Fundamentals of ceramics: introduction, classification, and applications

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Chapter outline

1. Introduction

1.1 Historical evolution and significance of basics in the development of ceramics

Ceramics have played an important role since prehistoric times and the discovery of ceramics goes back to several hundreds of decades. Clay, which is abundant in nature, was used by mankind to fabricate objects by mixing with water, followed by firing. The oldest known ceramic artifact is dated 28,000 BCE (Before Common Era). Additionally, several hundred sculptures of Ice Age animals were also unraveled near the remains of the Czech Republic.

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Several decades later in eastern Asia in China, broken pieces of pots dated 18,000−17,000 BCE were found and it is believed that the use of pottery spread from China to Japan and Russia.

Subsequently, during the Neolithic period, the application of ceramics was significantly promoted by the agricultural community. Around 9000 BCE, clay-based containers for water and food, art objects, tiles and bricks, spread from Asia to the Middle East and Europe. These products were dried in sun or fired at low temperature in rudimentary kilns dug into the ground. The pottery was painted with decorative design.

Around 7000 BCE, the first man-made glass was accidently made by Phoenician merchants in 5000 BCE. While relaxing at a beach, the cooking pots were placed on sodium-rich rocks near a fire. The heat from the fire melted the rocks and mixed them with sand, forming molten glass. Simple glass items, such as beads, were discovered in Mesopotamia and Egypt.

Prior to 2000 BCE, cutting tools were largely made of flint. Flint is a ceramic and was an important material in an age when stone, pottery, and wood were believed to be the only engineering materials. Metals were unknown. Flint had a special role, because it could be shaped to a cutting edge and used as a weapon or as a knife. It was one of the engineering materials of Stone Age, or—as we could now call it—the age of ceramics (Fig. 1.1).

One of the earliest fabricated ceramic product to be processed was a wheel in 3500 BCE, which led to the wheel-forming technique and extended to other ceramic products characterized by radial symmetry. Greek vases were part of evolution.

In the 16th century CE (Common Era), earthenware was the ceramic product made in Europe and the Middle East. Kilns capable of reaching up to 1350°C were first introduced by the Chinese. Subsequently, around 600 CE, porcelain from kaolin clay was developed that later moved to Europe through Asia and along the Silk Road through a Venetian merchant Marco Polo.

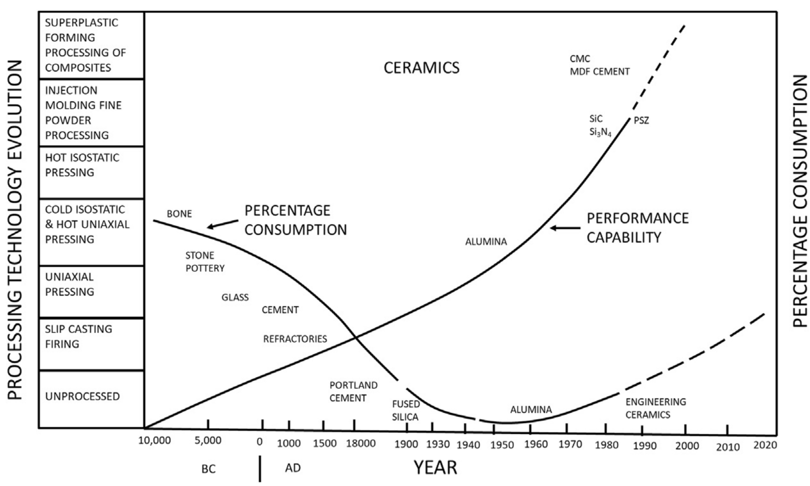

Figure 1.1 Evolution of ceramics from early stage to the advanced.

By 15th century, in Europe the earliest blast furnaces were developed in Europe using natural materials that attained a temperature of 1500°C and were used to melt iron. Later on, in the 16th century, refractories with superior resistance to high temperature were developed to melt glass and to make coke and cement. This was the birth of an industrial revolution and triggered the development of new products to exploit the unique properties of ceramics, notably, low thermal and electrical conductivity, high chemical resistance, and high melting point.

Up until the past 80 or so years, the most important materials in this class were "traditional ceramics," those for which the primary raw material was clay. Products considered to be traditional ceramics are china, porcelain, bricks, and tiles, in addition to glasses and high-temperature ceramics.

In the last 2−3 decades, significant progress has been made in understanding the fundamental characteristics of these materials and of the phenomena that occur in them that are responsible for their unique properties. Consequently, a new generation of these materials has evolved, and the term "ceramic" has taken on a much broader meaning.

After World War II, ceramics and glass contributed to the growth of many technologically advanced fields, including electronics, optoelectronics, medical, energy, automotive, aerospace, and space exploration. In addition, innovations in ceramic processing and characterization techniques have enabled the creation of materials with tailored properties that meet the requirements of specific and customized applications. To 1° or another, these new materials have a rather dramatic effect on our lives; electronic, computer, communication, aerospace, and a host of other industries rely on their use.

In general, ceramic materials used for engineering applications can be divided into two groups: traditional ceramic materials and the engineering ceramic materials. Typically, traditional ceramics are made from three basic components: clay, silica (flint), and feldspar. Examples of traditional ceramics are bricks and tiles used in the construction industries and electrical porcelain in the electrical industry. The engineering ceramics, in contrast, typically consist of pure or nearly pure compounds such as aluminum oxide (Al_2O_3), silicon carbide (SiC), and silicon nitride (Si_3N_4). Examples of the use of the engineering ceramics in high technology are silicon carbide in the high-temperature areas of the experimental AGT-100 automotive gas turbine engine and aluminum oxide in the support base for integrated circuit chips in a thermal conduction module.

The properties of ceramic materials differ because of differences in chemical bonding. Ceramics are generally good electrical and thermal insulators because of the absence of conduction electrons. Furthermore, they have relatively high melting temperatures and high chemical stability in many hostile environments because of the stability of their strong chemical bonds (covalent and ionic bonds). As a result of these properties, ceramic materials are indispensable for many engineering designs.

The three properties that are basic to structural applications are modulus, strength, and toughness. Ceramics are the strongest as well as stiffest solids, but are brittle with least toughness, when compared with metals and polymers. However, significant developments have taken place that have rendered ceramics tougher and improved their resistance to failure, which led to their emergence as engineering materials, particularly for high-temperature applications. The brittleness of ceramics has been considerably reduced. For instance, the fracture toughness of zirconia has been increased from 8 to 20 MPa$\sqrt{m}$. Fig. 1.2 summarizes two microstructural techniques for significantly increasing fracture toughness. Partially stabilized zirconia (PSZ), a variation of the zirconia formed by adding 5−10 wt.% Y_2O_3 or MgO adequate to stabilize the high temperature cubic phase, is used as dies in hot extrusion processes with demonstrated advantages of long maintenance-free life and better surface finish product. Fig. 1.2A illustrates the mechanism of stress-induced transformation toughening in PSZ. Having second-phase particles of tetragonal zirconia in a matrix of cubic zirconia is the key to improved toughness. A propagating crack creates a local stress field that induces a transformation of tetragonal zirconia particles to the monoclinic structure in that vicinity. The slightly large specific volume of the monoclinic phase in comparison to tetragonal zirconia causes an effective compressive load locally and, in turn, the "squeezing" of the crack shut. Another technique of arrest is shown in Fig. 1.2B. Microcracks purposely introduced by internal stresses during processing of the ceramic are available to blunt the tip of an advancing crack. In the light of these developments, a number of ceramic materials are being considered for engineering (structural) applications. Another technique is reinforcement with fibers.

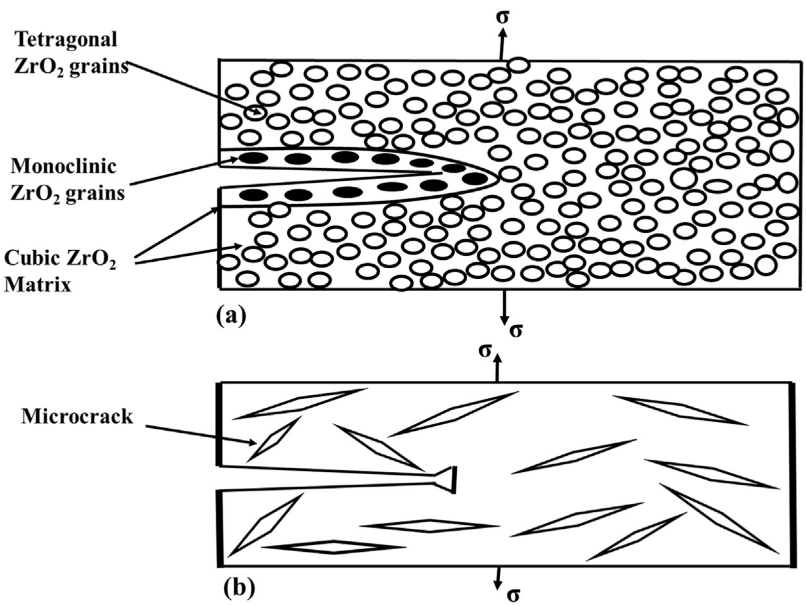

Figure 1.2 Two microstructural techniques for significantly increasing fracture toughness of ceramics. (A) Stress-induced transformation toughening of zirconia and (B) microcracks purposely introduced by internal stresses during processing of the ceramic are available to blunt the tip of an advancing crack.

In the development of ceramic materials, basic scientific inputs have played a major role. This can be illustrated with the example of cement, a successful material. The primitive Pozzolana cement had very poor flexural strength and possessed extremely low ductility. Later, Portland cement was developed in the 19th century. The flexural strength of this material was about 10 MPa and a fracture energy of about 20 mJ/m^2. After a century of this development, we have today what has been termed macro defect-free (MDF) cement with strength 15−20 times larger (150−200 MPa) and at the same time ductility 8 times better (fracture energy—50,000 J/m^2). This dramatic improvement in properties is a result of special processing adopted for MDF cement on the basis of scientific insight into the structure−property relationship (Fig. 1.3). The advent of MDF cement radically widens the application areas for this cement referred to also as lithoplastic, a low energy consuming material to replace plastics and metals in several applications. In a similar manner, the manufacture of otherwise brittle engineering ceramics on tonnage basis is also closely linked with the development of relatively new processing technologies (Fig. 1.1). The growing consumption of ceramics has no doubt been facilitated by the developments in ceramics processing. Important developments include powder manufacturing techniques like sol−gel and freeze drying, preconsolidation by slip casting or injection molding, consolidation through hot pressing and sintering, and finally the development of special nondestructive inspection techniques using the acoustic microscope [1].

The capacity to resist tensile loads, combined with the inherent properties of high strength, high stiffness, oxidation resistance, and ability to perform in the highest temperature environments, has rendered ceramic materials the most important candidate materials for a variety of applications including the aircraft gas turbine engine. Silicon carbide, silicon nitride, zirconia, and sialon represent the important engineering

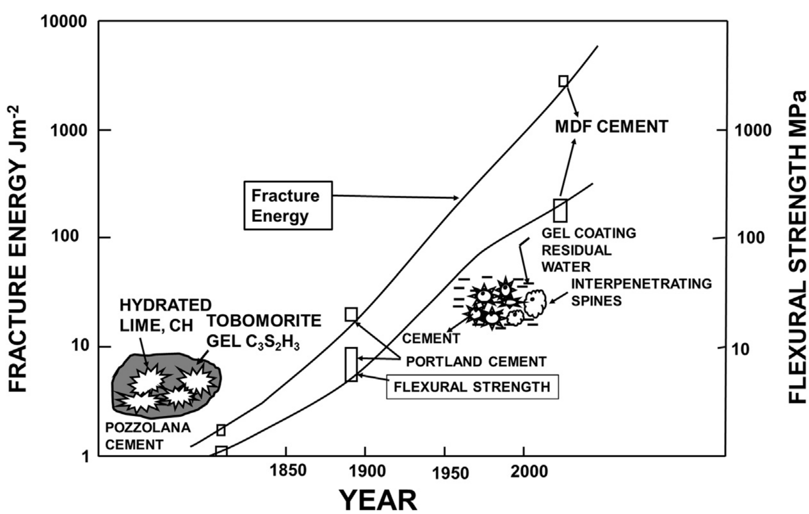

Figure 1.3 Summary of microstructural techniques for significantly increasing fracture toughness.

ceramics. They formed a nucleus for the development of a new class of engineering ceramics. The thrust for the development of these structural ceramics came from the intense effort made in producing more efficient engine systems. The most important requirements for such an engine are low thermal conductivity, high strength, high fracture toughness, high thermal shock resistance, good wear resistance, chemical inertness, high resistance to erosion and corrosion, at high operating temperatures of an engine. Zirconia-toughened ceramics are extremely promising in this regard. The thermal conductivity is extremely low and varies little with temperature. This means that it can be used as a thermal barrier coating on turbine blades and in adiabatic diesel engines. The thermal expansivity is relatively high. This is advantageous when joining the ceramic to metallic components. Engineering applications of zirconia are based on the fact that zirconia can be toughened. Zirconia-toughened alumina ceramics are promising tool materials. Fully stabilized zirconia has found promising applications for thermal barrier coatings on gas turbine engine components. The economic impact for engineering ceramics and their use as cylinder liners, piston caps, valve guide seats, etc., in the adiabatic engine for automobiles [2].

Silicon nitride has proved to be a material suitable for high-temperature applications particularly for jet engine blades which can enable one to increase the turbine entry temperature. It is also suitable for integral moving components of ceramic engines. Several synthetic routes are available for making Si_3N_4. They include chemical vapor deposition, direct combination of Si and N, etc. Final shapes (consolidation and compaction) are achieved by hot pressing, reaction bonding, and sintering with and without additives [3].

More recently, nanotechnology has led to significant development of ductile and transparent ceramics with broad range of applications from healthcare to capacitors.

2. Classification of ceramics

There are multiple ways to classify the ceramic materials. All-ceramic classification systems are useful for communication and teaching, yet they require constant changes and upgrades to integrate new materials. The basic composition of ceramics varies widely. The phrase "ceramic" conjures up images of earthenware, clay pots, and other items present in many homes. These objects are manufactured from naturally occurring clay and sand. Ceramics are produced into a wide range of industrial products using a variety of components and processing techniques. The other technical ceramic materials are made in a laboratory under the supervision of scientists to achieve suitable technological advancements.

Looking at the ceramics, simply as solid state materials, they can be classified into the traditional categories like monocrystalline, polycrystalline, and amorphous. Multiple crystal grains are linked together throughout the manufacturing process to generate polycrystalline materials, whereas monocrystalline materials are grown as a single three-dimensional structure. When compared to single crystals, polycrystalline materials fabrication procedures are comparatively affordable. Polycrystalline materials should not be mistaken with single crystals due to these distinctions (e.g., numerous crystals with varying orientations, existence of grain boundaries, fabrication procedures) and should be the only ones included within the definition of ceramics. The grain sizes and shapes of ceramics have a big impact on their qualities and processing. Density, hardness, mechanical strength, and optical properties all have a lot to do with the microstructure of the sintered item.

Glass, on the other hand, is formed of nonmetallic inorganic components having an amorphous structure. Amorphous structure refers to atoms that are not structured in a well-ordered, repeating pattern, as they are in crystals. Glass ceramics are made up of tiny grains encased in a glassy phase with characteristics that fall somewhere between glass and ceramics.

Ceramic materials have a wide range of properties due to changes in bonding and have thus found a wide range of engineering uses. In general, there are two types of ceramic materials utilized in engineering applications: traditional ceramics and engineering (advanced) ceramics. Clay, silica (flint), and feldspar are the three main ingredients in traditional pottery. For instance, bricks, tiles, and porcelain are the popular examples of traditional ceramics. An illustration given in Fig. 1.4 shows the various categories of traditional ceramics.

Engineering ceramics, on the other hand, are made up of various inorganic compounds like aluminum oxide (Al_2O_3) and silicon di oxide (SiO_2), etc. Even though ceramics are classified in a variety of ways, the two most important are based on their specialized applications and composition. Hence, based on their composition, ceramics are classified as oxides, carbides, nitrides, silicates, sulfides, fluorides, etc. Some of the important and popular ceramic materials falling under the categories of various chemical compositions are given in Figs. 1.4−1.8.

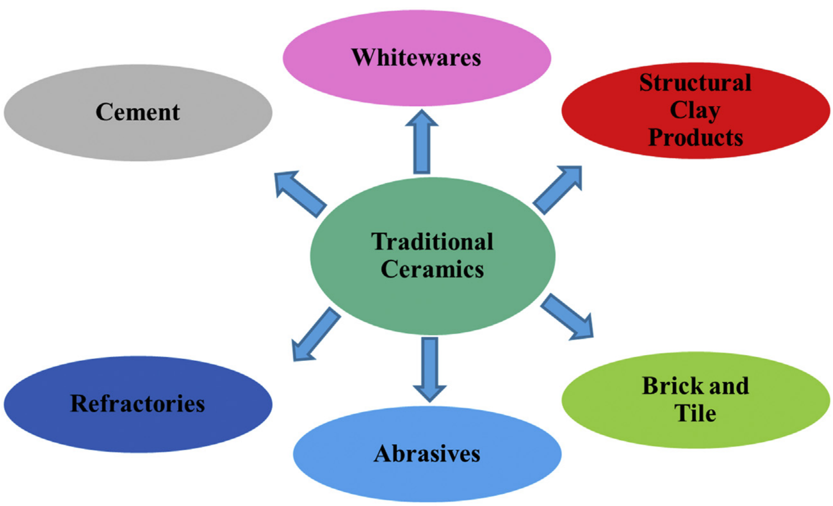

Figure 1.4 Various traditional ceramics.

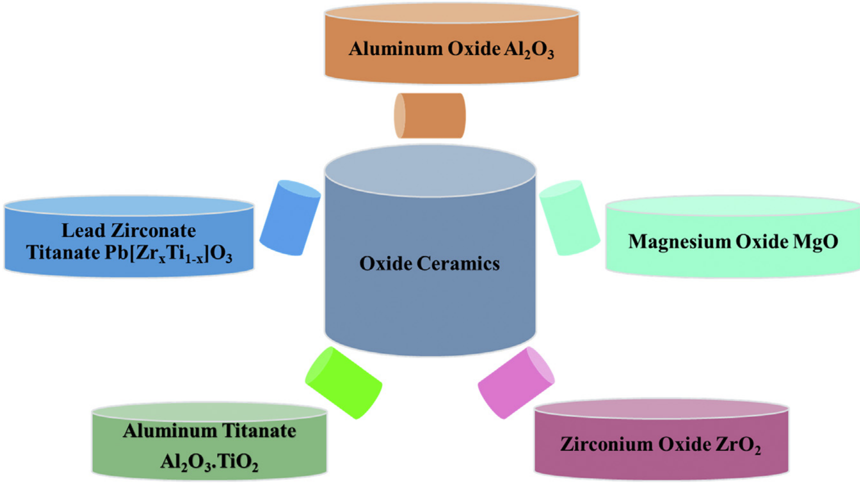

Figure 1.5 Various oxide ceramics.

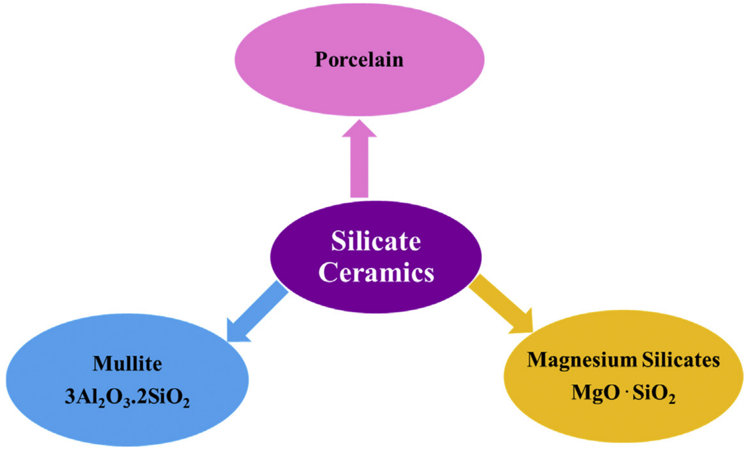

Figure 1.6 Various silicate ceramics.

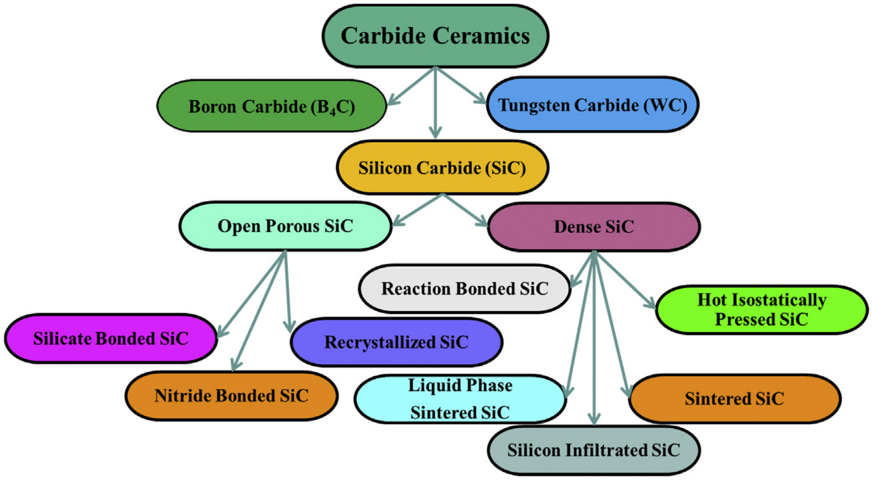

Figure 1.7 Various carbide ceramics.

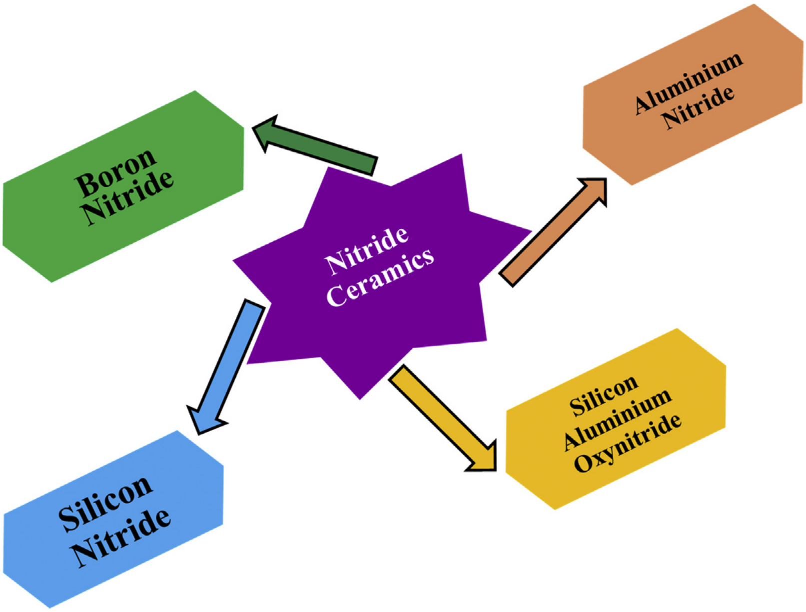

Figure 1.8 Various nitride ceramics.

Undoubtedly, advanced ceramics are constantly enhancing our lives by their persistent usefulness. They play a critical role in diverse fields like electronics, telecommunications, manufacturing, transportation, medicine, and defense and space exploration. Based on their application areas, the ceramic materials can be put into numerous categories as demonstrated in Fig. 1.9.

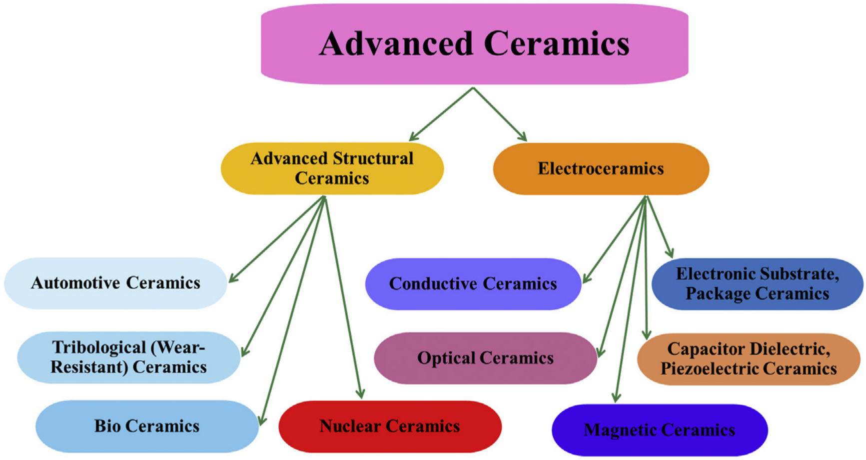

Figure 1.9 Application based on classification of advanced ceramics.

3. Applications

It is well known now that the use of ceramic materials is not only limited to the industry or scientific domain, but also they have been an essential part of every household. They offer numerous important advantages over metal and polymers. As they possess a wide range of superior properties such as hardness, wear resistance, brittleness, refractoriness, thermal insulations, electric insulation, nonmagnetism, oxidation resistance (anticorrosiveness), prone to thermal shock, and chemical stability, ceramic materials offer themselves for multitude of applications. Here a brief overview of structural, refractory, energy-related, biotechnological, electronic, and magnetic applications is presented.

3.1 Structural applications

The ceramic materials which serve as structural members and are often passed through mechanical loading or unloading are called as structural ceramics. They demonstrate the enhanced mechanical properties under demanding conditions. A variety of typical structural ceramics including commercial yttrium-stabilized tetragonal zirconia polycrystal (5Y-TZP), Si_3N_4, SiC, and Al_2O_3 ceramics as well as self-prepared ZrB_2-based ceramics are constantly being used as the study objects [4]. The popular examples of structural applications of ceramic materials are bearings, seals, armors, liners, nozzles, and cutting tools. Boron carbide and silicon nitride are widely being used in the gas turbines [5–7]. These ceramics offer many advantages over the conventional materials like steel, for such areas. The most important advantages are their high resistance to wear, lower density, and ability to withstand high temperature.

A good amalgamation of high dielectric power, resistance to corrosion, and mechanical stability makes the ceramic materials first choice for many other structural applications. Various laser components like pump chambers, feedthroughs, insulators, waveguides, ion tubes, etc., are also preferably made of ceramics. The prominent choice for laser components have been alumina and other porous ceramics.

Plumbing fixtures like faucet washers and mechanical seals for pumps are generally manufactured by alumina and silicon carbide because of high hardness, good corrosion resistance, lower coefficient of friction, and minimum deposition. Ni-bonded tungsten carbide is employed to form mechanical seals for boiler feeds. Currently, tungsten carbide is being replaced by SiC−Si due to selective corrosion.

Ceramic materials are preferred in high-performance valve applications for handling the corrosive and erosive media such as coal slurries and drilling muds [8]. Alumina, boron nitride, and SiC are used as rolling components in steel plants [9]. Corrosive and abrasive environments are common in pulp and paper industry where graphite and carbon being resistant to wetting and corrosion (except with metals which form carbides) are widely used.

A new application of structural ceramics has emerged in food and beverage industry; pistons and soft-drink beverage valves are made of silicon nitride which can withstand both the corrosion and erosion caused due to CO_2 and sweet syrups. Another recent development is the use of ceramic membrane in the industries based on dairy products, juice, beer and wine processing, and biotechnology. To separate the materials/chemicals which are contaminated and corrosive in nature, the ceramic membranes are the great choices. Alumina membranes are popularly used for such microfiltration.

3.2 Defense/military applications

High-performance ceramic materials are an indispensable part of modem weapons and defense systems. Military ground vehicles, aircraft, and missile guidance system, etc., widely use various ceramics. Radar communication systems also depend upon the ceramics. Military attack helicopters have the armors made up of the lightweight ceramic materials. Carbon-carbon (C—C) composites offer high specific strength, temperature strength, toughness, resilience to thermal shock, ablation, and high-speed friction, etc. Such properties open up the applications of C—C composites for rocket nozzles, exit cones, brake discs for military vehicles, and strategic missiles.

Soldier armors made up of ceramic materials have been in use since very long. Ceramic materials find applications in armor manufacturing mainly because of their superior ballistic performance, high projectile resistance, high hardness, compressive strength, and lightweight [10]. Modern day experimental or manufactured ceramic armors usually contain ceramic matrix composites such as borosilicate glass reinforced with SiC or B_4C particles and many other processed monolithic ceramics such as Al_2O_3, B_4C, SiC, TiB_2, or AIN [11,12]. Typically, armor ceramics are used in combination with metal or polymer composites as backing plates. The market for advanced ceramic armor is specialized and performance-driven due to high cost.

3.3 Cutting and polishing tools

The stronger hot-hardness, high compressive strength, ample wear resistance, and suitable chemical inertness of some of the ceramic materials are the promise to design and develop the cutting and polishing tools for various industries. Advantages of ceramic tools include long lives, machining at very high speeds, and very high metal removal rates. Diamond, cemented carbides (WC, TiC, TaC and NbC, etc., cemented together using suitable binder), and SiC are the most popular cutting and grinding tools. Specifically, cemented carbides are used in steels, cast iron, Ni-based alloys, soft materials such as Al, and hard materials such as Ti, for various machining purposes [5]. Many other ceramic-based cutting tools have also been developed recently. The examples are Si_3N_4, sialons, PSZ, and zirconia-toughened alumina, etc. These ceramics offer additional strength and toughness than conventional ceramics. Silicon nitride is the most preferred tool for cast iron industries because of higher thermal shock resistance and toughness as compared to oxide ceramics.

Polishing materials which are also called as abrasives are used for abrading the other materials. Their general application is in grinding the wheels and tools with special shapes. High hardness, wear resistance, toughness, crumbling ability of the individual grains, etc., are the general requirements for the abrasive ceramics. Phenolic resins, sodium silicates, shellac, rubber, vitrified bonding, and metallic bonding are common materials or methods to attach the abrasive grits for the purpose of machining or polishing. Cloth, paper, or polymer substrates coated with abrasives are also available in belt or disk form. The traditional abrasive was a naturally hard materials such as emery (combination of alumina and magnetite) and diamond. Currently the polishing operations for glass, marble, metals, and ceramics are performed with SiC, Al_2O_3, diamond, etc. The fact is that Al_2O_3 is the most common abrasive materials for today's industries. SiC, diamond, and boron nitrides are the other popular choices. Steel polishing and ferrous alloys are commonly ground and polished by Al_2O_3. Surface morphology of the abrasive grits is the most important parameter for better efficiency and performance. There are lots of recent inputs to precisely control the surface structures of the abrasive grits.

3.4 Automobile applications

Ceramics find important application in many parts of automobiles. Different ceramic filters are used to control the emission from diesel engines. The two most important features must be possessed by the filters of an automotive; one is the capability to filter the solid particles, and the second is the ability to regenerate and eliminate these particles just to avoid plugging. The popular ceramics used in the filters of diesel engines are SiC, mullite, cordierite, and titanium aluminate ($TiAl_2O_5$).

Many times ceramic filters are coated with a suitable catalysts like Pt and Pd to reduce the emission of hydrocarbons and CO with ample efficiency. For emission control in the passenger cars the ceramic materials like cordierite and mullite-aluminum titanate have also been used which help to convert the harmful CO into harmless CO_2 and H_2O.

There are many sensors used in automobiles which ensure their smooth and safe functioning. Knock sensor, lambda sensor, seat pressure sensor, temperature sensor, oil sensor, impact sensor, and road surface sensor are some of the examples. Most of them are fabricated using piezoelectric ceramics.

Spacecrafts also have multiple applications of ceramics. At the high speeds (supersonic), the surface of the aircraft faces a high temperature and substantial atmospheric friction, which necessitates the applications of refractory ceramics such as Al_2O_3, MgO, ZnS, CdTe, MgF_2, and ZnSe etc. [13]. Apart from this, in many aerospace applications, borosilicate, lithium aluminosilicate, or calcium aluminosilicate glass matrices reinforced with C or SiC fibers are employed. Compressor cylinders, valves, brake systems, turbine blades, and satellite mirror supports are all included [5].

3.5 Refractory applications

The refractory characteristics of ceramic materials are widely recognized. Boilers, ladles, kilns, and other vessels have all been lined with refractory ceramics. In many applications, multiple layers of a refractory are employed. Refractories with a higher density are used in the inner layers, which come into touch with the harshest environment. These layers must resist corrosive and erosive media such as molten metal, slag, fluidized particles, high-velocity corrosive gases, and corrosive waste. The outer layers must provide heat insulation. Critical qualities include low heat conductivity, high melting or decomposition temperatures, and low thermal expansion. The outer linings are rarely subjected to severe pressures or are exposed to corrosive and erosive fluids. Porous refractories are more suitable for this application because they are less expensive, lighter, and provide superior insulation [13].

Municipal waste incinerators also use ceramic lines where thermal cycling temperature is generally very high (above 1300°C). For combustion chambers bricks are preferred which are made up of SiC or Al_2O_3. To offer higher oxidation resistance the additives like BaO, CaO, and other metal oxides are used for lining the bricks which are supposed to pass through high thermal stress or corrosive attack [14].

Single and multiphase oxides, as well as various types of graphite, are used in traditional refractories. Many refractories are made from naturally existing minerals, and they have a lot of impurities in them. Examples of conventional refractories include silica, alumina-silica, and basic refractories such as dolomite, magnesite, calcite, forsterite, zirconia, zircon, and spinel, etc. [14].

Most refractories are porous and impure; however dense, high-tech ceramics such as SiC, ShN4, BN, AlN, and pure oxides are used in many refractory applications. Other examples of refractory applications that use dense ceramics are crucibles, tubes, thermocouple sleeves, and igniters.

3.6 Ceramics for energy production (nuclear ceramics)

Ceramic materials are finding numerous applications in both the fission and fusion reactors. Many ceramics are foreseen as the future materials for the production and conservation of safe nuclear energy. Role of moderators is well known in the fast breeder reactors. They slow down the fast moving thermal neutrons. Graphite and BeO are the popular choices for moderators. Ceramic sensors are employed for measuring the oxygen level in liquid metal-cooled fast breeder reactors. Oxides of uranium, plutonium, and thorium, etc., which act as nuclear fuel for fission reactors, are the ceramic materials. So-called advanced nuclear fuels like carbides, nitrides, and carbonitrides of uranium and plutonium are constantly being investigated to make fission process more efficient robust and safe [15].

Fusion reactors also use ceramic materials in variety of ways. Insulators for magnetic coils, active coils, and diverter coils; windows and dielectrics for radio frequency (RF) heating; structural components; current breaks; and insulators for neutral beam injectors, magnets, and direct converters are just a few examples of potential applications in the complicated structure of fusion reactor. To fulfill these need magnesium aluminate spinel ($MgAl_2O_4$), MgO, and Al_2O_3, etc., are the popular choices. Tritium breeding is an important functional component of fusion reactors. Ceramics are used in the production of tritium-breeding materials. These are Li-based solid blanket ceramics that breed and release tritium as a fuel to keep the fusion reaction going while also converting the energy into useable heat. Li_2O, γ-$LiAlO_2$, $LiAl_5O_8$, Li_2SiO_3, Li_4SiO_4, Li_2TiO_3, and Li_2ZrO_3 are examples of such materials. These materials are appealing due to their inherent safety benefits.

Present-day technologies have evolved and enabled the ceramic materials such that they can serve the purpose of nuclear waste storage which is one of the most important demands of safe nuclear energy production.

Other energy production areas like gasification, fuel cells, heat exchangers, magnetohydrodynamic power generators, etc., are also strongly dependent on various ceramics.

3.7 Biotechnological applications

Dental and bone implant to physiological modifications are currently using ceramic materials effectively. There are three major categories of ceramics used for bone implants. First is the porus ceramic coatings on metals which show a strong mechanical bonding to the tissues with self being inert to the bioenvironment. The examples of such ceramics are Al_2O_3 and hydroxyapatite (HA). The second category is where the implants degrade slowly and are replaced by the natural surroundings. Calcium phosphate is the popular example. The third category is of the bioactive ceramics. They interact with the bone and create chemical bonds. Hydroxyapatite and bioactive glasses are the examples of such category. Hydroxyapatite is also used in plastic surgery and filling of the bone defects in dentistry. Bone implants of knee and hips utilize various composites derived from glass, phosphosilicates, Ti, and Ag. Orthopedic load bearing is performed by alumina and zirconia. Dental and ear implants are too made of modified alumina, HA, and bioactive glasses.

Because of their chemical, thermal, and biological resistance, porous ceramics are employed as supports for immobilizing enzymes, antibodies, antigens, and microorganisms. Biocatalytic carriers include controlled porosity glass, porous sintered glass, cordierite, alumina, silica, and charcoal. Bioaffinity supports for diagnostic reagents and clinical therapy, adsorbents for proteins and chemicals, purification or biotransformation of chemical compounds, and microfiltration are some of the other ceramic applications [16]. Eyeglasses, thermometers, tissue culture flasks, and fiber optics for endoscopy are all examples of biotechnological applications that use ceramics and glasses.

3.8 Electronic, electrical, and magnetic applications

Of the today's market of advanced ceramics, the major share belongs to the electronic ceramics. Ceramics offer high resistance to the electronic conduction process. This insulating nature of ceramics makes them suitable for the substrate development of the printed circuit boards. Any materials used as a base of electronic circuitry essentially requires high thermal conductivity, mechanical strength, and chemical stability, apart from high resistance. These promises are fulfilled generally by the ceramic materials such as Al_2O_3, BeO, and AlN.

Dielectric ceramics have the potential to enhance the performance of capacitors. Ceramics with higher dielectric constants allow the use of capacitors with smaller surface area. Capacitors play a very significant role in the electrical and electronic circuits.

$BaTiO_3$, $SrTiO_3$, lead zirconate titanate (PZT), etc., are the ceramic materials which find a vast variety of application in capacitors.

Piezoelectric ceramics is another class of ceramics which caters to the transducers, sensors, and vibrators. The mechanical signal can be converted into electrical signal by piezoelectric ceramics and vice versa. Microphones and loudspeakers are the popular examples of the employment of piezoelectric ceramics. The vibration caused by a diaphragm of a microphone is passed to the piezoelectric element and converted into an electric signal. $BaTiO_3$, $SrTiO_3$, PZT, etc., demonstrate the piezoelectric behavior.

Semiconductors, which are backbone of the today's majority of industries, too carry the certain features of ceramics. Varistors and thermistors are the well-known examples of use of semiconductor ceramics. SiC, $MoSi_2$, and Cu_2O are used for such purpose. One of the most common materials utilized as a varistor in these applications is ZnO. Temperature sensors, temperature compensators, infrared sensors, switches, and heating systems are all examples of thermistor uses. Gas sensors also use semiconductor ceramics [17].

Ferrites are commonly employed as magnetic ceramics in high-fidelity speakers and small electric motors, magnetic field detectors, audio and video recording cassettes, computer discs, generators, and video recorders, among other applications. Magnetoplumbites like $BaFe_{12}O_{19}$ and $PbFe_{12}O_{10}$ [13] are examples of hard magnetic materials. Many more applications for electrical, magnetic, electronic, and electro-optic ceramics are persistently being explored and generation would witness many new breakthroughs in future.

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