or alumina, would be necessary for their application. A metallic coating resistant to oxidation is applied directly onto the metal substrate to form the bond coat. It usually has a thickness ranging from 75 to 150 μm and is composed of an alloy of NiCrAlY or NiCoCrAlY; however, other bond coatings are constructed of Ni and Pt aluminides. Bond coats primarily prevent oxidation and corrosion of metal substrates, especially those exposed to oxygen and other corrosive elements through the porous ceramic top layer [38].

7 | Types of TBCs

TBCs are essential in protecting high-temperature materials from degradation in harsh environments or protecting the underlying metal substrate from heat and corrosion. They are widely used in various applications due to their unique properties and performance characteristics. The various types of TBCs are highlighted as follows:

I. ThermaCote is a proprietary TBC developed by ThermaCote, Inc. It is a high-performance ceramic coating that provides excellent thermal insulation and corrosion resistance. ThermaCote is applied as a spray-on coating and forms a protective barrier that can withstand temperatures up to 2000°F. Its unique formulation allows superior adhesion to various substrates, making it an ideal choice for aerospace, automotive, and industrial applications [39].

II. YSZ is a well-known TBC material that consists of ZrO2 stabilized with Y2O3. YSZ is widely used in gas turbine engines and other high-temperature applications due to its high thermal conductivity, low thermal expansion coefficient, and excellent thermal shock resistance. The Y2O3 stabilization helps prevent phase transformation at high temperatures, making YSZ a durable and reliable TBC material [40].

III. GZO and Lanthanum Zirconate (LZO) are emerging TBC materials that offer unique advantages over traditional YSZ coatings. GZO is a promising TBC material with superior thermal conductivity and phase stability compared to YSZ. GZO coatings have improved thermal barrier performance and durability in high-temperature environments, making them a preferred choice for next-generation TBC applications [41].

IV. LZO is another advanced TBC material with excellent thermal insulation and chemical stability. LZO coatings have demonstrated superior resistance to thermal cycling and oxidation, making them suitable for demanding aerospace and power generation applications. The unique combination of lanthanum and ZrO2 in LZO coatings provides enhanced thermal barrier performance and extended service life [42].

V. GZO is a promising TBC material known for its high thermal stability and low thermal conductivity. It has been shown to exhibit excellent resistance to thermal cycling and thermal shock, making it a suitable candidate for high-temperature applications. Additionally, GZO has a high melting point and good chemical stability, further enhancing its performance as a TBC material [43].

VI. Yttria-Calcia-Zirconia (YCZ) is another popular TBC material with excellent thermal insulation properties and high-temperature resistance. YCZ has a low thermal conductivity and high thermal expansion coefficient, which effectively protects the substrate from heat and thermal stresses. Furthermore, YCZ has good adhesion to the substrate, ensuring long-term durability and performance of the TBC system [44].

VII. Magnesium Zirconate (MZO) is a relatively new TBC material with promising thermal insulation and durability results. MZO exhibits low thermal conductivity and high thermal stability, making it suitable for high-temperature applications. Additionally, MZO has good chemical resistance and mechanical properties, further enhancing its performance as a TBC material [45].

VIII. Hafnium Oxide (HfO2) is a well-known TBC material with excellent thermal insulation properties and high-temperature resistance. HfO2 has a high melting point and low thermal conductivity, making it an ideal candidate for TBC applications. Furthermore, HfO2 has good adhesion to the substrate and excellent thermal stability, ensuring long-term performance and reliability of the TBC system [46].

IX. Al2O3 is one of the most widely used TBC materials due to its high thermal stability, excellent thermal conductivity, and resistance to thermal shock. It is typically applied using plasma spraying or EB-PVD techniques. Al2O3 coatings protect against high temperatures, preventing the underlying substrate from overheating and maintaining its structural integrity [47].

X. Platinum-based TBCs are known for their exceptional thermal conductivity and oxidation resistance. These coatings are often used in aerospace applications where high thermal efficiency is crucial. Platinum-based TBCs are typically applied using techniques such as sputtering or Chemical Vapour Deposition (CVD), resulting in a thin, uniform coating that provides superior thermal protection [48].

XI. Nickel-based TBCs are widely used in industrial gas turbines due to their excellent corrosion resistance and mechanical properties. These coatings are typically applied using High-Velocity Oxy-Fuel (HVOF) or air plasma spraying. Nickel-based TBCs form a dense, adherent layer that protects the underlying substrate from high temperatures and corrosive environments [49].

Cobalt-based TBCs are known for their high-temperature resistance and thermal stability. These coatings are commonly used in applications with extreme heat and thermal cycling, such as in power generation systems. Cobalt-based TBCs are typically applied using techniques such as thermal spraying or PVD, resulting in a durable, protective coating that enhances the performance and longevity of the substrate [50].

8 | Processing Techniques for TBCs

Developing advanced coatings and processing methods is a field of active research. Several examples are addressed in this section, which have been used to create TBCs with some of the lowest reported thermal conductivities without sacrificing thermal cyclic durability. A number of processing techniques have been developed in recent times for TBS, some of which include the following:

I. Electron Beam-Physical Vapor Deposition (EB-PVD): EB-PVD is a highly advanced and sophisticated technique that involves the deposition of ceramic coatings onto substrates using an electron beam to vaporize the coating material (see *Fig. 2*). This process allows for precise control over the microstructure and composition of the coating, resulting in superior thermal insulation properties and excellent adhesion to the substrate. Additionally, EB-PVD coatings exhibit high-temperature stability, low thermal conductivity, and resistance to thermal cycling, making them ideal for applications in gas turbine engines and other high-temperature environments [12].

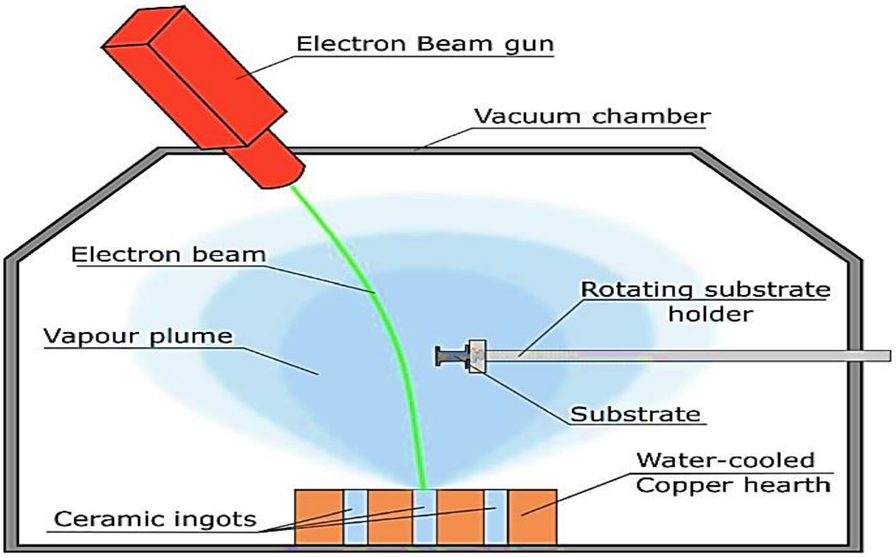

Fig. 2. Electron-beam physical vapour deposition of thermal barrier coatings.

I. Atmospheric Plasma (AP): AP spraying is a more cost-effective and versatile technique for applying TBCs, where ceramic powders are fed into a plasma jet and accelerated onto the substrate surface (see Fig. 3). While AP coatings may not offer the same level of control and uniformity as EB-PVD coatings, they are suitable for large-scale production and repair applications. AP coatings also exhibit good thermal insulation properties and can be tailored to meet specific performance requirements [51].

II. Plasma-Enhanced Chemical Vapour Deposition (PECVD): PECVD is another promising technique for TBCs, where plasma deposits thin films of ceramic materials onto substrates at relatively low temperatures, as demonstrated in Fig. 4. This process allows for the deposition of conformal and uniform coatings with excellent adhesion and thermal insulation properties. PECVD coatings are also known for their high chemical and thermal stability, making them suitable for applications in harsh environments [35].

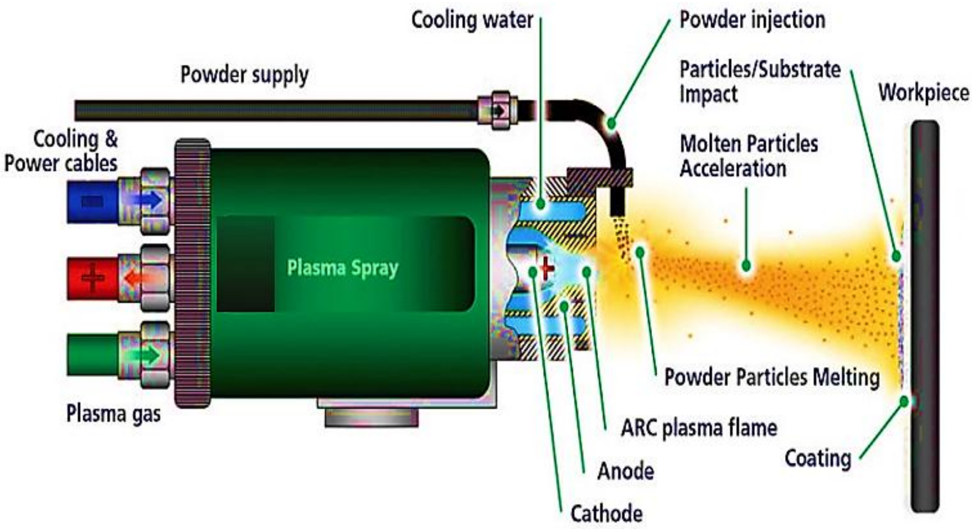

Fig. 3. Atmospheric plasma spray.

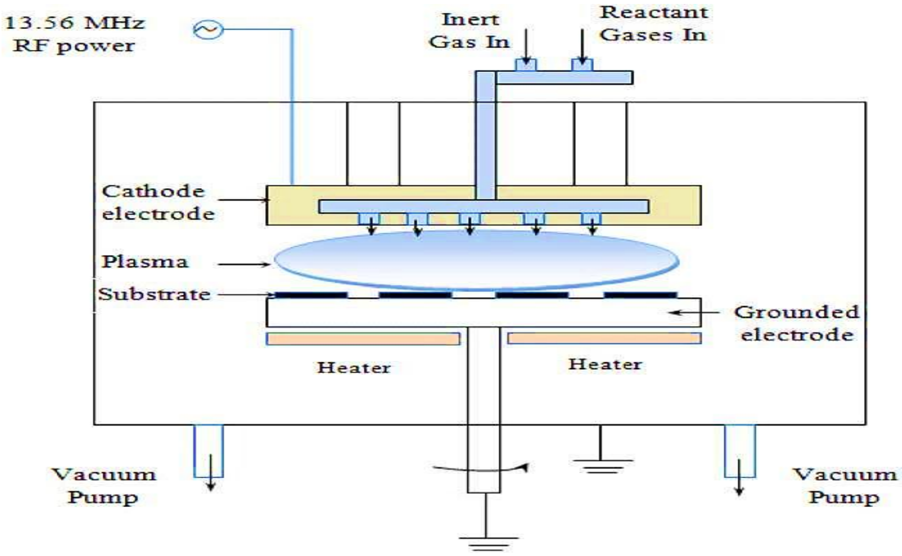

Fig. 4. Plasma-enhanced chemical vapour preposition process.

I. Electrostatic Spray-Assisted Vapour Deposition (ESAVD): ESAVD is a relatively new technique combining vapour deposition and electrostatic spraying benefits. In this process, a precursor material is vaporized and then sprayed onto the substrate using an electrostatic field. The charged particles are attracted to the substrate, resulting in a uniform and dense coating. ESAVD offers excellent control over the coating thickness and composition, making it ideal for producing high-quality TBCs. In terms of performance, ESAVD coatings have been shown to exhibit superior thermal insulation properties. This is due to the dense and uniform microstructure of ESAVD coatings, which provide better resistance to heat transfer. Additionally, ESAVD coatings have been found to have higher bond strength and lower porosity, resulting in improved durability and longevity. Despite these advantages, ESAVD has some limitations, such as the need for specialized equipment and expertise.

II. Solution Precursor Plasma Spray (SPPS): SPPS is a well-established technique that uses a plasma torch to melt and spray a precursor solution onto the substrate. The high temperatures generated by the plasma torch allow for the rapid deposition of coatings, making SPPS a cost-effective and efficient method for producing TBCs.

III. The Sol-gel process is a versatile and widely used method for synthesizing inorganic materials, particularly for producing thin films and coatings. This process involves converting a precursor solution into a solid material through chemical reactions, typically hydrolysis and condensation reactions (see *Fig. 5*). The resulting material can have many properties, including high purity, uniformity, and controlled porosity. One of the Sol-gel process's critical applications is producing TBCs for high-temperature applications, such as gas turbines. TBCs protect the underlying substrate from high temperatures, thermal shocks, and corrosion, thereby extending the lifespan and performance of the component. The Sol-gel process offers several advantages for the production of TBCs, including the ability to tailor the composition, microstructure, and coating properties to meet specific requirements. By tailoring the composition and microstructure of the coating, it is possible to achieve improved thermal insulation, mechanical strength, and corrosion resistance [52].

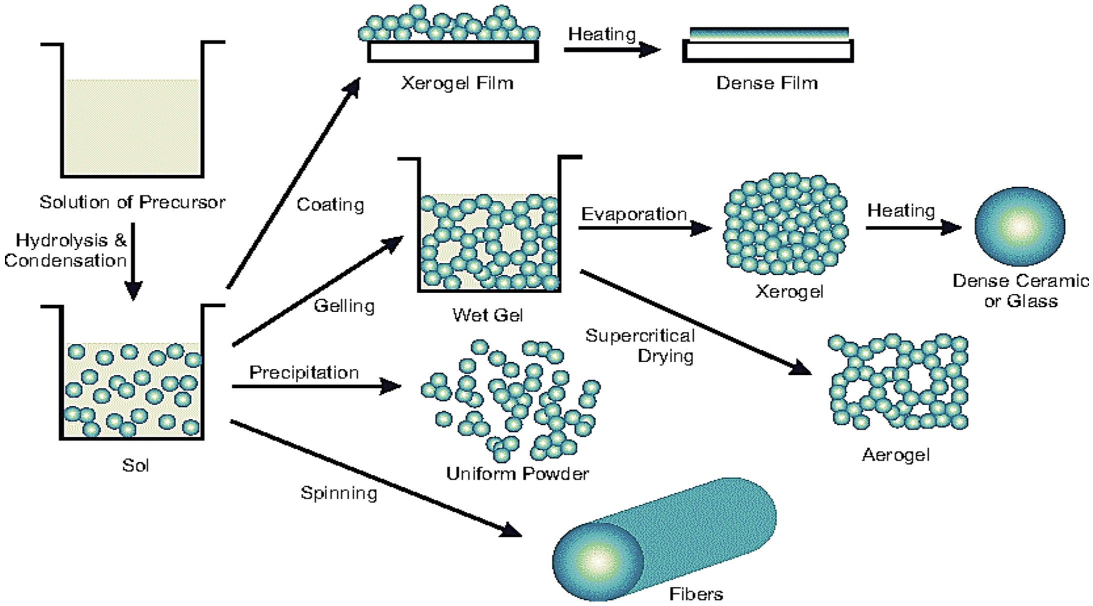

Fig. 5. Sol-gel process for thermal barrier coating.

I. Composite Sol-gel processing techniques have been developed to enhance TBCs' performance further. These techniques involve incorporating additional materials, such as nanoparticles, fibers, or polymers, into the Sol-gel matrix to improve the coating's mechanical, thermal, and chemical properties. For example, adding ceramic nanoparticles can increase the hardness and wear resistance of the TBC, while incorporating fibres can enhance the toughness and crack resistance. One of the critical challenges in composite Sol-gel processing is achieving uniform dispersion of the additional materials within the Sol-gel matrix. Agglomeration and poor adhesion between the components can lead to a decrease in the performance of the coating. Various methods, such as ultrasonication, mechanical mixing, and surface modification, have been developed to improve the dispersion and adhesion of the composite materials.

Spark Plasma Sintering (SPS): SPS is a relatively new sintering technique that has gained popularity in recent years due to its ability to produce dense and high-quality materials quickly. The process involves applying pressure and electrical current to the powder material simultaneously, resulting in rapid heating and densification (see *Fig. 6*). This leads to the formation of TBCs with excellent mechanical properties and thermal stability. Additionally, SPS allows for precise control over the microstructure and composition of the coating, making it ideal for producing customized TBCs for specific applications [53].

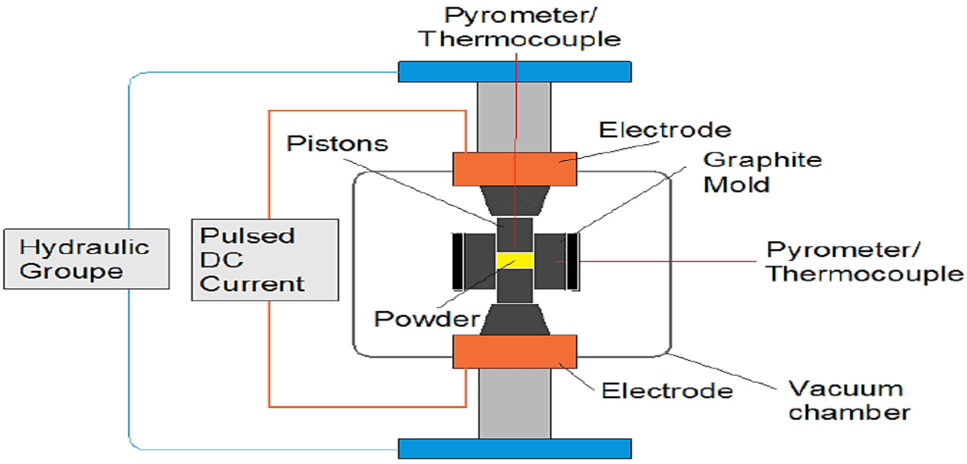

Fig. 6. Diagram of spark plasma sintering process.

I. Low-Pressure Plasma Spraying (LPPS): LPPS, more suitable for large-scale production and complex geometries, is a well-established thermal spraying technique widely used for TBCs in various industries. The process involves feeding powder material into a plasma jet, which then deposits the molten particles onto the substrate surface. LPPS is known for its high deposition efficiency and ability to coat complex geometries, making it suitable for large-scale production of TBCs. However, the coatings produced by LPPS are typically porous and have lower thermal conductivity compared to those produced by SPS.

While the aforementioned techniques are effective for processing TBCs, some offer superior coating quality and performance. The precise control over the coating process and the ability to use a broader range of materials make them more versatile and reliable options for TBC applications. Further research and development in this area are needed to explore the potentials of each TBCs processing technique fully.

9 | Characteristics of TBCs

TBCs increase the system's efficiency when applied and improve performance against the detrimental effects of extreme heat and temperatures. It showcases thermal insulation and expansion characteristics [53]. These coatings possess a unique combination of properties that make them ideal for this application. Some key characteristics of TBCs include low thermal conductivity, high thermal shock resistance, high coefficient of thermal expansion, high surface emissivity, high melting point, low density, resistance to corrosion, resistance to mechanical erosion, and oxidation resistance. These characteristics are highlighted as follows:

I. One of the most essential properties of TBCs is their low thermal conductivity. This property allows the coatings to effectively insulate the underlying component from high temperatures, reducing heat transfer and minimizing thermal stresses [54].

II. High thermal shock resistance is another critical characteristic of TBCs, as it enables the coatings to withstand rapid changes in temperature without cracking or spalling. This is particularly important in applications where components are subjected to frequent thermal cycling.

III. The high coefficient of thermal expansion of TBCs is also a key feature, as it allows the coatings to expand and contract with the underlying component without delaminating. This property helps to maintain the integrity of the coating and prolong its service life [55].

IV. Additionally, the high surface emissivity of TBCs allows them to radiate heat efficiently, further enhancing their thermal insulation properties.

V. TBCs also exhibit a high melting point, which enables them to withstand extreme temperatures without degrading. This property is essential in high-temperature applications that expose components to intense heat.

VI. Furthermore, the low density of TBCs helps to minimize the added weight to the component, making them suitable for aerospace and other weight-sensitive applications.

VII. TBCs are also highly resistant to corrosion, mechanical erosion, and oxidation. This makes them ideal for use in harsh environments where components are exposed to corrosive gases, abrasive particles, and oxidative conditions. The ability of TBCs to withstand these challenges helps extend the coated components' service life and reduce maintenance costs [56].

The unique combination of properties exhibited by TBCs makes them indispensable for protecting components in high-temperature environments. Their low thermal conductivity, high thermal shock resistance, high coefficient of thermal expansion, high surface emissivity, high melting point, low density, corrosion resistance, resistance to mechanical erosion, and oxidation resistance all contribute to their effectiveness in insulating and safeguarding components from the damaging effects of heat [57]. As technology advances, developing new and improved TBCs will play a crucial role in enhancing the performance and durability of components in a wide range of industrial applications.

10 | Applications of TBCs

TBCs have become essential in various industrial applications, including gas turbines, diesel engines, combustion chambers, and piston rings. These coatings protect critical components from high temperatures and thermal stresses, improving their performance and longevity. The various applications of TBCs are highlighted as follows:

I. One of the key applications of TBCs is on nozzle guide vanes in gas turbines. These vanes are subjected to extremely high temperatures and thermal gradients during operation, which can lead to thermal fatigue and degradation. By applying a TBC to the surface of the vanes, the heat transfer is reduced, and the temperature of the underlying material is effectively lowered, thereby extending the lifespan of the vanes [58].

II. Transition ducts in gas turbines also benefit from TBCs, as they are exposed to high temperatures and thermal cycling. The coating acts as a thermal insulator, reducing the heat flux to the duct walls and preventing overheating and premature failure.

III. TBCs protect the metal components in combustor cans from the intense heat generated during combustion. By applying a TBC to the inner surfaces of the cans, the temperature is reduced, and the risk of thermal degradation is minimized.

IV. Turbine blades in gas turbines are another critical component that benefits from TBCs. These blades operate at high temperatures and are subjected to thermal stresses, which can lead to creep and fatigue. By applying a TBC to the surface of the blades, the temperature is reduced, and the risk of thermal damage is mitigated.

V. In diesel engines, TBCs are used in combustion chambers to improve efficiency and reduce emissions. The coating helps to maintain higher combustion temperatures, leading to better fuel efficiency and lower emissions.

VI. Cylinder heads and piston rings in internal combustion engines also benefit from TBCs. The coating helps to reduce friction and wear, leading to improved performance and longevity of these components [59].

TBCs are crucial in protecting critical components in various industrial applications. By reducing heat transfer and thermal stresses, TBCs improve the performance and longevity of components such as nozzle guide vanes, transition ducts, combustor cans, turbine blades, gas turbines, diesel engines, combustion chambers, cylinder heads, and piston rings. Their widespread use in these applications highlights the importance of TBCs in enhancing the efficiency and reliability of industrial systems.

11 | Advantages of TBCs in High Temperature Applications

TBCs have become increasingly popular in high-temperature applications due to their numerous advantages and benefits. TBCs are thin layers of ceramic material that are applied to the surface of components exposed to high temperatures, such as gas turbine blades, to protect them from thermal degradation. The advantages and benefits of TBCs in high-temperature applications are highlighted as follows:

I. One of the main advantages of TBCs is their ability to significantly reduce the operating temperature of components, thereby extending their service life. By insulating the component from the high temperatures, TBCs help to minimize thermal stress and prevent premature failure. This is particularly important in applications where components are subjected to extreme temperatures, such as gas turbines used for power generation or aircraft engines [4], [5].

II. TBCs can improve the efficiency of high-temperature applications. By reducing the heat transfer to the component, TBCs help to increase the system's overall efficiency. This can result in cost savings and improved performance, making TBCs a valuable investment for industries that rely on high-temperature applications.

III. TBCs can also enhance the durability and reliability of components in high-temperature applications. The protective layer provided by TBCs helps to shield the component from harsh environmental conditions, such as corrosion and oxidation, which can degrade the material over time. This can lead to longer service life and reduced maintenance costs, making TBCs a cost-effective solution for industries that operate in high-temperature environments.

IV. TBCs are known for increased engine power; by insulating the engine components, TBCs help to reduce heat loss and improve combustion efficiency, resulting in a more powerful engine.

V. TBCs also contribute to reduced fuel consumption by reducing heat transfer to the surrounding environment; TBCs help to maintain higher temperatures within the engine, which leads to more complete combustion of fuel. This, in turn, results in improved fuel efficiency and reduced fuel consumption.

VI. TBCs also play a crucial role in improving fuel economy. By reducing heat loss and improving combustion efficiency, they help optimize the engine's overall performance, leading to a better fuel economy. This is particularly important in today's environmentally conscious society, where reducing fuel consumption and emissions is a top priority.

VII. TBCs have the advantage of improved thermal conductivity. TBCs are designed to have low thermal conductivity, which means they can effectively insulate components from heat. This can help reduce heat transfer to the underlying substrate, improving thermal efficiency and performance.

VIII. TBCs offer high thermo-mechanical stability. This implies that the coatings are able to withstand high temperatures and mechanical stresses without degrading or failing. This stability is crucial when components are exposed to extreme conditions, such as gas turbine engines or industrial furnaces.

IX. TBCs have the advantage of reducing fatigue and stress on components. When exposed to high temperatures, metal parts can experience thermal expansion and contraction, leading to fatigue and stress. TBCs act as a barrier between the metal component and the high temperatures, reducing the thermal gradients and minimizing the stress on the component. This can help extend the component's lifespan and prevent premature failure [60].

X. TBCs can also increase the lifespan of metal parts. By providing a protective layer that shields the metal from harsh environments, TBCs can help to prevent corrosion, oxidation, and other forms of degradation. This can result in longer-lasting components that require less frequent maintenance and replacement, ultimately saving time and money for industries that rely on high-performance materials.

XI. TBCs can protect metal structural components from extreme temperatures. In applications where components are exposed to high temperatures, such as gas turbines or exhaust systems, TBCs can help insulate the metal and prevent it from reaching critical temperatures. This can help improve the overall performance and efficiency of the component and reduce the risk of thermal damage or failure.

Additional benefits arise when a bonding layer is used to enhance the adherence of a TBC. A few examples include a decrease in the potential for stress in the top coat and an increase in the coating's resistance to wear and tear. The TBC's total lifespan will also be enhanced thanks to the improvement in thermal shock resistance [61]. The advantages of TBCs make them a valuable tool for improving the performance and efficiency of components in a wide range of industries. By increasing exhaust gas temperature, improving thermal conductivity, and offering high thermo-mechanical stability, TBCs can help enhance critical components' reliability and longevity. These coatings play a crucial role in enhancing the performance and durability of components in industries where high temperatures and thermal cycling are common. By investing in TBCs, industries can benefit from improved reliability, efficiency, and cost savings in the long run. By incorporating TBCs into their engines, manufacturers can enhance their vehicles' performance and contribute to a more sustainable and efficient transportation system.

12 | Conclusion and Recommendation

The research has shown that TBCs can significantly reduce the heat transfer to the underlying substrate, extending the components' lifespan in high-temperature environments. The study has demonstrated that the composition and microstructure of TBCs play a crucial role in determining their thermal insulation properties. By optimizing these factors, researchers have enhanced the thermal resistance of TBCs and improved their overall performance. Despite the advancements made in the field of TBCs, there are still challenges that need to be addressed. For instance, the durability of TBCs under harsh operating conditions remains a concern, as does the development of cost-effective and environmentally friendly coating materials. Findings from this study have laid a solid foundation for further research and development in this area. By continuing to explore new materials and techniques, researchers can further improve the performance and reliability of TBCs, ultimately leading to more efficient and durable thermal protection solutions for a wide range of industrial applications.

The findings from this study on TBCs have provided valuable insights into the performance and characteristics of these coatings in protecting materials from high temperatures, leading to the following recommendations for their effective use in high-temperature environments.

I. One key recommendation based on findings obtained from this study is the importance of selecting the suitable material composition for TBCs. It has been noted that the choice of materials can significantly impact the thermal conductivity, thermal expansion coefficient, and durability of TBCs. Therefore, it is essential to carefully consider the properties of different materials and their compatibility with the substrate material to ensure optimal performance.

II. Another important recommendation is the need for proper surface preparation before applying TBCs. It has been observed that surface roughness, cleanliness, and bond coat quality can significantly influence the adhesion and effectiveness of TBCs. Therefore, following recommended surface preparation procedures is essential to ensure a strong bond between the TBC and the substrate.

III. Another key recommendation is the importance of optimizing the thickness of TBCs for maximum thermal protection. It has been observed that optimal thickness can provide the necessary insulation while minimizing thermal stresses and potential failure modes. Therefore, it is crucial to carefully control the deposition process and monitor the thickness of TBCs to achieve the desired performance.

IV. Another significant recommendation is proper monitoring and maintenance of TBCs in high-temperature applications. Regular inspections, thermal cycling tests, and performance evaluations can help identify potential issues and prevent premature failure of TBCs. Therefore, it is essential to establish a comprehensive maintenance program to ensure the long-term reliability and effectiveness of TBCs in high-temperature environments.

Recommendations based on the findings obtained from this study underscore the importance of material selection, surface preparation, thickness optimization, and maintenance practices. By following these recommendations, industries can enhance the performance and durability of TBCs, ultimately improving the efficiency and reliability of high-temperature components.

Author Contribution

Aniekan Ikpe: Sourcing for materials, writing and development of the paper, Imoh Ekanem: Conceptualization and arrangement, Emem Ikpe: Review and editing. All authors contributed in their own capacity to ensure the successful completion of this research.

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Conflicts of Interest

The authors declare that there is no conflict of interest with the findings derived from this research work. There was no second or third party involved in the conceptualization, numerical simulation, analysis, interpretation of results, or decision-making on the publication of this research.

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