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ADVANCED CERAMIC COATINGS: FUNDAMENTALS, MANUFACTURING, AND CLASSIFICATION

Edited by
RAM K. GUPTA, AMIR MOTALLEBZADEH
SAEID KAKOOEI, TUAN ANH NGUYEN
AJIT BEHERA

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Environmental impacts and benefits of ceramic coatings

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Manjunath S. Hanagadakar[1] *and Raviraj M. Kulkarni*[2]
[1]Department of Chemistry, S.J.P.N. Trust's Hirasugar Institute of Technology, Nidasoshi, Karnataka, India; [2]Centre for Nanoscience and Nanotechnology, Department of Chemistry, KLS Gogte Institute of Technology, Belagavi, Karnataka, India

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.

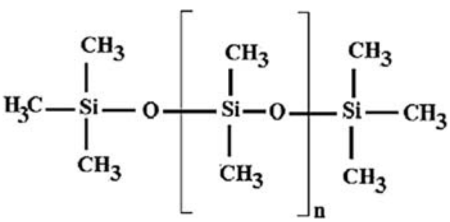

Figure 20.2 Polydimethyl-siloxane-PDMS structure.

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]

Advanced ceramic coatings containing multifunctional components are now finding application in transportation and automotive industries, in electronics, and energy sectors, in aerospace and defense, and in industrial goods and healthcare. Their wide application and stability in harsh environments are only possible due to the stability of the inorganic components that are used in ceramic coatings.

Advanced Ceramic Coatings: Fundamentals, Manufacturing, and Classification introduces ceramic coating materials; methods of fabrication; characterization; the interaction between fillers and reinforcers and environmental impact; and functional classification of ceramic coatings.

The book is one of four volumes that together provide a comprehensive resource in the field of Advanced Ceramic Coatings, also including titles covering energy; biomedical; and emerging applications.

The books will be extremely useful for academic and industrial researchers and practicing engineers who need to find reliable and up-to-date information about recent progresses and new developments in the field of advanced ceramic coatings. It will also be of value to early career scientists providing background knowledge to the field.

Key Features:

- Comprehensive coverage of the production, characterization, and properties of advanced ceramic coatings
- Features the latest manufacturing processes
- Covers basic principles of surface chemistry and the fundamentals of ceramic materials and engineering
- Features latest progress and recent technological developments
- Discusses the basic science particularly relevant to both the materials and preparation methods

About the Editors

Dr. Ram K. Gupta is an Associate Professor, Department of Chemistry, Pittsburg State University, USA

Dr. Amir Motallebzadeh is a Senior Researcher, Koç University Surface Science and Technology Center (KUYTAM), Koç University, Turkey

Dr. Saeid Kakooei is a Senior Research Engineer (Research Scholar) with the School of Materials Engineering, Purdue University, West Lafayette, Indiana, USA

Dr. Tuan Anh Nguyen is a Principle Research Scientist, Institute for Tropical Technology, Vietnam Academy of Science and Technology, Vietnam

Dr. Ajit Behera is an Assistant Professor in the Metallurgical and Materials Engineering Department at the National Institute of Technology, Rourkela, India.

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