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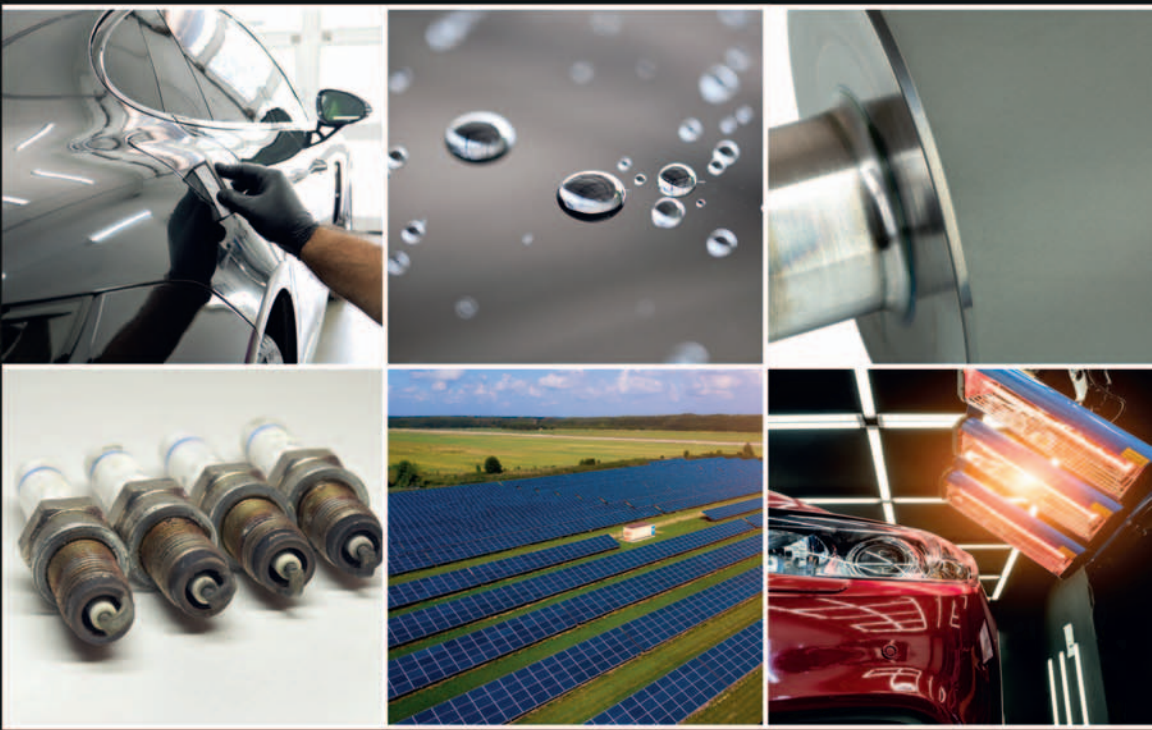
ADVANCED CERAMIC COATINGS: FUNDAMENTALS, MANUFACTURING, AND CLASSIFICATION



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Advanced Ceramic Coatings

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Elsevier Series on Advanced Ceramic Materials

Advanced Ceramic Coatings

Fundamentals, Manufacturing, and Classification

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1. Introduction

The term "ceramics" is derived from the Greek word "Keramos," which means "pottery," "potter's clay," or "a potter." This Greek term derives from a Sanskrit root that means "to burn," although it was originally applied to "burned goods."

Ceramics are inorganic, nonmetallic solids. Sand and clay ceramics, by far the most ubiquitous terrestrial materials, have been utilized for thousands of years for art ware, pottery, and brick. In contrast, new structural ceramics are constructed of exceedingly pure, tiny particles so as to be cemented at high temperatures to generate a long-lasting and dense structure.

Ceramic coatings are a semipermanent, nonmetallic, inorganic protective transparent layer that can be applied to a wide range of surfaces.

Other names for them include glass coatings, nanocoatings, silica (SiO_2) coatings, and hydrophobic coatings. Ceramic coatings are employed in a range of industries, including automotive, maritime, and architecture, due to their ease of cleaning and resistance to weather.

Any ceramic coating's essential ingredients are resin (a polymeric component that forms the coating's structure), solvent(s), additive(s), and pigment(s).

2. Poly-dimethylsiloxanes as a common resins

The resin used in a ceramic coating system is a necessary component. Common resins include silicon-based polymers like poly-dimethylsiloxanes (PDMS). Because it is nontoxic, inert, nonflammable, optically transparent, has excellent thermal characteristics, and is UV stable, PDMS is frequently used in the formulation of ceramic coatings, as shown in Fig. 20.1 and its structure in Fig. 20.2.

In order to furnish ceramic coating systems with their hard, glossy, and hydrophobic properties, PDMS is commonly used as the most important component. PDMS adheres poorly to paints, plastics, metals, and wood substrates on its own. A semipermanent thin protective film can be created between PDMS and the substrate by adding silane additions to the formulation to increase adhesion.

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Figure 20.1 Ceramic coatings' fundamental composition.

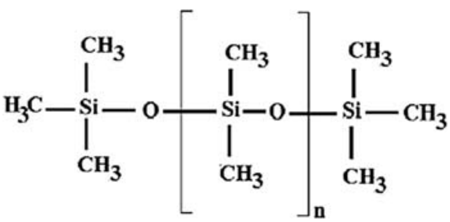

Figure 20.2 Polydimethyl-siloxane-PDMS structure.

The silane functional group (-Si-O-R) forms a strong covalent bond with the surface when subjected to mechanical abrasions, such as washing and rubbing, which improves overall coating adherence and contributes to an increase in ceramic coating lifespan.

Nonmetallic, inorganic ceramics are commonly produced using high temperatures during some stages of the manufacturing process. Technically, ceramics comprise a far wider spectrum of items than is often understood. Dinnerware, figurines, vases, and other ceramic art are commonly associated with ceramics. The vast majority of ceramic products are unknown to most people. A few examples include earthenware, porcelain enamel, glass, hollow tiles, glazed building tiles, floor and wall tiles, electrical insulators, pipes for water and sewage, and bricks.

Ceramic coating is a thin protective film that can significantly extend the useful life of all types of parts, boosting productivity by reducing maintenance downtime and extending the time between repairs. Ceramic coatings are crystalline thin films that are formed by deposition, heating, and cooling. They are inorganic, nonmetallic, solid, and inert. In other words, inorganic crystalline thin films are frequently referred to as "ceramic coatings."

The two primary methods for producing ceramic coatings are physical deposition and chemical deposition, and both can affect the microstructures and properties of the ceramic coatings. Examples of physical deposition processes include magnetron sputtering deposition and plasma spraying procedures [1].

Industry-grade ceramic coating is a chemical polymer solution used to coat a car's exterior to guard against external paint damage. It's normally applied by hand and mixes in with your car's paint, adding a layer of hydrophobic defense. This chemical interaction and the development of a fresh layer have no impact on the car's original paint job. While many auto enthusiasts and even detailing specialists mistakenly think that ceramic coating is a clear bra (paint protection film) replacement, it is actually a waxing replacement.

The clear coat must remain intact, and the paint must remain free of dirt, filth, and stain marks. Depending on the coating and polymer employed, ceramic coating, also known as nano-ceramic coating, might be a permanent or semipermanent solution to your difficulties. Due to its fundamental chemical characteristics, it does not decay in typical atmospheric circumstances like rain or summer. The superior mechanical and physical qualities of Fe, Cu, Ti, Al, and their alloys make them popular materials in a variety of industries, including biomedicine, marine engineering, and architecture [2−7].

The surface properties of metallic materials are important in working environments in a variety of ways. Metallic materials' corrosion resistance, antifouling, self-cleaning, wear resistance, oil/water separation, and biocompatibility can all be improved through surface fictionalization [8−10]. In this situation, surface coating works well and uses little resources to functionalize the surface of metallic objects.

Ceramic coating is also environmentally benign and has benefits including cheap cost, easy preparation, resistance to corrosion and wear, thermal stability, and mechanical endurance. Therefore, coating the surface of a metallic material with a ceramic layer is a practical way to achieve surface multifunction.

This chapter discusses the many types and characteristics of ceramic coatings. The methods for coating metals with ceramics and the uses for metals with ceramic coatings are then compiled. Chemical resistance, wear resistance, temperature resistance, and corrosion resistance are just a few benefits of using ceramic materials [11].

Ceramic materials are exceptional in their ability to perform. For instance, ceramic tiles are coated with layers of ceramic glaze to provide a surface that is stain-resistant, durable, and aesthetically pleasing. Ceramic enamel coatings are used to prevent thermally sprayed ZrO_2 (zirconia) deposits on aircraft turbines and chemical reactors. The advantage of utilizing ceramic enamel coatings is that they may change the properties of the vitreous matrix by including more oxide and functional particles [12].

Ceramic coatings that are composed of molten glass and other additions include enamels and glazes. Molten glass contains a variety of oxides including SiO_2, B_2O_3, Al_2O_3 (alumina), Na_2O, K_2O, CeO_2, MgO, ZnO, CaO, ZrO_2, and TiO_2 (titania), as well as adhesion promoters for metal surfaces, including CoO_2, NiO_2, Fe_2O_3, and MnO_2. It is feasible to predict ultimate characteristics such as the thermal expansion coefficient, melting temperature, and chemical resistance since a glass' composition can be altered. Quartz, TiO_2, zircon silicate, or ceramic colors can be used as raw materials to alter ceramic coatings for a certain metal type or end purpose [13].

3. Ceramic materials some common uses in surface coating processes

One of the most popular and adaptable coatings in the plant, equipment, and services sectors is ceramic coating. With the help of our ceramic coating technique, we can produce high-performance coatings using a range of ceramic material compositions. Coating functionality, thickness requirements, and other economic considerations all influence the coating process and ceramic materials chosen. The various types of ceramic materials, their applications, and the benefits of ceramic coatings will be discussed in this article.

A list of typical ceramic materials used in surface coating procedures is provided below:

ZrO_2: This substance is frequently used in molten contacts and thermal barrier coatings TBCs.

Al_2O_3: Nonconductivity, wear resistance, and corrosion resistance are all common uses for this material.

TiO_2: Frequently used for abrasive grain and hard surface wear resistance.

Chrome oxide (CrO_2): For wear and corrosion resistance, it's frequently used to seal surfaces.

Al_2O_3-TiO_2: Corrosion resistance is commonly used in a variety of seawater applications. Its nonconductive properties are also excellent.

4. The significance of ceramic coatings

Any high-tech system, such as those used in nuclear power, space exploration, missiles, and aviation, must operate under challenging circumstances, such as those involving extremely high and low temperatures, high gas flow rates, highly corrosive-erosive fluids, and concentrated energy fluxes, all of which are damaging to the materials used in construction. New materials are being investigated for their ability to withstand extreme circumstances. Because of their excellent characteristics, including high-temperature stability, corrosion, erosion, wear resistance, chemical inertness, and others, ceramics are being used in high-tech systems increasingly frequently. However, structural sections made of metals and alloys cannot usually be replaced with ceramic components due to the low mechanical qualities of ceramics. Additionally, different surface qualities are required at the core of various technical components as opposed to those that are wanted in numerous applications. A shaft's core, for instance, needs to be strong the seal needs to be wear-resistant and the outside surface needs to be fatigue-resistant. The best solution in these situations is ceramic coating technology, which involves preparing or depositing a ceramic layer on a surface. Ceramic coatings have been used to enhance metal qualities like refractoriness, insulation, erosion resistance, oxidation and corrosion resistance, electrical resistance, and various optical properties rather than replacing metals and alloys. The design engineer can also choose the base material based on mechanical and other design considerations utilizing coating technology before coating it with a ceramic layer to prepare it for use.

5. Recent increases in the use of advanced ceramic materials

Advanced ceramic materials are proving to be the ideal materials for many technical applications, including cutting tools, motors, turbines, spacecraft, and biomedical applications, as a result of their superior properties as compared to ordinary ceramics. Processed, chemical, and microstructural differences set advanced ceramics apart from conventional ceramic materials. As a result, in order to comprehend advanced ceramic materials better and promote their development for a particular technical application, a substantial study is required to evaluate their microstructural, mechanical, electrical, optical, and biological properties [14].

5.1 Nuclear applications of advanced ceramics

Nuclear reactors come in two varieties: fission reactors and fusion reactors. Ceramic materials play a key role in the fission nuclear fuel cycle, from nuclear fuel to the confinement of high-level radioactive waste. To keep the fusion nuclear fuel cycle going, a variety of ceramic materials are used in fusion reactors. The fundamentals of neutron-material interactions, where transmutation effects generate gaseous products and high-energy neutron knock-on introduces crystalline defects, are most important at first. In crystals or along the grain boundary, gaseous atoms congregate to form bubbles, causing significant swelling, mechanical strength degradation, and eventual material failure. Vacancies, interstitial atoms, dislocation loops, and voids are examples of induced crystal defects. These materials' electrical conductivity, chemical stability, and thermal diffusivity are all impacted by the formation of these crystalline defects in them [15].

5.2 Turbine applications for advanced ceramics

Advanced ceramic materials provide a variety of potential benefits for turbine applications. However, as it is not possible to make a completely dense ceramic turbine engine, metal-ceramic connections must be produced. Because ceramics and metals have different coefficients of thermal expansion (CTE), ceramic materials cannot be used in turbine applications. When a product is in use, thermal cycling may result in excessive strain at the metal/ceramic contact, which may induce catastrophic ceramic failure. In order to mix high-temperature metals like nickel alloys with ceramic substances like silicon nitride, a variety of procedures are needed. A successful joint design and vacuum brazing technique have been developed and optimized based on the insertion of a mechanically flexible metal interlayer between the metal and the ceramic. The variance in CTE that causes joint stress is compensated for by this. It is simpler to wet the ceramic by using an active metal braze alloy or a surface wetting agent. For the joint design, finite element analysis was used to generate design information on the expected lifespan of the components [16].

5.3 Coatings for thermal and environmental barriers

Gas turbine operating temperatures are raised, enhancing efficiency and reducing environmental impact by using cutting-edge ceramic components. On the other hand, in the presence of hot corrosive gases and water vapor flowing at high speeds, these silicon-based ceramics are susceptible to hot corrosion and recession. Environmental barrier coatings (EBCs), which are resistant to extreme combustion conditions and serve as diffusion barriers, must be employed to stop harmful gas-phase components from reaching the ceramic substrates. The substrate can function at temperatures much below the combustion temperature thanks to the poor thermal conductivity of TBCs, which cause a significant temperature decrease across the coatings. For the CTE match and absence of harmful chemical interactions at the interfaces, the effective thermal conductivity of the TBC, the hot corrosion and recession resistance of the EBC, as well as EBC/TBC coating systems, were taken into consideration [17].

6. Recent applications of surface coatings

Surface coatings are discussed in a variety of technological fields, including electronics, food, mining, aviation, and the chemical and petroleum sectors. Recently, surface coatings have become more popular in a variety of specialized industries. Thermal sprayed coatings are used in biomedical and orthopedic applications, dentistry, cancer treatment, sports (horse hooves, clothing, golf, swimming), the arts (glass coloring and enameling), and bronze applications [18].

Components can have surface coatings applied to them to affect a range of their attributes. Pure metals and alloys, nitrides, carbides, diamond-like carbon, aesthetic coatings, and TBCs are a few of the most popular kinds of coatings. Without a thin protective covering, contemporary cutting applications are hard to execute. High-speed cutting, harsh machining of highly hard materials, dry cutting, and cutting of challenging materials like titanium, Al-Si alloys, and other nonferrous abrasive materials are some of the uses. Tool surface coatings are generally just a few microns thick. They lessen dispersion and friction while raising the cutting edge's wear resistance [18].

The transportation industry benefits significantly from surface engineering. Coating technologies account for about 6% of the total cost of engine and transmission production. Surface coatings are used on motors, car parts, and fixed, permanent structures in the transportation industry. Among other power generating systems, engineering coatings are utilized in diesel engines and transmissions. Surface coatings shield power units from degradation and wear. Some auto parts, such as the suspension and brakes, are coated with thermally sprayed coatings to enhance wear resistance and hence prolong service life. On exposed parts like bumpers and wheel arches, epoxy-based polymer coatings are used.

Some automobiles have body coatings to boost their resistance to corrosion and abrasion. Noise reduction is further aided by polymer coatings. Surface coatings are also used to protect stationary constructions like bridges and oil rigs from the corrosion and abrasion caused by sand and seawater [18].

For more than 50 years, the aircraft industry has used surface coatings on engine components. Gas turbine engines with surface coatings offer special properties like load bearing, corrosion resistance, and high-temperature strength. The pieces are covered with thermally sprayed polymer coatings to prevent air corrosion. MoS_2 may also be applied to spacecraft components like gears and ball bearings via PVD magnetron sputtering. By doing this, the transmission system produces less heat and protects the gears from overheating.

Surface changes can improve the performance of a component. For instance, the slat track, which is made of maraging steel and is a component of light combat aircraft landing gear, needs its surface modified to increase wear resistance. Traditional, harder chrome plating can interfere with machining. For this application, a surface modification using plasma nitriding was recently created. Contrary to chromium plating, it does not require any postmachining operations and has no impact on fatigue life [18].

6.1 Ceramic coating applications

Coatings are made using ceramic coating technology for a range of applications. They can be divided into three categories.

a) High-temperature and electrically insulating coatings, as well as coatings that are anticorrosion, antierosive, and antiwear.
b) Process improvement and control coatings, such as coatings with specialized optical properties for spacecraft, coatings with heat barriers for internal combustion engine components, and coatings that absorb neutrons for nuclear components.
c) Fabrication of complex thin-wall components for diverse applications using a free-standing structure coating method.
d) Reclamation coatings, which are used to recycle old component coatings.

7. Surface coating methods

The most popular surface coating techniques are discussed in the next section and are mentioned in the tables below Table 20.1A–C.

8. Coating techniques for ceramics

Ceramic coatings are needed for a wide range of applications in a wide range of sectors, and the requirements and standards of the coatings vary depending on the application.

Table 20.1 A description of the research on stainless steel substrates with ceramic coatings.

S. No.	Year	Substrate	Coating material	Coating method	Properties findings	References
1	2014	304 stainless steel	Alumina	Laser/Sol gel	Same	[19]
2	2014	Martensitic stainless	Glass	Sprayed	The glass coated steel oxidizes according to a linear law.	[20]
3	2014	303 stainless steel	TiC composite	Tungsten Inert gas method	—	[21]
4	2014	316L stainless steel	Bio glass silica	Sol—gel method	Superior electrochemical performance compared to bare surfaces	[22]
5	2014	316L stainless steel	Molten multi—component oxides	Plasma spray (9 MB system)	—	[23]
6	2014	Stainless steel	Ceramic Matrix composite	Air spraying	Stainless steel oxidation was reduced by more than 91%.	[24]
7	2014	316 L stainless steel	Polymers	Lubricating additive	—	[25]
8	2014	304 stainless steel	Alumina	Detonation spraying	Cross-sectional hardness was found to be inversely proportional to wear rate.	[26]
9	2014	Stainless steel	WC—(W,Cr) 2C-Ni and WCCoCr	HVOF spraying	—	[27]
10	2014	Stainless steel	YSZ	Joining experiments	A better option for YSZ and steel joining in SOFC applications	[28]
11	2013	316 L stainless Steel	Ziconia (3YSZ)	Sol-gel/Laser	In comparison to the background region, area one has a much higher coating amount.	[26]
12	2013	Martensitic stainless steel	Al2O3	Pulsed laser deposition	-	[29]

13	2013	304 stainless steel	Ti-N-O films	Cathodic arc Plasma deposition	–	[27]
14	2013	304 stainless steel	Silica or/and alumina	Sol—gel/dip coating	–	[28]
15	2013	304 stainless steel	Oxide ceramics	Cathodic plasma Electrolytic oxidtion	–	[30]
16	2013	Austenitic stainlesssteel	W-B	Magnetron sputtering	–	[31]
17	2012	AISI316L stainless steel	Alumina	Sol-gel/laser	–	[32]
18	2012	316 L stainless steel	TiO_2	Sol—gel method	–	[33]
19	2012	AISI 316LN stainless steel	–	Plasma nitriding	–	[34]
20	2012	Austenitic stainless steel	ZrN	Sputter deposited	–	[35]
21	2012	304 stainless steel	WC—Co and Cr_2O_3	Plasma spraying	–	[36]
22	2011	1020 and 304 stainless steel	Ti—Al_2O_3 composite	Laser clad process	There was more microstructural refinement observed.	[37]
23	2010	Stainless steel	Yttrium, cobalt	Electron beam evaporation	Because of the low cost, it is ideal for SOFC interconnect applications.	[38]
24	2009	304 stainless steel	Alumina	Cathodic plasma Electrolytic deposition	The novel method used is cathodic plasma electrolytic deposition.	[39]

Continued

Table 20.1 A description of the research on stainless steel substrates with ceramic coatings.—cont'd

S. No.	Year	Substrate	Coating material	Coating method	Properties findings	References
25	2009	Ferritic stainless steel 441 HP	(Co,Mn)3O4	Magnetron sputtering system	The creation of thinner coatings on preoxidized samples has implications for SOFC interconnects and may eventually lower interfacial tension between the cathode and the interconnect.	[40]
26	2007	AISI 316L stainless steel	Si3N4 and Ti	Laser irradiation	Good interfacial bonding was observed	[41]
27	2006	Stainless steel	Al2O3, Cr2O3, and ZrO2	Plasma spraying (metco 3 MB)	With a zirconia coating, an engine part's merit score will rise.	[42]
28	2006	AISI 316 stainless steel	Zirocnia	Plasma spraying (F4-MB)	–	[43]
29	2005	AISI 316 L stainless steel	Alumina and Al2O3–13wt% TiO2	Plasma spray	The engine part's figure of merit will be improved with the addition of zirconia coating.	[44]
30	2005	Stainless steel	TiN and AlN	Reactive magnetron sputtering	–	[45]
31	2005	Stainless steel	SiC-composite	Laser clad process	–	[46]
32	2005	AISI304L stainless	Al_2O_3, Al_2O_3+TiO_2, ZrO_2	Plasma spraying (metco 3 MB)	–	[47]
33	2003	Austenitic stainless steel	Al_2O_3—13wt% TiO_2 and alumina	Plasma spaying (metco 7 MC)	Al_2O_3 coating increased hydrogen permeation resistance, and Al_2O_3-13 wt%TiO2 ceramic coating had a greater hydrogen resistance efficiency.	[48]

34	2003	304L stainless steel	FGMs	Plasma spraying (metco 3 MB)	–	[49]
35	2002	316 L stainless steel	Alumina, MSZ, YSZ	Air plasma spray	–	[50]
36	2000	Stainless steel	WC+12Co	Plasma nitriding	Use of an effective erosion resistance barrier is employed to prevent wear from high-energy particle impact.	[51]
37	2000	316 stainless steel	SiN based ceramics	Liquid lubricants	–	[52]
38	1998	316 stainless steel	Nitirding process	Plasma nitriding	–	[25]
39	1998	Austenitic and ferritic stainless steel	Nitrogen ions	Ion implantation	–	[53]
40	1998	Stainless steel	Mullite	Plasma spraying	High surface roughness and great thermal stability	[54]
41	1998	Stainless steel	Zircon sand	Plasma spraying	Good thermal shock resistance	[55]
42	1998	Stainless steel	Alumina	Duplex conversion	Increased greatly the oxidation resistance	[56]
43	1997	410 stainless steel	Zirconia	Plasma spraying	Average thermal conductivity value was determined	[57]
44	1992	Stainless steel rings	WC and Cr_2O_3	Plasma spraying	–	[58]

In conclusion, the following characteristics should be present in an ideal ceramic coating:

- Chemical inertness, which results in resistance to oxidation and corrosion at high temperatures
- Erosion resistance
- Inter and atomic diffusion resistance at high temperatures
- Dense layers
- Chemical inertness, which confers resistance to high-temperature oxidation and corrosion.

Since there is no ideal coating, it is usually crucial to pick a coating material that will allow the coating/substrate system to fulfill operational requirements. The operating environment, substrate type, availability of coatings, and economics all affect the coating choice for a particular application. Thankfully, several ceramic materials can be produced as coatings using the thermal spray (TS) or chemical vapor deposition (CVD) processes, and they are effective in a range of applications.

8.1 Process of thermal spraying

The most flexible technique for creating ceramic coatings is TS. Any material that melts can be coated with this technique without deteriorating or vaporizing [59]. Furthermore, the substrate can be any size or shape, and the coatings can be applied in situ, which is necessary in some special applications. As a result, this technique has been adopted by a variety of industries [60]. Even if certain cutting-edge spray coating techniques have been tried, such as pulse arc spray [60] and liquid fuel gun spray [46,59], only two procedures—combustion flame spray and plasma spray—are applied regularly in the business sector [61].

Utilizing the exhaust gas to melt and project the spray material after igniting oxygen and fuel gas is the combustion flame spray technique (Fig. 20.3). The fuel gases employed in this process include acetylene, hydrogen, and propane. With this method, flames that are roughly 3000 K in temperature are produced. The substance is sprayed into the blazing flame as wire, rod, or powder. In the flame powder spray system, ceramic powder is introduced directly into a part of the oxygen flow, which aspirates it through the center of the burner nozzle, where it is heated and transferred to the

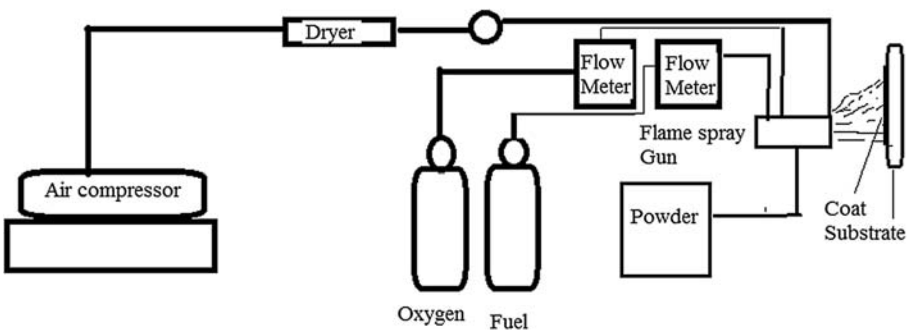

Figure 20.3 Combustion flame spray system schematic.

substrate at a velocity of 50−150 m/s. For ceramics with melting temperatures below 3000 K, spraying is an alternative [46].

The end of the rod or wire is placed in a high-temperature flame, where it melts. After being quickly vaporized by a compressed gas flow, the molten material is then quickly sprayed onto the substrates by a high-velocity gas stream [48]. Chagnon and Fauchais [61] the spray material in this system must be fully molten before it can be pushed with the effluent, unlike powder particles, which may still be partially melted after impact. The spray rate is governed by the rod's melting properties and gas enthalpy, which together define the melting rate of the rod.

The viscosity of the liquid phase is another factor. The rod spray system's average particle velocity is 150−200 m/s, which is higher than the particle velocity of powder spraying. Only a few ceramics, including $A1_2O_3$, ZrO_2, CrO_2, $ZrSiO_4$, and $MgAl_2O_4$, may be coated using the rod spray process, which has one significant drawback: not all materials can be manufactured in wire or rod form.

Another element is the liquid phase's viscosity. The average particle velocity of the rod spray system is 150−200 m/s, which is more than the particle velocity of powder spraying. The rod spray procedure, which is limited to coating a select few ceramics like $A1_2O_3$, ZrO_2, CrO_2, $ZrSiO_4$, and $MgAl_2O_4$, has one key drawback: not all materials can be produced in wire or rod form.

9. The properties of ceramics

The features of a few popular structural ceramics (Table 20.2) are compared to those of metals in this table. In terms of high-temperature strength, hardness, density, and

Table 20.2 Some potential uses for structural ceramics.

Application	Benefits of performance	Examples
Seals, bearings, nozzles, valves, and wear parts	Low friction, high hardness	Silicon carbide, alumina
Cutting instruments, Engines that generate heat components for diesel engines, Turbines (gas)	High tensile strength, hot hardness, thermal insulation, high temperature strength, and fuel efficiency are a few advantages of this product.	Silicon nitride, silicon carbide, silicon nitride, and zirconia
Hips, teeth, joints medical implants	Corrosion resistance, biocompatibility, and surface bonding to tissue.	Bio-glass, alumina, zirconia and hydroxylapatite,
Highways, bridges, and buildings construction	Durability is improved, and the overall cost is reduced.	Advanced concretes and cements

The Ceramics and Ceramic Composites Research Briefing Panel's report makes specific recommendations for improving ceramics education (Washington, DC: National Academy Press, 1985). 1988, Office of Technology Assessment.

thermal conductivity, ceramics often perform better than metals. The main problem with using ceramics as structural materials is that small flaws like cracks, voids, and inclusions may significantly weaken their strength. A ceramic structure's strength can be reduced to a few percent of its theoretical strength by flaws as small as 10−50 μm.

Small strength-controlling defects might be challenging to find and fix because of their size. This is an increase from the $112 million in 1985, according to statistics given by Business Communications Co., Inc. of Norwalk, Connecticut. Examples of these include wear parts, cutting tools, heat exchangers, engine components, bioceramics, and aerospace applications [62].

10. Processing of ceramics

The preparation of the powder, forming, densification, and fsinishing processes are the four fundamental steps in the production of the majority of ceramics, including both conventional and advanced ceramics. Table 20.3. includes a list of the key processing methods employed in these steps.

11. Powder preparation

Even though most of the essential building blocks for ceramics are abundantly available in nature, they must first go through a significant amount of processing or refining

Table 20.3 Common processing operations for advanced ceramics.

Operation	Process	Examples
Preparation of powder	Solution chemistry, synthesizing, granulating, and blending	SiC Si_3N_4 ZrO_2 Glasses
Forming	Extrusion, injection molding, tape casting, slip casting, dry pressing, melting/casting	Combustors and stators are two types of combustors. Instruments for cutting Honeycomb tubing rotors for turbochargers and capacitors Ceramics made of glass
Densification	Reaction bonding sintering Using a hot press Isostatic pressing in a hot environment	SiC, BN, Si_3N_4 Si_3N_4, SiC, Al_2O_3, and Si_3N_4
Finishing	Radiation laser, Electric, mechanical Chemical	Electron beam. Electric discharge, diamond grinding, and etching

before being used to create structures. With the exception of SiO2, all silicon-based ceramics are synthetic materials. It is necessary to synthesize all three gases, as well as silicon carbide, silicon nitride, and sialon (a silicon nitride-aluminum oxide alloy in which oxygen and aluminum atoms, respectively, take the place of silicon and nitrogen in the crystal structure).

Even naturally occurring minerals need to be processed before use to ensure purity, uniformity in particle size and distribution, and other qualities. Examples include bauxite, which is used to make Al_2O_3, and zircon sands, which are used to make ZrO_2. In recent years, the crucial relevance of powder preparation has been highlighted. Particle sizes and size distributions are crucial for advanced ceramics to provide consistent green (unfired) densities that allow consolidation and produce completely dense sintered ceramic components.

Ceramic powders are processed with a variety of dopants or sintering aids. Sintering ability can be improved by dopants, which control particle rearrangement and diffusivities. These dopants enable lower temperatures and/or quicker sintering. Dopants are helpful for boosting final densities and regulating grain growth. Dopants can affect a material's characteristics negatively despite its many benefits. The final product may be weaker due to dopant segregation at grain boundaries, and final properties like conductivity and strength may differ greatly from those of the pure material.

11.1 Forming

Ceramic raw materials need to be molded and formed before burning. The final ceramic characteristics are frequently determined by the forming process. Critical factors in the forming process include pore location, phase distribution, particle packing and distribution, and particle shape.

Cold forming and hot forming are two distinct techniques for shaping ceramics. The most popular cold-forming methods are slip casting, extrusion, dry pressing, injection molding, tape casting, and combinations of these. By following these steps, a green body that can be machined before firing is produced. The homogeneity of the cold-formed component determines how uniformly the component shrinks after burning.

Hot-forming techniques combine the forming and sintering processes into a single phase to produce basic geometric shapes. Hot pressing and hot isostatic pressing, both of which apply pressure in a single direction, are two of these procedures (Hello Ping, in which pressure is exerted simultaneously on the ceramic from all sides).

11.2 Densification

The primary method for transforming loosely bonded powder into a thick ceramic body is sintering. During sintering, atomic-scale diffusion compacts the powder. When the matter moves from the particles into the empty spaces between the particles in the temperature range where the diffusion process occurs, matter is first burned out of the green body and then causes densification and contraction of the portion. Intricate ceramic components can be produced at a reasonable price using sintering in conjunction with slip casting or other forming methods. To achieve high densities, it requires the use of additives and long sintering times. In the discussion of powders, we mentioned the complications caused by dopants.

11.3 Finishing

Chemical etching, laser and electric discharge machining, diamond and boron nitride grinding and milling tools, and other techniques are used in this procedure. Because of the extreme hardness and chemical inertness of densified ceramics, finishing procedures are some of the most difficult and expensive in the entire process. A significant amount of the component's cost may be attributed to grinding alone. Furthermore, during machining, surface cracks are frequently introduced, reducing the part's strength and fabrication yields.

12. Ceramic coatings types

12.1 Silicate ceramics

Materials consisting of silicon and oxygen are known as silicates. Alumino-silicates and magnesium silicates are the two most popular silicate ceramic kinds. Based on their capacity to absorb water, silicate ceramics are frequently categorized as coarse or fine, dense (2% for fine and 6% for coarse), and porous (>2% and >6%, respectively).

12.1.1 Oxide ceramics

Examples of oxides of ceramics include Al_2O_3, ZrO_2, SiO_2, aluminum silicate, magnesia, and other metal oxide-based compounds. These are categorized as inorganic, nonmetallic compounds because they contain oxygen, carbon, or nitrogen. The properties of oxide ceramics include the following: (a) Low wear resistance, (b) High melting points, and (c) a variety of electrical characteristics.

These ceramics have a number of unique characteristics. For instance, glazes and protective coatings increase the joining of metal and other materials, improve water and chemical resistance, and seal porosity.

In a variety of processes, including foundries and metal processing, radiofrequency and microwave applications, electrical and high-voltage power applications, as well as material and chemical processing, oxide ceramics are used. The most important technical oxide ceramic material is aluminum oxide. This synthetic material is composed of Al_2O_3 in concentrations ranging from 80% to over 99%.

12.2 Nonoxide ceramics

Nonoxide ceramics have been successfully employed to address severe wear and corrosion problems even at high temperatures and under difficult thermal shock circumstances. A few of the many applications for ceramics include the pharmaceutical industry, the oil and gas industry, valves, seals, rotating components, wear plates, projection welding location pins, cutting tooltips, abrasive powder blast nozzles, metal forming tools, and others.

12.2.1 Ceramics of glass

Polycrystalline materials are created by controlling the crystalline structure of the base glass. Both glasses and ceramics share many glass-ceramic properties. Amorphous and crystalline phases coexist in glass ceramics. A controlled crystallization process creates these. Glass ceramics combine the benefits of glass processing with the distinct characteristics of ceramics.

Due to the compact oxide layer (TiO_2) that spontaneously develops on surfaces, titanium, and its alloys have high corrosion resistance to alkalis, chlorides, and some strong acids. Consequently, TiO_2 coating is recognized as a trustworthy corrosion-resistant layer for protecting metal substrates. Shen et al. applied TiO2 nanoparticles uniformly to 316 L stainless steel using the sol-gel method. According to the electrochemical data, 316 L stainless steel with a TiO_2 coating effectively prevents corrosion in a chloride-containing solution at room temperature [63]. Additionally, research revealed that the TiO_2 nanostructure coating showed good photoactive antibacterial and hemocompatibility capabilities [64,65]. Similarly, SiO_2 is a popular coating material for metallic materials due to its wear and corrosion resistance. By employing metal-organic CVD, the SiO_2 ceramic layer on alloys was created, and it is corrosion-resistant (MOCVD) [66]. Additionally, Sadreddini et al. discovered that boosting the bath's concentration of SiO_2 nanoparticles reduced the rate of corrosion and coating porosity [67,68].

13. Structural ceramics

Engineering ceramics' physical and mechanical properties are studied in structural ceramics research. Engineering ceramics are utilized in practical applications that benefit from qualities like high-temperature capacity, high wear resistance, and thermal shock resistance, which sets them apart from pottery ceramics.

Examples of structural ceramics include silicon nitride ceramics, which are used as cutting tools, cordierite-mullite refractories, which are used for their good thermal shock behavior and Al_2O_3, which is used as crucibles.

Various structural ceramics-related topics have been the subject of research at Cambridge over the years, such as how to join them to other materials, like metals, using active metal brazing so that the finished component can be used at temperatures above 400°C or temperatures outside the range of conventional adhesive glues.

Active metal brazing is a rapid and versatile method for joining different ceramics to metals or to one another. Al_2O_3 has been bound to itself using braze filler alloys based on the Ag-Cu-Ti system. Although there is an abundance of research on the interfacial structures of Ag-Cu-Ti-based alloys and Al_2O_3, the chemical pathways that lead to the evolution of interfacial phases and, ultimately, the formation of strong bonds, were unknown until our most recent study.

Using a number of electron microscopy-based methods, we have demonstrated that when the Ag-Cu-Ti-based alloy melts, Ti initially interacts with the Al_2O_3, dissolving considerable quantities of oxygen, to generate a transitory reaction layer that permits the braze to wet the Al_2O_3. In a few seconds, this reaction layer breaks down, allowing Ti3Cu3O atoms to form behind it and make contact with the liquid braze. TiO_2 particles were discovered to be the final interfacial phase to develop in the joint. Long bonding periods, far longer than would be required in an actual brazing procedure, cause TiO_2 to become the only interfacial bonding phase.

Using the findings of this study's comprehensive experimental observations as a function of bonding temperature, a clear bonding mechanism for the joining of high-purity Al_2O_3 with Ag-Cu alloys driven by trace amounts of Ti was created. The dependability of ceramic components is negatively impacted by brittle structural ceramics.

Four approaches are frequently utilized to fix this flaw: (a) toughening the ceramic with fiber reinforcement or microstructural control; (b) high-level nondestructive examination; and (c) repair of harmful faults; proof testing to choose high-reliability components; and (d) usage of self-crack-healing materials.

- Si_3N_4: Parts of gas turbines, bearing balls, cutting tools, heat exchangers, turbocharger rotors
- SiC: Ballistic armors, abrasives, disc brakes, pipes for corrosive liquids
- WC, Ti(C, N): cermets, cutting tool inserts
- B_4C: Nuclear reactor neutron absorbers, ballistic armor, nozzles, and abrasives
- Al_2O_3: thermal insulation, spark plugs, substrates, crucibles, furnace tubes, ballistic armors
- $Mg_2Al_3(Si_5AlO_{18})$ (cordierite) and $3Al_2O_3$•$2SiO_2$ (mullite): ceramic filters, catalytic converters
- ZrO_2: Knives, watch cases, orthopedic implants, grinding media, and TBCs.
- UO_2: Nuclear power
- $Ca_{10}(PO_4)_6(OH)_2$ (hydroxyapatite): artificial bone, biomedical implants

14. Functional ceramics

Functional ceramics are described as ceramics created specifically for purposes requiring extra qualities beyond structural ones, such as electric, magnetic, or optical. Of course, structural ceramics have specific functions, which are usually based on their ability to withstand mechanical and thermal loading, as well as chemically aggressive environments, such as body fluids (bioceramics). Functional ceramics are ceramics created specifically for uses needing electric, magnetic, or optical qualities.

Because of their great diversity in terms of composition, structure, and related features, advanced and functional ceramics and glasses may be employed for a wide range of human applications. The articles published in the Advanced and Functional Ceramics and Glasses journal cover all varieties of ceramics and glasses, including single-crystal and polycrystalline ceramics, amorphous ceramics (glasses), partially crystalline ceramics (glass-ceramics), nanoceramics, and composites based on or containing the materials mentioned. Here are just a few examples of potential topics:

Processing: colloidal science, new forming and sintering methods, additive manufacturing, patterning, templates, self-assembly, large-scale/complex shape processing, hybrid processes, cofiring of metals and ceramics, and composites manufacturing are all examples of techniques that are used to prepare powders.

Properties: photoelectric; magnetic; interfacial; transport; thermodynamic; biocompatible; bioactive; mechanical; electrochemical; electrical; ferroelectric; thermal; thermoelectric; and optical Table 20.4.

The "Functional Ceramic Coatings" Special Issue sought to illustrate achievements in the creation of ceramic coatings for a variety of applications with a focus on how their internal structure and morphology impact functional characteristics and potential uses. Fourteen peer-reviewed scientific papers on a range of subjects were featured in the special issue, including.

- Applications in bioactive/biomedical fields [1−4,69−72].
- Properties that act as a barrier and provide protection [5−7,73−75].
- Mechanical and wear resistance properties [8−10,76−78].
- Photocatalytic and optical properties [11,12,79,80].
- Mechanisms of deposition and adhesion [13,14,81,82].

15. Applications of zirconia in functional ceramics

A broad list of ceramic coating uses is shown below:

Heat-and oxidation-resistant surfaces, high-temperature wear-and abrasion-resistant layers, corrosion-and erosion-resistant layers, TBCs, and diffusion barrier coatings.

15.1 Zirconia ceramic ball for ball pen

Zirconium dioxide balls are extremely resistant to corrosion, abrasion, and stress from repeated impacts. In fact, at the point of impact, they will become even tougher. Zirconia oxide balls are also exceptionally hard, durable, and strong. Zirconia balls can tolerate temperatures of up to 1800°F and are resistant to extreme heat and corrosive substances.

15.2 Zirconia ceramic knives

High-strength, wear-resistant ZrO_2 ceramic knives are nonrusting, nonoxidizing, acid and alkali resistant, antistatic, and do not react with food. At the same time, ZrO_2a ceramic knives are an excellent nonpolluting high-tech tool. Zirconia ceramic table knives, scissors, razors, scalpels, and other items are currently the most popular items on the market.

Table 20.4 Functional ceramics are ceramics created specifically for uses needing electric, magnetic, or optical qualities.

Functionality	Material	Applications
Resistors	$LaCrO_3$, $MoSi_2$, and SiC	High-temperature furnace heating elements
Thermostats (PTCR and NTCR)	Spinels, $BaTiO_3$	Temperature sensors and heating elements that self-regulate
Extremely low-loss dielectrics ($\varepsilon_r = 3-10$)	Cordierite, Al_2O_3, AlN	Electronic circuit substrates and chip packaging
Microwave dielectrics are a type of dielectric that is used in microwave applications. ($\varepsilon_r = 30-80$)	$Zr(Ti,Sn)O_4$, $(Ba,Sr)TiO_3$, $BaMg_{1/3}Ta_{2/3}O_3$, $BaTi_4O_9$	For mobile communications and GPS devices, MW resonators, filters, and antennas, as well as tunable MW devices
Dielectrics that are temperature stable ($\varepsilon_r \approx 100$)	BaO-Nd_2O_3-TiO_2,$CaTiO_3$	Temperature-independent capacitance capacitors
High-dielectric-constant dielectrics ($\varepsilon r \approx 3000$)	$BaTiO_3$	Ceramic capacitors with multiple layers
Ceramics with piezoelectric properties	$Pb(Zr,Ti)O_3$ (PZT)	Transducers, actuators, and resonators are all types of transducers.
Ceramics with pyroelectric properties	$Pb(Zr,Ti)O_3$	Detection and imaging of infrared radiation
Ceramics with ferroelectric properties	$SrBi_2Ta_2O_9$ $Pb(Zr,Ti)O_3$	Memories made of ferroelectric material (FeRAMs)
Ceramics that are electrostrictive	(PMN-PT) $PbMg_{1/3}Nb_{2/3}O_3$ -$PbTiO_3$	Actuators
Ceramics that are magnetic	$BaFe_{12}O_{19}$ Spinels $(Ni,Zn) Fe_2O_4$ $Y_3Fe_5O_{12}$ (YIG)	Permanent magnets are used as inductors. Devices that use microwaves (radars)
Conductors of ions	$Gd:CeO_2$ β-Alumina $Y:ZrO_2$ (YSZ)	Solid-oxide fuel cells (SOFCs) electrolytes, oxygen sensors Na-Batteries
Superconductors	$MgB_2YBa_2Cu_3O_{7-x}$ (YBCO)	Magnet superconducting cables
Ceramics that are transparent	$Y_3Al_5O_{12}$ (YAG) Al_2O_3, $MgAl_2O_4$	Phosphors, optical materials for lenses and laser systems, heat-seeking missile nose cones, and high-pressure sodium street lamps are just a few examples.
Materials for optoelectronics	$LiNbO_3$ PLZT	Modulators, waveguides, frequency doublers, and voltage-controlled optical switches

15.3 Zirconia high temperature heating elements

At room temperature, ZrO_2 is an insulating material with a specific resistance of 1015 cm; however, when heated to 600°C, it becomes conductive and is a good conductor above 1000°C. At 1800°C, it can be used as a high-temperature heating element. Temperatures as high as 2400°C can be reached while working. It has been successfully used in heating elements with temperatures above 2000°C.

15.4 Zirconia bioceramics

Zirconia porcelain teeth have good biocompatibility, do not stimulate the oral mucosal tissue, and easy to clean.

15.5 Zirconia coating materials

High-performance Y_2O_3-stabilized ZrO_2 can be used in high-performance turbine aeroengines as thermal barrier ceramic coating materials. The thermal barrier coating uses the characteristics of thermal insulation and corrosion resistance to protect the metal material. It can not only improve the combustion efficiency of the oil but also greatly increase the life of the engine. It has important application value in aviation, space, sea surface ships, large thermal power generation, and automotive power.

15.6 Zirconia communication materials

The structure, stability, and electronic properties of a series of ZrO_2 nanoparticles ranging in size from 1.5 to 2 nm, $(ZrO_{2\pm x})_n$, were studied in the $n = 13$ to $n = 85$ range.

15.7 Zircona oxygen sensors

In the automotive industry, oxygen sensors are indispensable for engines that use three-way catalytic converters to reduce emission pollution. The currently used oxygen sensors are TiO_2 and ZrO_2a, of which the most widely used is the ZrO_2 oxygen sensor.

16. Features of the various classes of ceramic coatings

Applying ceramic coatings, which are two-dimensional layered structures, to the surface of a substrate or item via a variety of deposition procedures enhances the performance and durability of engineered materials (such as plasma spraying, vapor deposition, and sol-gel methods). These coatings protect against a variety of wear processes that operate in various service environments. Ceramic coatings have lately gained a lot of industrial and technological interest due to their special features and have been suggested as potential candidates for considerable use in a range of different engineering applications. For example, in endurable abrasive-resistant ceramic coatings primarily used for tool materials in machining and casting to provide excellent mechanical protection against abrasion and erosion, the extreme hardness combined with the good toughening character of ceramic coating materials is the key property. Similarly, the insulation property of electric insulation ceramic coatings is critical for applications in microelectronic circuits and heating elements, superior chemical inertness of corrosion-resistant ceramic coatings is a must-have property in hostile corrosive environments, and high-temperature resistance properties are required for thermal barrier ceramic coatings used in various zones of gas turbine engines, nuclear reactors, and other applications [2]. Table summarizes the key characteristics of the various classes of ceramic coatings, organized by application area.

16.1 Environmentally ecofriendly

Ceramic, in contrast to other materials, is completely eco-friendly. a sustainable option that offers an alternative to items like plastic, which pollutes our oceans, vinyl and laminate flooring, which may release VOCs, and some types of wood, which contain formaldehyde. Ceramic is made from the ground and is produced using natural resources. Due to its natural nature, it is completely recyclable.

Ceramic tiles don't burn or melt, so they don't release harmful gases that are bad for the environment or your health. There is less pollution during the supply since the factories are close to the raw material sources. Its production process is efficient, requiring fewer raw materials, energy, and water, as well as upgrading and recycling garbage and cogenerating electricity. It is a sustainable material because of its excellent resilience and longevity, which prevent unnecessary resource usage.

16.2 Health-friendly

The most important thing is our health, thus it's crucial to utilize products that promote good health and don't impair it. Ceramics is the ideal material for your home as a result.

VOC focal points, which are poisonous gases that can irritate the ear, nose, and throat as well as cause flu-like symptoms, may be found in laminated flooring, but ceramic tiles shield individuals from exposure to these hazardous pollutants. For example, it contains no formaldehyde, no VOCs, no PVC, and no odors. Ceramics improves the health of your house since it is an inert, dust-proof substance, ideal for those who have allergies or asthma. Because ceramic is watertight, wetness may be avoided, and bacterial and fungal colonies cannot grow. One of the most sanitary materials, it can be washed with any common home cleaner and has no odor. Its joints are also well constructed and do not collect dust or dirt. Because of this, disinfecting floors and walls is relatively simple.

17. Conclusions

Numerous industries all around the world have adopted ceramic coatings for process optimization and life extension, demonstrating the technology's immense potential.

The technology's full potential hasn't yet been realized in India, though. Several surface properties, including roughness, hardness, wear resistance, corrosion resistance, and oxidation resistance, have been improved by advanced ceramic coatings.

Due to their improved surface and thermal qualities, modern surface coating processes, particularly the air plasma spraying technique, are used for a range of TBCs. Due to their excellent wear resistance and low heat conductivity, contemporary ceramic materials routinely use surface coatings and surface modification techniques. Due to their excellent wear resistance and low heat conductivity, contemporary ceramic materials routinely use surface coatings and surface modification techniques. The use of contemporary ceramic materials minimizes heat transfer from component walls in nuclear power-producing areas. A variety of TBCs are applied using air plasma spraying processes, which are especially cutting-edge surface coating techniques due to their improved surface and thermal properties. Surface roughness, hardness, wear resistance, corrosion resistance, and oxidation resistance, among other surface properties, are enhanced in advanced ceramic coatings. They are applied in nuclear power-producing areas to lessen heat transmission from component walls. It is not unexpected that metallic materials with extremely hydrophobic ceramic coatings can be used in biotechnology, corrosion control, wear resistance, self-cleaning, antifouling, and oil/water separation.

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