Research on the Application of Thermal Spraying Technology in the Gas Turbine Field

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Abstract:This paper systematically reviews the major research achievements and engineering advancements in thermal spray technology for gas turbine applications, based on a comprehensive logical framework encompassing "operating conditions—coating requirements—process methods—material systems—failure mechanisms—development trends." Chapter 1 serves as an introduction, outlining the research background, technical significance, and overall structure of the paper. Chapter 2 analyzes the service environments of key gas turbine components and their differentiated coating requirements. Chapter 3 provides detailed descriptions of the principles, characteristics, and application scenarios of mainstream thermal spray technologies. Chapters 4 through 7 focus respectively on four primary coating types: thermal barrier coatings, abradable seal coatings, erosion-resistant coatings, and oxidation/corrosion-resistant coatings. Chapter 8 discusses coating failure mechanisms and life prediction methods. Chapter 9 summarizes the entire paper and outlines future research directions. It is hoped that this systematic review will provide valuable references for researchers and engineers involved in gas turbine design and manufacturing, thermal spray process development, and coating materials research.

Key words:thermal spraying technology; gas turbine; thermal barrier coating; wear-resistant coating; plasma spraying; high-velocity oxy-fuel spraying

1 INTRODUCTION

1.1 Research Background

A gas turbine is a thermal rotary machine that converts the chemical energy of fuel into shaft power or thrust. Its basic operating principle is as follows: a compressor compresses air to a high-pressure state; the compressed air mixes with fuel and combusts in the combustion chamber, generating high-temperature and high-pressure gas that expands to produce work inside the turbine. Part of the work drives the compressor to rotate, while the remainder is output externally. Since its practical application in the 1930s, gas turbine technology has undergone tremendous progress from low parameters and short service life in the early days to high parameters and long service life today, evolving into a landmark product that measures a country's industrial foundation and comprehensive scientific and technological strength.

Thermodynamic analysis of the Brayton cycle indicates that the thermal efficiency of a gas turbine mainly depends on the turbine inlet temperature and compressor pressure ratio, and raising the turbine inlet temperature is the most direct approach to improve efficiency. Supported by advances in material science, the turbine inlet temperature has gradually risen from approximately 800 ° C in early jet engines to 1650 - 1750 ° C in state-of-the-art modern aero-engines and heavy-duty gas turbines. This temperature far exceeds the safe service temperature limit (roughly 1100 - 1150 ° C) of the most advanced uncoated nickel-based single-crystal superalloys currently available. In other words, in the highest-temperature zones of gas turbines, the temperature resistance of the base material alone cannot meet service requirements, and thermal barrier coating technology must be adopted to provide external thermal insulation and surface stabilization for hot-section components.

The vital position of thermal spraying technology in the gas turbine industry stems precisely from this fundamental contradiction. Thermal spray coatings form a protective layer with tailored thermal, mechanical and chemical properties on component surfaces, creating an artificial barrier between the superalloy substrate and the extreme gas environment. The performance of this barrier determines whether hot-section components can operate reliably under overtemperature conditions, and it also directly affects overhaul intervals, full-lifecycle costs and safety margins. Statistics show that without thermal barrier coating protection, the service life of turbine blades in modern aero-engines will be reduced by 60% - 80%. Taking General Electric's (GE) LM series heavy-duty gas turbines as an example, the adoption of advanced thermal barrier coatings and abradable seal coatings improves overall unit efficiency by approximately 1.5 to 2 percentage points, equivalent to cutting tens of thousands of tons of carbon dioxide emissions each year, delivering remarkable economic and environmental benefits.

From the perspective of technological evolution, the role of thermal spraying in gas turbines has undergone profound

changes. In the early stage, thermal spraying was mainly used for dimensional restoration during post-failure maintenance. After the 1960s, anti-oxidation coatings represented by aluminide coatings were applied for turbine blade protection, shifting thermal spraying from passive repair to active protection. In the 1980s, the practical application of YSZ thermal barrier coatings marked the formal upgrade of thermal spraying from an auxiliary process to a core technology that determines the performance ceiling of engines. Entering the 21st century, with the emergence of new-generation platforms such as PS-PVD and SPS, thermal spraying has further advanced into a refined stage featuring controllable microstructures, customizable functions and predictable performance. It can be stated that the developmental trajectory of thermal spraying technology and the performance leap of gas turbines are closely interdependent and mutually reinforcing.[1,2]

In China, the gas turbine industry is at a critical stage of transformation from reverse engineering copying to independent forward design. The implementation of the National Science and Technology Major Project for Aero-Engines and Gas Turbines (the "Two Engines Project") has opened up the full innovation chain spanning basic research to engineering application. As one of the most widely applicable surface technologies deployed across numerous production stages, the research depth and engineering maturity of thermal spraying directly impact the development schedule of domestically developed gas turbine models in China. Nevertheless, obvious gaps still exist compared with developed European and American countries in areas including the development of advanced coating materials, manufacturing of high-end spraying equipment, coating life prediction methodologies and database construction, requiring simultaneous intensive efforts in both fundamental research and engineering application.

1.2 Brief History of Thermal Spraying Technology

The origin of thermal spraying technology dates back to the early 20th century. In 1909, Swiss engineer Max Ulrich Schoop invented the world's first practical wire flame spraying device. The equipment melts metal wires via oxyacetylene flame and atomizes the molten metal onto substrate surfaces using compressed air. This pioneering work laid the foundation for thermal spraying technology, and flame spraying is still adopted for certain simple protection applications to this day.

Arc spraying was further proposed by Schoop in 1918. It uses an electric arc generated between two continuously fed metal wires as the heat source; molten metal is atomized by compressed air and deposited to form coatings. Arc spraying features higher deposition efficiency than flame spraying, yet its sprayable materials are limited to conductive metal wires.Plasma spraying technology emerged in the 1960s. It melts powder feedstocks by high-temperature plasma jets generated by direct-current electric arcs (with core temperatures exceeding 15000 ° C), greatly expanding the scope of sprayable materials and enabling thermal spraying of high-melting-point ceramics such as ZrO_2 and Al_2O_3. This breakthrough directly gave rise to thermal barrier coating technology.High-velocity oxy-fuel (HVOF) spraying was invented by James Browning in the early 1980s. Specially designed combustion chambers and nozzles accelerate the flame jet to supersonic speeds (>1000 m/s). The particles carry far higher kinetic energy than those in conventional flame spraying and atmospheric plasma spraying (APS). The resulting carbide and metallic coatings possess extremely high density, making HVOF one of the dominant techniques for fabricating wear-resistant coatings and MCrAlY bond coats ever since.Low-pressure plasma spraying (LPPS) maintains a low-pressure inert atmosphere during spraying, eliminating oxidation loss of oxidation-prone materials during APS processing and providing a reliable processing window for manufacturing high-quality MCrAlY coatings.

Entering the 21st century, thermal spraying technology has ushered in a new upsurge of innovation. Plasma Spray-Physical Vapor Deposition (PS-PVD) reduces the operating pressure to approximately 100 - 200 Pa, and realizes vapor deposition on the basis of low-pressure plasma spraying. It can regulate the nucleation and growth modes of coatings within a wider pressure range, producing composite coatings that integrate columnar structures from vapor deposition and lamellar structures of conventional thermal spray coatings. Suspension Plasma Spraying (SPS) adopts suspensions of nano or submicron powders instead of traditional micron-sized dry powders, opening up a new route to tailor coating microstructures using nano feedstocks. Cold Spraying (CS) requires no high-temperature heat source; deposition is achieved via plastic deformation of high-velocity solid particles, making it particularly suitable for temperature-sensitive materials and special applications such as thick copper coatings. A shared characteristic of these emerging technologies is that they no longer simply pursue fully dense or porous single structures. Instead, precise functional design of coatings is realized through multi-scale and multi-morphology microstructure regulation.[3.4]

2 Analysis of Key Gas Turbine Components and Coating Requirements

2.1 Overview of Basic Gas Turbine Structure and Operating Conditions

Despite differences in specific configurations arising from diverse application scenarios (including aero turbojet/turbofan engines, marine gas turbines, heavy-duty land-based gas turbines, micro gas turbines, etc.), all gas turbines follow the

Brayton cycle for their core thermodynamic cycle. Structurally, they can be uniformly divided into three major modules: compressor, combustion chamber, and turbine.

The compressor is responsible for compressing intake air stage by stage to elevate the working fluid pressure. In advanced aero-engines, the outlet temperature of the high-pressure compressor exceeds 650 ° C with an outlet pressure of 3 - 4 MPa. Heavy-duty land-based gas turbines adopt higher compressor pressure ratios (over 30:1 in some models), and their compressor outlet temperatures also surpass 500 ° C. The primary loads borne by compressor blades include aerodynamic bending stress, centrifugal tensile stress, alternating vibration stress, and fretting wear at joints between blades, casings and disks. When operating in desert, coastal or industrially polluted environments, compressor blades also suffer threats of salt spray corrosion and solid particle erosion. The combined effect of these factors requires compressor blades to maintain precise aerodynamic profiles while possessing excellent wear resistance, corrosion resistance and moderate erosion resistance.[5] The combustion chamber serves as the site where chemical energy of fuel is converted into thermal energy. The flame temperature inside the combustion chamber normally approaches or exceeds 2000 ° C. The inner wall of the flame tube is subjected to intense thermal radiation and convective heat transfer, with local heat flux density reaching 1 - 2 MW/m^2. Although film cooling technology is commonly adopted on combustion chamber walls to reduce metal temperature, thermal stress, thermal fatigue and high-temperature oxidation remain major risks to the structural integrity of combustion chambers. Most combustion chamber components are manufactured from nickel-based or cobalt-based superalloys, whose maximum anti-oxidation temperature without coating protection is far lower than the actual gas temperature. Therefore, combustion chamber coatings are critical to guarantee long-term reliable operation. The turbine is the component operating at the highest temperature and bearing the maximum stress in a gas turbine. The inlet temperature of high-pressure turbines in state-of-the-art modern gas turbines generally reaches 1650 - 1750 ° C, approaching or even exceeding the melting points of many superalloys. Under such extreme conditions, turbine blades withstand multi-axis combined loads including enormous centrifugal loads (centrifugal stress in the mid-span of blade airfoils can reach 200 - 300 MPa), aerodynamic loads, thermal stress and vibration loads, together with oxidation and hot corrosion attack from high-temperature gas. It can be stated that turbine blades operate under the harshest service conditions among all gas turbine parts, and represent the area with the most concentrated and urgent coating demands.[6]

2.2 Compressor Blade Coatings

Compressor blades are usually fabricated from titanium alloys (TC4, TC11, Ti-6Al-4V, etc.) or high-strength stainless steels such as 17-4PH. Blades of advanced compressors mostly adopt hollow structures for weight reduction, and the surface quality directly determines aerodynamic efficiency and anti-fatigue performance. Coating requirements for compressor blades can be subdivided into the following categories according to component positions and functional demands.

Fretting wear resistant coatings are applied on contact areas between blade dovetails and disk slots. During operation, variations in centrifugal and aerodynamic loads trigger tiny reciprocating sliding of blade dovetails inside slots. Without protection, such fretting wear rapidly causes dimensional out-of-tolerance of dovetails, intensified stress concentration and even fatigue fracture.[7] CuNiIn coating acts as a classic solution for fretting protection. It features moderate hardness (approximately 150 - 250 HV), low friction coefficient and certain self-lubricating properties, suitable for medium- and low-temperature service environments. Nevertheless, CuNiIn coatings exhibit insufficient oxidation resistance above 450 ° C, restricting their application on rear-stage compressor blades. Dry film lubricant coatings represent another vital solution. Organic-inorganic composite coatings containing MoS_2 or graphite are deposited on blade roots to reduce friction coefficients to 0.1 - 0.2 and greatly extend fretting fatigue life. International aero-engine manufacturers including GE, Rolls-Royce and Safran have widely adopted dry film lubricant coatings as standard protection for compressor blades.

Corrosion resistant coatings mainly protect compressor blade airfoils from corrosive media in service environments. In marine conditions, saline air drawn into the compressor forms an electrolyte film on blade surfaces, inducing pitting corrosion and stress corrosion cracking. Traditional chromium-containing coatings such as hard chrome plating deliver favorable protection performance, yet hexavalent chromium is highly carcinogenic, leading to strict usage restrictions imposed by the European REACH Regulation and the U.S. EPA.[8] Against this backdrop, chromium-free zinc-aluminum coatings (e.g., zinc-aluminum flake coatings) have developed rapidly. Relying on the sacrificial anode effect of zinc and aluminum as well as dense corrosion product films, they provide salt spray corrosion resistance comparable to chromium-containing coatings while meeting environmental compliance standards.

Erosion resistant coatings shield front-stage compressor blades from erosive wear induced by sand and dust particles in intake air. Erosion alters the leading-edge profile curvature of blades, resulting in declined compressor efficiency and reduced surge margin. Carbide coatings (Cr_3C_2-NiCr, etc.) and nitride coatings (TiN, TiAlN, etc.) constitute mainstream erosion-

resistant coating systems, normally deposited via HVOF or PVD processes. In recent years, multi-layer laminated structures such as TiN/TiAlN demonstrate outstanding erosion resistance owing to interfacial deflection and blocking effects on crack propagation.

Fire-resistant coatings represent a special requirement for titanium alloy compressor blades. Titanium alloys tend to ignite under specific conditions (high temperature, high pressure, sparks generated by friction with hard particles), posing severe safety hazards in aero-engines. Fire-resistant coatings mitigate titanium fire risks by isolating oxygen or inhibiting combustion reactions, and relevant research remains in the exploratory stage at present.

2.3 Coatings for Turbine Blades and Hot-Section Components

If coatings on compressor blades merely serve as an enhancement, coatings on turbine blades are an indispensable necessity — without protective coatings, turbine blades cannot survive under the harshest operating conditions at all. Turbine blades impose the most concentrated and stringent requirements on coatings, which mainly consist of thermal barrier coatings, anti-oxidation coatings, hot corrosion resistant coatings and abradable seal coatings.

Thermal barrier coatings (TBCs) represent the core coating system for turbine blades. By depositing low-thermal-conductivity ceramic layers on blade surfaces, TBCs can reduce the surface temperature of the metallic blade substrate by 100 - 200 ° C. This either enables a higher turbine inlet temperature with identical substrate materials, or extends blade service life by 3 to 5 times under the same temperature level. A typical dual-layer TBC system comprises a metallic bond coat (MCrAlY, 100 - 150 μm thick) and a ceramic top coat (YSZ, 300 - 500 μm thick). The bond coat mitigates the mismatch in thermal expansion coefficients between the ceramic layer and superalloy substrate ($10 - 11 \times 10^{-6}$/K for YSZ versus $14 - 16 \times 10^{-6}$/K for superalloys). Meanwhile, it generates a protective α-Al_2O_3 scale at high temperatures to block substrate oxidation, while the ceramic top coat undertakes the primary thermal insulation function.

Anti-oxidation and hot corrosion resistant coatings form another critical protective barrier apart from TBCs. The severity of oxidation and hot corrosion varies across different blade regions: the blade leading edge suffers intense erosion by high-temperature flue gas, where oxidation dominates degradation; the concave and convex blade surfaces operate at relatively lower temperatures, yet condensed and accumulated molten salt deposits lead to severe hot corrosion; the inner walls of internal blade cooling channels are attacked by high-temperature oxidative gas streams. Overlay MCrAlY coatings are manufactured via vacuum melting, powder crushing, followed by LPPS or HVOF deposition, featuring flexible compositional tuning, high coating density and strong bonding strength. Diffusion aluminide coatings (primarily NiAl and Pt-modified NiAl) are fabricated by CVD or pack cementation, forming metallurgical bonding with substrates. They are irreplaceable for protecting thin-walled blades and complex internal cooling cavities.

Abradable seal coatings perform gas sealing between turbine blade tips and the casing. The linear velocity of turbine blade tips can reach 400 - 500 m/s; every 0.1 mm increase in radial clearance reduces turbine efficiency by approximately 0.5 - 1.0 percentage points. Abradable coatings form a sacrificial layer on the inner casing wall that can be lightly scraped by blade tips. This allows minimal cold assembly clearance, and the optimal running clearance automatically forms through slight tip abrasion during hot operation.[9,10]

2.4 Coatings for Combustion Chambers and Sealing Components

Combustion chambers are free of centrifugal loads yet exposed to extremely harsh thermal environments. The inner walls of flame liners undergo drastic temperature fluctuations during startup-shutdown cycles, generating severe thermal fatigue stress. Combustion chamber coatings primarily provide thermal insulation and oxidation resistance. Porous YSZ coatings deposited via APS are the most widely used insulation material for combustion chambers due to their low thermal conductivity (0.8 - 1.7 W/m · K) and controllable cost. Ultra-high-temperature coating materials such as rare-earth zirconates have also drawn research interest for advanced combustion chambers with higher temperature requirements.

Sealing structures run through the entire gas circuit of gas turbines, and all stages of seals from the compressor to the turbine exert a critical influence on overall unit efficiency. Apart from abradable coatings on turbine blade tips, interstage seals and bearing chamber seals also adopt thermally sprayed wear-resistant coatings (e.g., WC-Co, Cr_3C_2-NiCr) to reduce abrasive loss and extend sealing service life.

3 Principles and Process Characteristics of Major Thermal Spraying Technologies

The essence of thermal spraying lies in feeding coating feedstocks (powders, wires or rods) into a high-temperature heat source to melt or semi-melt them. The molten particles are accelerated by gas streams and impact the substrate surface to form coatings. All thermal spraying processes follow the fundamental physical sequence: heating - acceleration - impact - spreading - solidification - deposition. Nevertheless, distinct technical routes differ greatly in heat source temperature, jet velocity, atmosphere control and feedstock form, and such discrepancies ultimately determine the microstructure and comprehensive performance of coatings.

3.1 Atmospheric Plasma Spraying (APS)

Atmospheric Plasma Spraying is one of the most widely applied and flexible thermal spraying processes. Its basic working principle is described as follows: A direct-current electric arc generated between the gun cathode (tungsten electrode) and anode (copper nozzle) ionizes working gases (primary gas: Ar or N_2; auxiliary gas: H_2 or He) to form high-temperature, high-speed plasma jets. Powder feedstocks are injected into the jet through carrier gas (typically Ar) from internal or external channels of the spray gun. After being heated to semi-molten or fully molten state, particles strike the substrate surface at 200 - 400 m/s and rapidly solidify to form coatings.

The core temperature of plasma jets can exceed 15,000 ° C, far higher than the melting point of any known material. Therefore, APS supports an extremely wide range of sprayable feedstocks, enabling effective deposition of low-melting-point metals (e.g., Al, Zn) as well as ultra-high-melting-point ceramics (e.g., ZrO_2, Al_2O_3, WC). APS is normally operated under atmospheric conditions with relatively low equipment costs, a broad process window and a high deposition rate (typically 30 - 150 g/min), making it suitable for mass production of large-area coatings.

Nevertheless, APS has inherent limitations. First, spraying proceeds in ambient air, so oxidation loss of oxidation-prone materials (such as alloys with high Ti or Al content) is unavoidable at high temperatures, which may severely impair compositional accuracy and bonding performance of coatings in severe cases. Second, APS coatings feature a typical lamellar microstructure stacked by flattened splats, accompanied by inevitable pores (porosity generally ranging from 2% to 15%) and microcracks between particles. Although such a structure helps reduce thermal conductivity, it moderately weakens the strain tolerance and thermal shock resistance of coatings. Third, powder particles undergo extremely rapid heating and cooling during APS, leading to complex thermal histories, and metastable phases as well as residual stresses may be retained within the coating.

Cascaded plasma spray guns represent the most noteworthy advancement in APS technology in recent years. By embedding insulating rings inside the anode to segment and fix the electric arc, cascaded guns eliminate arc wandering defects in conventional guns, achieve longer stable arc roots and higher voltages, and thus deliver higher power and more stable jets under identical current. Another prominent advantage of cascaded guns lies in prolonged particle heating time and improved heating uniformity, which drastically enhances the melting quality of high-melting-point powders such as YSZ and rare-earth zirconates. In practical production, cascaded guns can operate stably at powder feed rates up to 150 g/min and cover a large area in a single spraying pass, which is particularly critical for coating fabrication on large-sized heavy-duty gas turbine components.[11]

For thermal barrier coating applications, conventional lamellar coatings fabricated by APS tend to generate interlaminar cracking during thermal cycling due to low strain tolerance. To address this drawback, researchers have developed APS thermal barrier coatings with dense vertical crack (DVC) structures. By precisely controlling the substrate temperature within a specific range (usually 500 - 900 ° C) and adjusting appropriate process parameters during spraying, a network of cracks perpendicular to the coating surface can be induced in the YSZ layer. These cracks produce an accordion effect during thermal cycling: they open upon thermal expansion and close upon cooling contraction, which effectively releases in-plane thermal stress and greatly elevates the thermal shock resistance of coatings. The density of vertical cracks (typically 1 - 5 cracks per millimeter) can be regulated via parameters including substrate temperature and powder feed rate, enabling customized coating microstructures for diverse service conditions.

3.2 High-Velocity Oxy-Fuel Spraying

High-velocity oxy-fuel (HVOF) spraying adopts the combustion reaction between fuel (kerosene, propane, propylene or hydrogen) and oxygen in a combustion chamber as the heat source. The generated high-temperature gas is accelerated to supersonic speeds (normally 1,000 - 1,500 m/s, with a maximum above 2,000 m/s) through a Laval nozzle. Powders are axially injected into the flame jet, heated and accelerated, and impact the substrate with extremely high kinetic energy to form coatings.

The core strengths of HVOF originate from its low-temperature, high-velocity process characteristics. The flame temperature generally ranges from 2,500 to 3,200 ° C, considerably lower than that of plasma jets. This means powder particles spend a short contact time with high-temperature gas during flight and suffer low oxidation levels. Meanwhile, ultra-high particle velocity (up to 500 - 800 m/s) endows molten droplets with tremendous kinetic energy for sufficient deformation upon substrate impact. The resulting coatings achieve porosity as low as 0.5% - 1.5%, and bonding strength often exceeds 70 MPa (some reports state values above 100 MPa). Such properties render HVOF ideal for manufacturing coatings requiring high density and chemical purity, such as MCrAlY bond coats and CrC_2-NiCr wear-resistant coatings.

HVOF-sprayed WC-Co coatings are widely applied for erosion resistance on compressor blades and bearing components due to exceptional wear performance. Special attention must be paid to WC decarburization during spraying: excessive temperature or prolonged residence time of particles in high-temperature zones decomposes WC into W_2C and free carbon, seriously deteriorating coating hardness and toughness.

Decarburization can be minimized by optimizing the oxygen–fuel ratio, controlling spray distance and adjusting powder particle size. For scenarios demanding superior oxidation resistance, Cr_3C_2–NiCr is a more favorable alternative than WC–Co, because Cr_3C_2 exhibits better high–temperature stability and can form a protective Cr_2O_3scale in oxidative environments.

Variants of HVOF technology include HVAF (High–Velocity Air–Fuel spraying, using air instead of pure oxygen as the oxidizer) and LFS (Liquid Fuel Spraying). HVAF significantly cuts costs and safety risks by utilizing air, making it competitive for applications insensitive to coating oxidation.

3.3 Low-Pressure Plasma Spraying

Low–pressure plasma spraying (LPPS), also referred to as vacuum plasma spraying, shares the fundamental working principle with APS. However, both the spray gun and substrate are enclosed in an evacuable sealed chamber, and spraying is carried out under an inert atmosphere (usually Ar or He) at 100 – 500 mbar. The low–pressure environment serves two primary purposes: first, it drastically reduces entrainment and mixing between plasma jets and surrounding cold gas, extending jet length and diameter to facilitate uniform deposition over large areas; second, it eliminates oxidation and nitridation reactions of molten metals induced by oxygen and nitrogen in air, restricting oxygen content in coatings below 0.1%.

The most mature and classic application of LPPS lies in the fabrication of MCrAlY coatings. During APS, active elements such as Al and Y within MCrAlY powders are prone to oxidation, and the formed oxide inclusions degrade coating oxidation resistance and substrate bonding strength. Operating under an inert atmosphere, LPPS effectively avoids this issue. The as–deposited MCrAlY coatings possess nearly identical chemical composition to the original feedstock, featuring high density, favorable interfacial adhesion and markedly superior oxidation resistance compared with APS counterparts of the same composition. In addition, LPPS can be used to prepare coatings of advanced structural materials susceptible to oxidation in air, such as TiAl and Nb–based alloys.

The main drawbacks of LPPS lie in high equipment investment, elevated operating costs and low batch production efficiency. These factors restrict its popularization in large–scale and low–cost applications. Nevertheless, LPPS still maintains an irreplaceable solid position for coating fabrication on critical components of high–end aero–engines and industrial gas turbines by virtue of its unmatched coating quality.

3.4 Emerging Advanced Spraying Technologies

Plasma Spray–Physical Vapor Deposition (PS–PVD) represents the most groundbreaking technological breakthrough in the field of thermal spraying over the past decade. Essentially an extension of LPPS, PS–PVD operates at an even lower working pressure (approximately 100 – 200 Pa), which leads to drastic volumetric expansion of the plasma jet with a jet length exceeding 2 m and a diameter ranging from 200 to 400 mm. Under such extreme conditions, the injected powder feedstock can not only be molten, but part of it is further vaporized into gas phase. Gaseous, liquid and solid particles coexist within the jet, enabling simultaneous multi–phase deposition of vapor, liquid and solid during coating formation — a capability unattainable by conventional APS and LPPS.[12]

Thermal barrier coatings fabricated by PS–PVD feature a unique feather–like columnar microstructure dominated by vapor–phase nucleation and columnar growth. Columnar grains grow perpendicular to the substrate surface with nanoscale inter–column gaps and a certain amount of pores inside each column. This structure combines the high strain tolerance of EB–PVD coatings (inter–column gaps fully release thermal stress) and the moderate–to–low thermal conductivity of APS coatings (pores scatter phonon heat transfer), delivering superior comprehensive performance in thermal cycle lifetime and thermal insulation compared with conventional coatings. After nearly 20 years of continuous research, the Institute of New Materials, Guangdong Academy of Sciences has established the world's largest PS–PVD multi–phase deposition platform. A series of original achievements have been obtained in theories of homogeneous and heterogeneous nucleation as well as manufacturing technologies for high–strain–tolerance coatings. The relevant coatings have been successfully applied to multiple types of aero–engines and land–based gas turbines, with more than one thousand coated components delivered in total. The aluminum plating surface modification technology developed by this team further improves the coating's resistance to thermal shock and CMAS corrosion, reaching internationally leading standards.

Suspension Plasma Spraying (SPS) adopts stable suspensions of nano/submicron powders in liquid (water or organic solvent) as feedstock to replace traditional dry powders. The solid particles inside suspensions measure merely 100 – 500 nm, far smaller than the 10 – 100 μm particles of conventional powders. Accordingly, the heating and acceleration kinetic behaviors of these tiny particles in the jet differ completely from those of traditional feedstock. By rationally regulating process parameters, SPS can fabricate coatings with columnar structures, dense vertical crack structures or hybrid lamellar–columnar structures. Compared with PS–PVD and EB–PVD, SPS requires much lower equipment investment and operating costs, roughly equivalent to those of APS, thus providing an appealing balance between cost and performance. In recent years, the development of water–based suspensions has further reduced the environmental footprint and material costs of SPS, laying a solid foundation for its transition from laboratory research to industrial application.[13]

Cold spraying is an innovative process fundamentally distinct from all thermal spraying methods mentioned above. In cold spraying, powder particles are not heated or melted. Instead, they strike the substrate at supersonic speeds (500 – 1200 m/s) under room or relatively low temperatures (typically < 1000 ° C). Mechanical bonding and metallurgical bonding between particles are realized via adiabatic shear instability and plastic deformation induced by high-velocity impact. Since the spraying temperature is far below the melting point and recrystallization temperature of materials, cold-sprayed coatings barely suffer from oxidation, phase transformation or thermal stress issues. It is especially suitable for heat-sensitive materials (e.g., nanocrystalline alloys, amorphous alloys, copper alloys) and scenarios where the original phase structure and material properties must be preserved. Within the gas turbine industry, cold spraying demonstrates unique advantages for repairing thermal conductive coatings on Cu-Cr-Zr alloy combustion liners and fabricating anti-corrosion coatings for magnesium alloy casings.

4 Thermal Barrier Coatings: Core Applications and Key Technologies

4.1 Functional Mechanism and Design Requirements of Thermal Barrier Coatings

The core function of thermal barrier coatings (TBCs) is to construct a thermal resistance barrier between superalloy substrates and high-temperature gas, so as to reduce the actual operating temperature of the base metal. The thermal insulation capacity originates from the inherently low thermal conductivity of ceramic materials: the thermal conductivity of ceramics such as ZrO_2 (1.5 – 3 W/m · K) is only roughly one-tenth that of superalloys (approximately 15 – 25 W/m · K). When a 300 – 500 μm-thick ceramic layer covers blade surfaces, a temperature difference of 100 – 200 ° C can be formed between the inner and outer coating surfaces under steady-state heat flow, which directly lowers the temperature bearing requirement of the substrate alloy.[12]

Nevertheless, the design of thermal barrier coatings is far simpler than merely selecting a low-thermal-conductivity material and depositing a thick coating. A practically applicable TBC must simultaneously satisfy a series of mutually restrictive performance requirements: ultra-low thermal conductivity to deliver thermal insulation; thermal expansion coefficient matched with the substrate alloy to mitigate thermal stress; sufficient fracture toughness and strain tolerance to resist thermal shock and cyclic thermal loads; outstanding sintering resistance to maintain structural stability and low thermal conductivity during long-term service; and favorable CMAS corrosion resistance to withstand inevitable pollutant erosion in real service environments. No single material can perfectly satisfy all these demands concurrently. Accordingly, material selection and structural design of TBCs are essentially a multi-objective trade-off and optimization process.

4.2 Classic Material System: Advantages, Drawbacks and Limitations of YSZ

Partially yttria-stabilized zirconia (6 – 8 wt% Y2O3 has remained the dominant top-coat material for thermal barrier coatings and served as the "gold standard" in this field ever since it was first evaluated as a TBC material by NASA in the 1970s. Its long-standing dominant position stems from a unique combination of superior properties: 1) Low thermal conductivity of 1.5 – 2.2 W/m · K from room temperature to 1200 ° C, far lower than most other oxide ceramics; 2) A thermal expansion coefficient of 10 – 11 × 10-6/K, lying between superalloys (14 – 16 × 10-6/K) and Al2O3 thermally grown oxide (TGO, ~8 × 10-6/K), which alleviates thermal mismatch stress to a certain extent;3) Relatively high fracture toughness among ceramics (K_IC ≈ 2 – 4 MPa · m1/2), delivering better thermal shock resistance than many alternative materials; Excellent phase stability over a wide temperature range. The addition of Y2O3 stabilizes the high-temperature tetragonal (t') phase of ZrO2 down to room temperature and avoids the monoclinic phase transformation of pure ZrO2 upon cooling, which is accompanied by a volume expansion of approximately 4%.

Two major defects emerge when YSZ operates above roughly 1200 ° C for prolonged periods. First, high-temperature sintering heals micropores and microcracks inside coatings, leading to elevated thermal conductivity, reduced strain tolerance, and subsequent degradation of thermal barrier efficiency and thermal shock resistance. Second, above 1200 ° C, the metastable t' phase slowly transforms into equilibrium tetragonal (t) and cubic (c) phases, which further convert to the monoclinic (m) phase during cooling. The volume variation accompanying such phase transformation may trigger the initiation and propagation of microcracks. For this reason, YSZ is generally regarded as unsuitable for long-term service at the temperatures exceeding 1200 ° C. As the turbine inlet temperature rises further above 1600 ° C, developing novel ultra-high-temperature TBC materials becomes an unavoidable necessity.

4.3 Novel Ultra-High-Temperature Thermal Barrier Coating Materials

Rare-earth zirconates (A2Zr2O7, where A represents rare-earth elements such as La, Nd, Sm and Gd) adopt pyrochlore or fluorite crystal structures and constitute the most extensively researched new-generation TBC material system after YSZ. Their thermal conductivity can reach as low as 1.0 – 1.5 W/m · K, lower than that of YSZ. Moreover, they exhibit markedly superior

CMAS resistance at high temperatures: dense apatite-phase layers generated from reactions between rare-earth zirconates and CMAS can effectively block further penetration of molten CMAS. Gd2Zr2O7 and La2Zr2O7 are representative candidates. Gd2Zr2O7 possesses lower thermal conductivity owing to the higher atomic mass of gadolinium, while La2Zr2O7 delivers better high-temperature phase stability. However, rare-earth zirconates generally have lower fracture toughness and slightly smaller thermal expansion coefficients (~9 - 10×10^{-6}/K) compared with YSZ, which poses challenges to the thermal shock resistance of coatings. The mainstream current strategy is to employ rare-earth zirconates as the top covering layer of YSZ to form dual-layer or multi-layer TBCs. The YSZ layer provides primary strain tolerance and bonding strength, while the rare-earth zirconate layer supplies ultra-high-temperature thermal insulation and CMAS protection, thus realizing complementary advantages of the two materials.

Rare-earth tantalates ($RETaO_4$) represent another category of promising novel TBC materials. Their thermal conductivity can drop to 0.8 - 1.3 W/m · K, and they feature a unique ferroelastic toughening mechanism that endows them with higher fracture toughness than rare-earth zirconates. In-depth research on the long-term phase stability of systems such as $GdTaO_4$ and $YTaO_4$ above 1400 ° C is ongoing.

High-entropy alloy coatings are another research hotspot in surface engineering in recent years. Composed of five or more principal elements at near-equimolar ratios, high-entropy alloys suppress the precipitation of intermetallic compounds via the thermodynamic high mixing entropy effect and tend to form simple solid-solution structures. For anti-oxidation coatings, systems including AlCoCrFeNiY display favorable high-temperature oxidation resistance and excellent thermal stability. Applying them as bond coats for TBCs or independent high-temperature protective coatings stands as one of the cutting-edge research directions at present.

4.4 Process Optimization and Microstructure Control of APS-Deposited Thermal Barrier Coatings

In engineering practice of fabricating TBCs via atmospheric plasma spraying (APS), minor variations in process parameters can induce remarkable changes in coating microstructure and performance. Key process parameters include arc power (current and voltage), composition and flow rate of working gas, powder feed rate, spray distance, substrate temperature, gun scanning path, and so on. Complex interactions exist among these parameters, making process optimization a systematic engineering task.

Spraying power and gas composition directly govern the melting state of powder particles. If the power is excessively low, particles cannot be fully molten and fail to deform sufficiently upon substrate impact, resulting in coatings with overly high porosity and inadequate bonding strength. Conversely, overly high power may cause evaporation or overburning of fine particles, which also deteriorates coating quality. The optimal process window is generally determined by balancing the maximization of molten particle fraction and the minimization of evaporation loss. For YSZ powder, Ar-H_2 or Ar-He mixed working gases are commonly adopted. The addition of H_2 or He raises the enthalpy and thermal conductivity of the plasma jet, facilitating improved melting of high-melting-point ZrO_2.

Substrate temperature acts as a critical parameter for regulating coating microstructures and residual stresses. Elevating substrate temperature promotes sufficient wetting and diffusion of molten splats after spreading, reduces inter-splat pores, and mitigates residual coating stresses. Nevertheless, an excessively high substrate temperature may induce excessive thermal compressive stress within the coating, which transforms into detrimental residual tensile stress after cooling. For fabricating YSZ coatings with dense vertical crack (DVC) structures, the substrate temperature must be precisely controlled within a specific range (typically 600 - 900 ° C, varying with powder characteristics and equipment configuration) to generate vertical cracks with appropriate density and distribution throughout the coating. Insufficient crack density leads to inadequate thermal stress relief, while excessively dense interconnected cracks degrade the overall coating strength and erosion resistance.

Post-treatment represents another vital method to enhance the performance of APS thermal barrier coatings. Laser remelting instantaneously melts a thin surface layer of the coating, eliminating surface pores and microcracks to boost surface smoothness and erosion resistance, yet it may simultaneously reduce coating strain tolerance. Vacuum heat treatment relieves residual stresses, improves interfacial bonding, and accelerates the formation of a continuous Al_2O_3 scale on the bond coat surface. Sealing treatments such as phosphate impregnation are primarily implemented to meet corrosion protection requirements under specific service conditions.

4.5 Fabrication of Advanced-Structure Thermal Barrier Coatings via PS-PVD and SPS

PS-PVD and SPS stand as cutting-edge fabrication technologies for thermal barrier coatings, each possessing distinctive strengths in microstructure customization.

The unique advantage of PS-PVD originates from its inherent multi-phase deposition characteristic. Under low operating pressure, volumetric expansion of the plasma jet extends the standoff distance between the spray gun and substrate to 1000 - 2000 mm, a range unachievable for conventional APS (with a typical standoff of merely 80 - 150 mm). The long deposition distance allows sufficient time for vapor species within

the jet to complete nucleation and growth, eventually forming a multi-phase composite structure dominated by columnar crystals mixed with a small amount of spherical particles and pores on the substrate surface. This structure delivers higher strain tolerance than lamellar APS coatings and superior thermal insulation performance compared with fully columnar EB-PVD coatings. Moreover, it possesses excellent shadow masking capacity for components with complex geometries such as turbine blades equipped with film cooling holes — vapor species can penetrate and deposit inside cooling holes, a capability difficult to realize with APS. The industrial application of PS-PVD has been validated on multiple domestic and foreign gas turbine models, and PS-PVD coatings exhibit remarkably better thermal cycle life and thermal shock resistance than equivalent APS coatings.

SPS provides richer diversity in microstructure regulation. By adjusting the solid content, solvent type, powder particle size of the suspension as well as spraying process parameters, SPS can fabricate coatings with diverse morphologies including lamellar, columnar and dense vertical crack structures on a single equipment platform. Columnar SPS coatings share similar morphological features with columnar coatings prepared by PS-PVD and EB-PVD, yet the diameter and inter-column spacing of columnar grains can be flexibly tuned via process parameters. SPS coatings with vertical crack structures resemble APS-DVC coatings; however, the adoption of nano-sized feedstock yields finer and more uniformly distributed pores, endowing the coatings with enhanced sintering resistance while retaining low thermal conductivity.

The major challenges restricting the industrial promotion of SPS include the control of suspension stability, droplet fragmentation and uniform dispersion under high liquid feed rates, as well as low deposition efficiency during large-area spraying. In recent years, advances in water-based suspension technology have significantly alleviated cost and safety concerns induced by organic solvents. SPS coatings with multi-layer and gradient structures have also demonstrated outstanding comprehensive performance at the laboratory scale. It can be anticipated that with the standardization of suspension formulations and higher specialization of dedicated spraying equipment, SPS will play an increasingly vital role in fabricating coatings for large-sized hot-section components.

5 Abradable Sealing Coatings

5.1 Critical Role of Sealing Coatings in Gas Turbines

Annular radial clearances exist between rotating blades and stationary casings of gas turbine compressors and turbines. Leakage flow of working fluid through blade tip clearances generates two adverse effects: first, leaked working fluid fails to produce work on turbine blades or gain compression work in compressors, directly reducing stage efficiency and overall unit efficiency; second, leakage flow disturbs the aerodynamic parameter distribution in the main flow channel, which may impair inter-stage matching and flow stability. Research indicates that every 1% increase in turbine tip clearance relative to blade height leads to a 1.5 – 2.5 percentage point drop in stage efficiency. Although the impact of compressor tip clearance is relatively milder, it remains significant in high-pressure stages.

From a design perspective, the determination of tip clearance presents a typical dilemma. Smaller cold assembly clearances raise the risk of blade-casing rubbing caused by inconsistent thermal expansion of different parts during hot operation, whereas larger cold assembly clearances induce greater leakage losses under operating temperatures. The application of abradable sealing coatings fundamentally resolves this dilemma: a coating with favorable abradability is sprayed onto the inner casing wall, enabling the adoption of minimal cold assembly clearances. During commissioning and initial operation, blade tips automatically scrape the coating to form the required running clearance, thus achieving optimal sealing performance while avoiding rubbing damage to blades.

5.2 Material Systems and Microstructure Design

The core contradictory demand for abradable coatings during service lies in the following aspects: the coating must be sufficiently soft and brittle to preferentially fracture and spall off under blade scraping without damaging rotating blades, yet meanwhile possess adequate strength and toughness to resist high-velocity gas erosion and thermal shock and avoid massive spallation. To unify these conflicting performance requirements, material design of abradable coatings generally adopts the strategy of multi-phase composite structure with controlled porosity.

A typical abradable coating consists of the following constituent phases.

The metallic matrix provides structural integrity and environmental durability for the coating. The selection of matrix materials varies drastically depending on service temperature. Al-Si alloys are widely used in compressor sections (service temperature usually below 450 ° C) due to their low density, favorable thermal conductivity and well-matched thermal expansion coefficients with aluminum alloy or titanium alloy casings. For turbine sections with service temperatures ranging from 800 to 1200 ° C, high-temperature alloy systems such as CoNiCrAlY or NiCrAl must be selected to guarantee oxidation resistance and structural stability at elevated temperatures.

Lubricating phases serve to reduce the friction coefficient during scraping and mitigate blade wear and frictional heat generation. Hexagonal boron nitride (h-BN) is the most commonly used high-temperature lubricating phase. Its layered crystal structure facilitates interlayer sliding, and it

can withstand temperatures exceeding 2000 ° C under inert atmospheres. Graphite and MoS2 deliver superior lubricity at low temperatures, yet their oxidation temperatures are approximately 400 ° C and 350 ° C respectively, limiting their application in high-temperature environments. Pore-forming agents decompose and volatilize during spraying or subsequent heat treatment, leaving uniformly distributed pores. Common pore formers include polyester, polyamide, graphite and carbonates. Taking Al-Si-polyester coatings as an example, polyester undergoes thermal decomposition and volatilization during APS spraying (temperature above 500 ° C), leaving spherical pores with sizes of 10 - 50 μm within the Al-Si matrix, and the porosity is generally controlled between 20% and 40%. For superalloy-based abradable coatings, inorganic salts such as CaF2 are sometimes adopted as pore formers. These salts are chemically inert under coating service temperatures and can simultaneously function as solid lubricants.[14]

5.3 Fabrication Process and Quality Control

Abradable seal coatings are mainly fabricated via APS, while HVOF is adopted for coatings requiring higher density. Key process control points for APS-prepared abradable coatings are summarized as follows:

Powder mixing and agglomeration granulation. Due to the vast differences in density, particle size and melting point among the metallic matrix, lubricating phase and pore-forming agent, directly spraying mechanically blended powder will cause component segregation and uneven coating composition. Industrially, spray granulation or agglomeration sintering is commonly used to prepare spherical composite powders from multi-component raw materials. Each component is uniformly distributed inside individual powder particles, thus guaranteeing consistent coating composition.

Refined regulation of spraying parameters. The decomposition degree of pore-forming agents depends on the thermal history of particles within the plasma jet. Excessively high flame temperature or prolonged particle residence time leads to premature decomposition of pore formers and reduced porosity; insufficient heating leaves residual pore-forming agents, impairing the thermal stability and abradability of coatings. For Al-Si-polyester coatings, spraying power and powder feed rate must be precisely controlled to enable complete polyester decomposition during splat spreading after particle substrate impact. This ensures effective pore generation without damaging coating-substrate bonding from escaping decomposition gas.

Coating thickness control. The designed thickness of abradable coatings normally ranges from 0.5 to 3 mm, far thicker than the ceramic top coat of thermal barrier coatings. Such thick coatings require multi-pass overlapping spraying. The thickness, cooling state and cumulative residual stress of each deposited pass jointly affect the final structural homogeneity and bonding performance of the coating.

5.4 Performance Evaluation Methods and Standards

The core characterization method for abradable coatings is service-simulating rub testing. A dedicated rub rig can perform rubbing tests under controllable atmosphere and temperature conditions, matching actual engine tip linear speeds (up to over 500 m/s), feed rates and penetration depths. Real-time signals including tangential force, normal force, friction coefficient, temperature rise and blade tip wear loss between blades and coatings are recorded during testing. After experiments, scanning electron microscopy (SEM) and optical profilometers are used to characterize scratch morphology on coatings and blade wear conditions, evaluating the abradability index and blade friendliness of coatings.

High-temperature thermal stability constitutes another vital evaluation indicator. Long-term high-temperature service of abradable coatings may trigger pore structure evolution (porosity reduction caused by sintering), oxidative failure of lubricating phases or matrix phase transformation. These changes break the balance between abradability and erosion resistance. Combined thermal cycling tests, high-temperature aging treatments and subsequent rub tests can comprehensively assess the performance evolution law of coatings under practical service environments.

6 Erosion-Resistant, Oxidation and Hot-Corrosion Resistant Coatings

6.1 Erosion Damage Mechanism and Design of Erosion-Resistant Coatings

Erosion of gas turbine blade surfaces induced by high-speed solid particles is a critical mechanism triggering aerodynamic performance degradation. Microscopic erosion damage can be categorized into two primary modes: brittle erosion and ductile erosion. For brittle ceramic materials, particle impact initiates and propagates microcracks, accompanied by micro-fracture and spallation as dominant damage modes. For ductile metals and alloys, material removal mainly arises from ploughing, cutting and extrusion deformation. Actual erosion processes are usually a mixture of both modes; the dominant mechanism depends on particle properties (size, shape, hardness), impact angle and mechanical performance of target substrates. From coating design perspective, ideal erosion-resistant coatings should possess high hardness, moderate fracture toughness and robust coating-substrate bonding strength. Although pure hard materials such as TiN and Al_2O_3 exhibit extremely high hardness, their intrinsic brittleness renders them prone to brittle fracture under particle bombardment. Their erosion resistance under oblique impact may even be inferior to composite coatings with superior ductility. This contradiction drives researchers to develop

composite coating systems featuring hard reinforcing phases embedded within ductile metal binders, among which Cr_3C_2–NiCr represents the most mature and successful candidate. Hard Cr_3C_2 particles (≈2000 HV) deliver wear resistance, while the ductile NiCr alloy binder provides sufficient coating toughness. The synergistic effect endows the coating with outstanding erosion resistance under both high and low impingement angles. Multi–layer coating structures represent an important research direction for erosion–resistant coatings in recent years. In laminated TiN/TiAlN multilayer systems, minor mismatches in crystal structure and lattice constant between adjacent layers form internal interfaces. These interfaces act as barriers to deflect crack propagation and absorb partial impact energy via interfacial sliding, effectively improving coating spallation resistance. Furthermore, residual stress distribution within multi–layer coatings can be optimized by tuning layer thickness ratios and layer counts.[15]

6.2 Fundamental Mechanisms of High-Temperature Oxidation and Hot Corrosion

High–temperature oxidation of superalloy hot–section components in gas turbines essentially originates from selective oxidation of alloying elements. In nickel–based superalloys, Al, Cr and Ti serve as primary oxidation–resistant elements with higher oxygen affinity than Ni. At the initial oxidation stage, mixed oxides dominated by Cr_2O_3 form on alloy surfaces. With prolonged oxidation time, the Cr_2O_3 scale is gradually replaced by a continuously growing dense α–Al_2O_3 layer beneath it, owing to superior Al diffusion rate and thermodynamic stability of alumina. The compact α–Al_2O_3 scale acts as an excellent protective oxide layer with low growth rate and strong substrate adhesion, effectively blocking inward oxygen diffusion.

Hot corrosion is a synergistic process combining oxidation and molten salt attack. Sulfur generated from fuel combustion reacts with atmospheric NaCl (marine environment), V_2O_5 and other contaminants to form low–melting molten sulfate or vanadate deposits on blade surfaces. These molten salts dissolve and destroy the protective oxide scale, accelerating corrosive consumption of substrate alloys. The severity of hot corrosion strongly correlates with temperature, reaching its peak within the 700 – 900 ° C range where molten salts maintain full liquidity and high chemical activity. Above approximately 1000 ° C, partial volatilization of molten salts reduces the corrosion rate.

6.3 Composition Design and Fabrication of MCrAlY Coatings

MCrAlY (M = Ni, Co or Ni+Co) is the most widely used overlay coating material for oxidation and hot corrosion resistance at present. Its compositional design follows the principles below: a Cr content of 15% – 25% guarantees hot corrosion resistance and the self–healing capacity of oxide scales; an Al content of 5% – 12% ensures the formation and retention of a protective α–Al_2O_3 scale; Y (0.1% – 1.0%) acts as a reactive element that drastically improves oxide scale adhesion by segregating at oxide grain boundaries and mitigating the detrimental effect of sulfur. The addition of Co enhances the coating' s hot corrosion resistance, especially under service conditions involving low–grade fuels containing vanadium and sulfur, while Ni mainly delivers oxidation resistance and good compatibility with nickel–based superalloy substrates.

MCrAlY coatings are predominantly fabricated by LPPS, HVOF and APS. Coatings deposited by LPPS feature the lowest oxygen content and the most precise compositional control, making them suitable for high–performance aero–engine blades. HVOF coatings possess high density and strong bonding strength, striking a favorable balance between cost and performance, and represent the most prevalent process for industrial gas turbines. Although APS incurs the lowest cost, its coatings inevitably contain oxide inclusions and relatively high porosity, resulting in inferior oxidation resistance compared with LPPS and HVOF counterparts.

Vacuum heat treatment serves as a critical post–processing step for MCrAlY coatings. Holding the coating at approximately 1000 – 1100 ° C under vacuum or low oxygen partial pressure for several hours accelerates interdiffusion of elements between the coating and substrate, relieves partial residual spraying stress, promotes recrystallization of the β–NiAl phase, and homogenizes coating microstructure. After heat treatment, MCrAlY coatings exhibit faster formation and superior adhesion of protective oxide scales during subsequent high–temperature service relative to untreated coatings.

6.4 Diffusion Aluminide Coatings

Diffusion aluminide coatings are formed by diffusing Al atoms into the near–surface region of substrates to generate an intermetallic layer dominated by β–NiAl or Ni_2Al_3. Unlike MCrAlY overlay coatings, aluminide coatings lack a distinct discrete coating–substrate interface; instead, interdiffusion creates a graded transition zone. This metallurgical bonding delivers extremely high interfacial adhesion, rendering the coatings resistant to interface spallation under complex thermal stress conditions.[12]

Chemical Vapor Deposition (CVD) is one of the most common techniques for manufacturing diffusion aluminide coatings, and it is particularly suited for coating the inner walls of film cooling holes on turbine blades. Since CVD transports aluminum precursors via gas phase, uniform coating thickness can be achieved on both external blade surfaces and internal cooling hole cavities — a capability unattainable by line–of–sight spraying processes such as LPPS and HVOF. Platinum–modified

aluminide coatings (Pt–Al) are fabricated by electroplating a thin Pt layer on the substrate prior to aluminizing, which substantially elevates hot corrosion resistance. They have been widely adopted for turbine blades of marine gas turbines and aero-engines operating in coastal environments. The beneficial mechanisms of platinum include: raising the activity of Al in β-NiAl to preferentially oxidize Al over Cr and Ni; modifying the interfacial bonding of oxide scales to boost spallation resistance; and forming platinum–sulfur compounds in hot corrosive environments to suppress inward sulfur diffusion into the substrate.

7 Coating Failure Mechanisms and Lifetime Prediction

7.1 Failure Mode Dominated by Thermally Grown Oxide (TGO)

During high-temperature service of thermal barrier coatings, Al contained in the bond coat reacts with oxygen diffusing through the ceramic top coat, generating a thermally grown oxide layer primarily composed of $\alpha-Al_2O_3$ at the bond coat/top coat interface. Normal TGO growth is an inevitable outcome of the bond coat's anti-oxidation function, yet continuous thickening of TGO constitutes one of the root causes leading to ultimate coating failure.

The mechanical essence of TGO-induced coating failure lies in the thermal expansion coefficient mismatch between TGO and adjacent materials. The thermal expansion coefficient of $\alpha-Al_2O_3$ is approximately 8×10^{-6}/K, lower than that of YSZ ($10-11\times10^{-6}$/K) and superalloy/bond coat substrates ($14-16\times10^{-6}$/K). During the cooling stage of thermal cycles, the TGO layer undergoes less shrinkage than the adjacent layers, subjecting the TGO to compressive stress while the neighboring ceramic top coat and bond coat sustain tensile stress. Meanwhile, volume expansion occurs during high-temperature TGO growth due to the formation of new Al_2O_3 phases (the Pilling–Bedworth ratio is around 1.28, meaning the molar volume of Al_2O_3 exceeds that of consumed Al), introducing additional growth stress within the TGO and at its interfaces. The superposition of these two stress mechanisms creates severe stress concentration zones at the front of the TGO/ceramic interface. Once the stress exceeds the critical threshold of the material, microcracks initiate at the interface and propagate either inside the ceramic layer or along the TGO/ceramic boundary, ultimately leading to lamellar spallation of the coating. It is generally acknowledged that the risk of coating delamination rises sharply when the TGO thickness exceeds roughly 8–10 μm.

The growth kinetics of TGO typically follows a parabolic law: $\delta^2 = k_p \cdot t$, where δ denotes TGO thickness, t represents time, and k_p is the parabolic rate constant that satisfies the Arrhenius relationship with temperature. This indicates that the TGO growth rate increases exponentially with rising temperature; therefore, a slight elevation in service temperature exerts a dramatic adverse impact on coating service life.

7.2 Thermal Cyclic Stress and Fatigue Failure

During startup–shutdown cycles of gas turbines, thermal barrier coatings undergo drastic temperature fluctuations (heating from room temperature to over 1000 °C followed by cooling back to ambient temperature). Thermal stress originating from thermal expansion mismatch between layered materials undergoes cyclic loading and unloading in every thermal cycle. Although structural designs such as vertical cracks and columnar architectures can partially release in-plane stress, the stress state in near-interface regions remains highly complex.

Thermal cycling damages coatings via two primary pathways: first, TGO growth is accelerated by the transient high-temperature window in each heating cycle; second, cyclic thermal stress inherently induces fatigue damage that accumulates progressively inside the coating. Severe stress concentration arises at locations with high interface roughness or sharp angular defects, which serve as preferential sites for crack nucleation. Extensive experimental data reveal that the thermal cycle lifetime of APS lamellar thermal barrier coatings at approximately 1100 °C ranges from hundreds to thousands of cycles (depending on coating thickness and specific service conditions), while coatings with dense vertical crack structures and PS-PVD columnar microstructures can multiply the service life several times over.

7.3 High-Temperature CMAS Corrosion

CMAS ($CaO-MgO-Al_2O_3-SiO_2$) constitutes the major component of atmospheric dust and volcanic ash. Above approximately 1200 °C, CMAS minerals melt into a liquid glassy phase that infiltrates the interior of thermal barrier coatings through open surface pores and microcracks. Molten CMAS imposes intense chemical attack on YSZ: cations such as Ca, Mg and Si in the melt substitute Zr^{4+} within the YSZ lattice and introduce charge-compensating defects, destabilizing the stabilized tetragonal phase and triggering its decomposition into monoclinic and cubic phases accompanied by volume variation and elevated thermal conductivity. Abrupt shifts in thermal and mechanical properties between CMAS-penetrated and unpenetrated regions frequently generate through-thickness cracks during cooling, which may result in complete coating spallation in severe cases. The severity of CMAS attack depends on the chemical composition, pore structure of coatings and operating temperature. Rare-earth zirconates outperform YSZ in CMAS resistance because their reaction with CMAS produces a dense apatite blocking layer that effectively hinders further penetration of molten CMAS. Surface modification treatments such as aluminum plating have also been proven to pre-form a protective surface film and slow down CMAS infiltration rates.

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7.4 Life Prediction Methods and Models

The core objective of thermal barrier coating (TBC) life prediction is to estimate the residual service life or judge whether the coating has reached its safe service limit under known service conditions (temperature history, number of thermal cycles, environmental media, etc.). At present, the mainstream methods are summarized as follows:

The life model based on the critical TGO thickness is the simplest and widely adopted engineering approach. The TGO thickness under specific temperature-time conditions is calculated via the Arrhenius-type TGO growth kinetic equation, and the end of service life is defined when the TGO thickness reaches a critical value (typically 6 - 12 μm, depending on coating systems and component locations). Its advantages lie in physically clear parameters and straightforward calculation; however, it fails to account for the influence of thermal cycle counts and stress states, leading to limited prediction accuracy under conditions with severe temperature fluctuations.

Crack propagation models based on fracture mechanics take the Paris Law as the theoretical foundation, correlating the crack growth rate induced by thermal cycles with the amplitude of the stress intensity factor. Such models require finite element analysis to compute internal coating stress distribution and stress intensity factors, and abundant crack propagation experimental data to calibrate material constants. Despite heavy computational load, they deliver relatively high prediction precision. Damage accumulation methods treat performance degradation of coatings during thermal cycling as a monotonic accumulation process of damage parameters. Each thermal cycle brings an incremental rise in strain energy density or a specific damage indicator, and coating failure is determined once the accumulated damage hits the critical threshold. These methods can flexibly handle variable-amplitude load spectra and be correlated with experimental observations such as coating stiffness degradation and elevated thermal conductivity.

In recent years, machine learning approaches have attracted growing attention in TBC life prediction. Massive datasets including coating process parameters, microstructure characterization results and thermal cycling test data are collected to train models such as artificial neural networks (ANNs) and support vector regression (SVR), enabling rapid prediction of coating service life. The prediction accuracy of such data-driven methods highly relies on the coverage range and quality of training data. Although still in the exploratory stage, they are expected to become vital auxiliary tools for coating design and life management with the gradual improvement of dedicated databases.

8 Future Outlook

8.1 Exploration of Novel Coating Materials

Innovation in coating materials serves as the fundamental driving force advancing thermal spraying technology. Within the next 10 - 15 years, research priorities in ultra-high-temperature thermal barrier coatings will center on the following directions:

Industrialization of rare-earth zirconate/tantalate systems

Materials including $Gd_2Zr_2O_7$, $La_2Zr_2O_7$ and $GdTaO_4$ have been verified at laboratory scale to possess superior phase stability, sintering resistance and CMAS resistance compared with YSZ. Nevertheless, their fracture toughness and thermal shock resistance still need improvement via second-phase toughening, laminated structural design and gradient transition layers. Composite application of these materials with YSZ to construct dual-layer or multi-layer TBC systems represents the most promising technical route for near-term industrial implementation.

High-entropy oxide ceramics

The design philosophy of high-entropy alloys is extended to oxide ceramics. Simultaneous introduction of multiple rare-earth cations into zirconate or cerate lattices further reduces thermal conductivity (via enhanced phonon scattering induced by lattice distortion) and improves phase stability and CMAS resistance. Synthesis and thermal spraying processes for high-entropy rare-earth zirconates are under active development.

Self-healing coatings

Embedding healing agents (glass phases or precious metals) that melt and flow to seal microcracks at designated temperatures enables automatic repair of microdefects during service, a forward-looking strategy to extend coating life. This concept has obtained preliminary laboratory validation, yet the compatibility between healing agents and substrate materials as well as healing efficiency still require in-depth optimization.

8.2 Process Equipment and Intelligent Manufacturing

Advancements in thermal spraying equipment will continue to play a pivotal role in the future:

Intelligent process control

Optical sensors (high-speed cameras, infrared pyrometers, laser scattering devices) realize real-time monitoring of particle temperature, velocity and flight trajectories within spraying jets. Combined with machine learning algorithms, mapping relationships among process parameters, particle states and

coating performance are established to support online quality prediction and closed-loop control of coatings. Preliminary progress has been achieved in APS and HVOF processes, with ongoing promotion toward industrial application.

Robotic automated spraying

Large gas turbine components (especially turbine vanes and combustion liners of heavy-duty gas turbines) feature complex geometric profiles. Conventional manual or simple mechanical spraying suffers from limitations in coating thickness uniformity and batch consistency. Multi-axis robotic spraying systems equipped with offline programming and online path planning achieve high-precision control of coating thickness on complex curved surfaces (tolerance controlled within ± 25 μm), drastically raising the yield rate of coated parts.

Digital thermal spraying workshops

Full-process digital management of process parameters, powder batch information, coating inspection data and component service history constructs a traceable, analyzable and optimizable closed-loop data system. This constitutes a critical transition of thermal spraying from empirical craftsmanship to systematic scientific engineering.

8.3 Environment-Friendly Coating Technologies

Against the backdrop of global sustainable development agendas, eco-friendly transformation of thermal spraying becomes imperative:

Chromium-free coating technologies

The application of hexavalent chromium in traditional anti-corrosion coatings faces increasingly stringent regulatory restrictions. Chromium-free zinc-aluminum coatings and novel rare-earth conversion films act as feasible alternatives, whose anti-corrosion performance has reached or approximated that of chromium-containing counterparts.

Water-based suspensions

In suspension plasma spraying (SPS), substituting organic solvents with water as suspension media drastically cuts VOC emissions and safety hazards while significantly reducing material costs, representing a key breakthrough for large-scale industrialization of SPS.

Waste coating recycling

Thermal barrier coatings and bond coats on retired gas turbine blades contain abundant strategic precious metals (Ni, Co, Cr, Y, etc.). Developing high-efficiency, low-cost coating stripping and material recycling technologies is of great significance for conserving strategic resources and lowering full-lifecycle environmental burdens.

9 CONCLUSIONS

This paper systematically reviews the research status and development trends of thermal spraying technology applied in gas turbines, and the main conclusions are drawn as follows:

1) The compressor, combustion chamber and turbine of gas turbines operate under remarkably distinct service conditions, which impose diverse functional requirements on coatings, including fretting wear resistance, erosion resistance, thermal insulation, oxidation resistance, hot corrosion resistance and abradable sealing. Benefiting from flexible material compatibility and versatile processing routes, thermal spraying has become the core technical approach to meet the above requirements.

2) Atmospheric Plasma Spraying (APS) stands as the dominant fabrication process for thermal barrier coatings and abradable seal coatings owing to its wide range of sprayable feedstocks and favorable cost-effectiveness. High-Velocity Oxy-Fuel (HVOF) spraying takes a leading role in preparing MCrAlY bond coats and carbide wear-resistant coatings by virtue of its low-temperature, high-velocity processing advantages. Low-Pressure Plasma Spraying (LPPS) and Plasma Spray-Physical Vapor Deposition (PS-PVD) serve as irreplaceable technical platforms for manufacturing high-quality anti-oxidation coatings and advanced columnar-structured thermal barrier coatings. Suspension Plasma Spraying (SPS) delivers a new balance between cost and performance and boasts enormous development potential.

3) Dual-layer thermal barrier coatings consisting of a YSZ top coat and an MCrAlY bond coat represent the most widely adopted system at present. Nevertheless, they encounter critical bottlenecks such as sintering, phase transformation and CMAS corrosion under long-term service above 1200 ° C. APS coatings with dense vertical crack structures, as well as columnar coatings fabricated via PS-PVD and SPS, achieve substantial improvements in strain tolerance and service life through microstructure optimization. Novel material systems including rare-earth zirconates and high-entropy oxides offer promising solutions to break through the temperature limit.

4) Abradable seal coatings reconcile easy scrapability and erosion resistance via multi-phase composite designs with controlled porosity, acting as a vital technical measure to boost gas turbine efficiency and guarantee operational safety. Crr_3C_2-NiCr and MCrAlY coatings exert irreplaceable protective effects against erosion and high-temperature oxidation/hot corrosion, respectively.

5) Coating failure is governed by the coupling of multiple factors including TGO growth, thermal cyclic stress and CMAS corrosion. Life prediction methods based on critical TGO thickness, fracture mechanics and damage accumulation provide theoretical support for coating design and in-service management from different perspectives.

6) The future advancement of thermal spraying technology for gas turbines will be driven by coordinated progress across

three dimensions: development of novel coating materials, exploitation of intelligent manufacturing processes, and implementation of eco-friendly technologies, continuously facilitating the evolution of gas turbines toward higher operating temperatures, superior efficiency and extended service life.□

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