Advanced Ceramics: Stages of Development

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Abstract Ceramics are inorganic nonmetallic materials (oxides, carbides, nitrides, etc.) processed after sintering of natural or synthetic precursors at high temperature. They can also be applied at or resist high firing temperatures. They are highly crystalline (most of the advanced and traditional ceramics), semi-crystalline (vitrified ceramics such as earthenware, stoneware, and porcelain), or completely amorphous (glasses). The composition/structure relationship, method of processing, raw materials, and applications determine the properties of ceramics and whether the ceramics are traditional or advanced ones. The first man-made ceramics were pottery objects and figurines from clays after firing. Several stages have been considered in the development of ceramic industry until reaching the production of advanced ceramics. The second stage for development of ceramic includes the production of glazed-colored ceramics, ceramic arts, and building products. Recently, new categories of advanced ceramics have been developed for electronics, biomedical, semiconductors, energy, and optical and structural applications. In the present chapter, we are going to shed light on the stages of development for advanced ceramics. Types and classifications, advanced processing techniques, properties, sintering as well as new forms of applications will be presented in the current chapter. Examples of these kinds of advanced ceramics, e.g., alumina, zirconia, Mg–Al spinels, silicon carbide, silicon nitride, ceramic composites, thin films, etc., with their specific applications will be also presented.

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1 Historical Background of Ceramics

Ceramic, as a word, comes from a Greek word called kéramos, “potter’s clay”. It is one of the most ancient products and its industry has been discovered since thousands of years. Its discovery returns to the discovery of clays and clay firing. The first ceramic artifact was produced in 28,000 BCE (before the Common Era), i.e., through the Paleolithic age. It was a statue of a woman, called the Venus of Dolní Věstonice, from Brno, Czech Republic. After thousands of years (18,000–17,000 BCE), the first pottery was detected in China and then in Japan and Russia in 14,000 BCE. The application of ceramic has been raised intensively though the Neolithic period (9,000 BCE) and the ceramic-clay products became common as vessels for water and food, art stuffs, tiles and bricks, and their application moved to the Middle East and Europe. The first products were withered under the sun or sintered at $\leq$1,000 °C in simple furnaces dug in the ground. In 7,000 BCE, sharp tools prepared from naturally occurring volcanic glass have been used. It has been stated by the Roman historian Pliny that the first artificial glass was unintentionally prepared by Phoenician merchants in 5,000 BCE during cooking on the fired sodium-containing rocks while relaxing on the beach. The heating led to fusion of rocks and formed glass. After that, some glass objects have been produced in Mesopotamia and Egypt dating to 3,500 BCE. Also, during that period the wheel-forming tool for the production of ceramic artifacts and pottery has been started to be applied. A new development, i.e., glazing of pottery, has been introduced in Mesopotamia in 3000 BCE. On the other hand, the Egyptians began to build firms for glassware industries in 1500 BCE. At the same time, the Greeks reached the maximum development for vases industry. In 600 CE (Common Era), the first kiln working at 1350°C was made in China to produce porcelain from kaolinite. This industry continued in Europe and the Middle East during 1600 CE. The first blast furnace made from natural or synthetic refractory materials working at 1500 °C was produced in Europe in 1500 CE for melting of metals, glasses, building materials, and porcelain. With the progression of industries, new materials with new properties have appeared. The electrical insulator ceramic was invented in 1850. After 1939, the application of advanced ceramics in different areas such as electronics–optoelectronics, biomedical, energy, automotive, and aerospace has been increased. With the emergence of nanotechnology, new applications such as transparent ceramics, ductile ceramics, hyperelastic-bones, microscopic capacitors, and ceramic coatings are developed. From the aforementioned stages of ceramic development, it is expected that the worldwide market will reach 1.1 trillion dollars against 800 billion dollars in 2018 [1].

2 Introductory Remarks on Ceramics

Ceramics are inorganic solid materials composed of metal/metalloid and nonmetal elements with ionic or covalent bonds, e.g., metal oxides, carbides, and nitrides. They can be prepared at and withstand high temperature. The nature of chemical bonds intensely affects the properties of ceramic materials such as high melting point, and thermomechanical and optical properties [2, 3]. Most of the ceramics are insulators for electricity due to the deficiency of free electron as in the case of metals [4]. The most common conventional raw materials are kaolin and the advanced ones are alumina, spinels, silicon carbide, tungsten carbide, silicon nitride, etc. These materials can be applied as wear-resistant materials, cutting tools, biomedical, electronics, and structural application. Most of the ceramic materials are crystalline, while the amorphous ones are being glasses. The properties of ceramics depend mainly on the structure and chemical composition of ceramics. The microstructure, density, grain size distribution, amount of porosity, and liquid phase contents are important factors affecting the overall properties of ceramic materials. The microstructure comprises the main grains, secondary phases, grain boundaries, closed and open pores, microcracks, and structural defects. These parameters in addition to the processing conditions are totally affecting mechanical, optical, thermal, electrical, and magnetic properties.

3 Classification of Ceramics

Ceramics are classified into two main categories including traditional (conventional) and advanced ones. The first group involves whitewares, structural and heavy clay products, cement, and refractories and they are derived from natural sources [5]. Also, it includes glass and glass-ceramics [4] which can be produced from pure chemicals or natural resources. Some types of glass and glass-ceramics belong to the category of advanced ceramics depending on their advanced applications. On the other hand, the advanced ceramics are fabricated by sophisticated chemical processing methods from synthetic or raw materials giving the desirable product with high purity and improved physical, mechanical, electrical, magnetic, superconducting as well as optical properties. The following scheme (Fig. 1) represents the classification of ceramic materials.

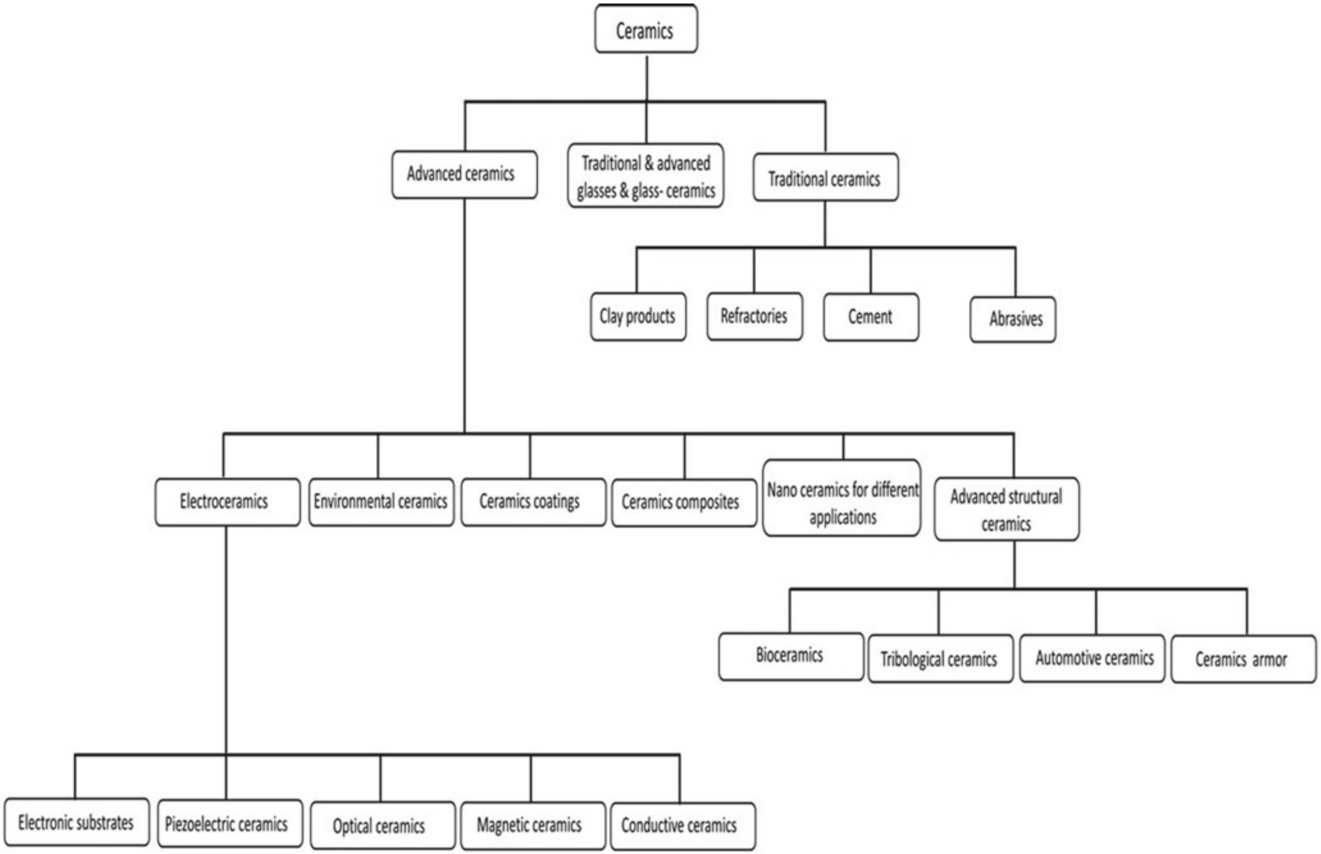

Fig. 1 Classification scheme of ceramic materials

3.1 Traditional Ceramics

3.1.1 Clay Products

Clay is an interesting widespread natural material widely applied in the globe [6]. It is the most known raw material utilized worldwide owing to its astonishing properties as abundance, feasibility, environmental friendly, and suitability for numerous practical and creative purposes containing applications like agriculture, engineering, geology, environment, pharmaceuticals, etc. [7, 8]. Economically, it is a low price raw material as compared with other pure and natural materials [9]. It is worth mentioning that the clay is formed through elongated time by regular chemical weathering of silicate rocks using diluted carbonic acid and solvents. Thus, the clay is categorized into two kinds; the main one is formed as a residual deposit in the soil and remains at the place of formation. The second one is that translated from its original place by water erosion and deposited in a new sedimentary deposit. It is crystalline with fine particles of pseudo-hexagonal shapes and few micrometer sizes [10]. It is mainly composed of hydrous-aluminum silicates with minor amounts of iron (Fe), magnesium (Mg), alkali metals, alkaline earths, etc. [11]. On the other side, their atomic structure is mainly composed of two basic units, i.e., octahedral- and tetrahedral-sheets. The first unit consists of closely packed oxygen atoms and hydroxyl groups in which Al, Mg, and Fe atoms are ordered in octahedral symmetry. On the contrary, silicon atoms are equidistant from four oxygen atoms or hydroxyls, arranged in a tetrahedron pattern [9, 12].

After giving a brief introduction on clay, now we are going to provide some examples of traditional clay products. They are classified as unvitrified or vitrified products. The vitrified one is fired at a higher temperature and formed of fused clay and other compounds having glassy feature, e.g., whiteware. Unvitrified products are fired at lower temperature and form porous ware such as pottery and earthenware. The following are some clay products:

(a) Pottery is a category of traditional ceramic products which has high porosity and is densified at low temperature ≤900 °C. It is not glazed but can undergo surface modification and decoration. Recently, they can be applied in flowerpots, roof tiles, bricks, and art ware.

(b) Earthenware is a known porous (10–25%), and opaque product which is densified at 900–1200 °C. Its raw materials are ball clay (25%), China clay (25%), flint/sand (35%), and feldspar (15%). It can be applied to bricks, tiles, and tin enameled majolica.

(c) Whitewares have many types of clay products such as hard porcelain for artware, tableware, semi-vitreous tableware, hotel china, vitreous sanitary ware, vitreous tile ware, electrical porcelain, and dental porcelain. Porcelain is one of the most interesting products in this category. Its raw materials are flint/quartz sand (13%, SiO_2), feldspars ($KAlSi_3O_8$–$NaAlSi_3O_8$–$CaAl_2Si_2O_8$, 12%), China clay (63% kaolinite, $Al_2Si_2O_5(OH)_4$), and ball clay (8.7%). It is produced by multiple steps of cycle heating at around 1400°C. The main phases of the fabricated porcelain are quartz, mullite ($Al_6Si_2O_{13}$), and glass; which are equivalent to about 60% SiO_2, 32% Al_2O_3, 4% K_2O, and 2% Na_2O oxides with minor amounts of iron, titanium, calcium, and magnesium oxides. The role of clay is to offer small particles, and good plasticity for easier shaping, while feldspar gives fluxes and forms liquid phases that increase the strength. On the other side, flint can be considered as filler that forms liquid phase and controls the thermal expansion of densified bodies.

The second interesting example of this category is sanitary ware. It includes several products such as bidets, wall urinals, water closets, washbasins, and cisterns. The main raw materials are ball clay (23–25%), china clay (25–27%), flint or quartz sand (20–30%), and feldspar or nepheline syenite (20–30%). It is formed by slip casting process with controlled rheology and then glazed by a spray gun. The body is coated by several layers of engobe, and glaze.

The third class of these ceramic products is the wall tiles. This type of ceramic has low shrinkage during firing (about 1%). The main composition of wall tile is ball clay (22.5–25%), china clay (22.5–25%), flint/quartz sand (40%), and limestone ($CaCO_3$) (10–15%). It is shaped by pressing in a die cavity and sintered at about 1100 °C. After fabrication, it is subjected to glazing.

3.1.2 Cement

There are several kinds of cement-binding materials as lime, gypsum plaster, natural cement, high alumina cement, pozzolana, masonry cement, magnesium oxychloride cement, calcium aluminate cement, Portland cement, and geopolymers. In spite of the pozzolana cement has been invented (in 1824) before Portland cement, the most famous one is the Portland cement. The pozzolana cement is formed by the reaction of lime water with silica to form bomorite gel $(CaO)_3(SiO_2)_2(H_2O)_3$. On the other hand, the Portland cement could be prepared by firing the limestone with clay at 1450 °C to produce clinker. The produced clinker is milled with about 5% gypsum to produce the Portland cement. The addition of gypsum is to control the setting. The chemical composition of Portland cement is 64–67% CaO, 5–5.5% Al_2O_3, 3% Fe_2O_3, 22% SiO_2, 1.4%MgO, and 2.1 % SO_3, in addition to minor quantities of alkali. The clinker consists of four main phases, namely, 50–70% alite (tricalcium silicate Ca_3SiO_5), 15–30% belite (dicalcium silicate Ca_2SiO_4), 5–10% aluminate (tricalcium aluminate $Ca_3Al_2O_6$), and 5–15% ferrite (tetracalcium aluminoferrite Ca_2AlFeO_5). Upon the reaction of cement with water, it hardens and forms hydrated gel due to the reaction of water with all cement phases. At the early ages of reaction, the strength is developed owing to the fast reaction of alite, while after a long time, the strength is developed due to the reaction of alite and belite with water [13].

Calcium aluminate cement (CAC) is fabricated by firing a mix of limestone and bauxite or any materials that contain alumina at 1450–1600 °C. The formed fused clinker is crushed and ground until getting very fine powder [14].

3.1.3 Refractories

Refractory ceramics are materials that can be fabricated and applied at high temperatures. They are mainly applied for lining and repairing the industrial furnaces, e.g., steel and metallurgical furnaces, cement kilns and glass melting furnaces. According to the type of industry in which they are applied, they can be classified into acidic, basic and neutral refractories. The acidic ones are based on SiO_2 and silica-containing refractories as fireclay series, sillimanite, and andalusite; these types resist the acidic slags. The second ones are basic refractories which depend on MgO as magnesite, dolomite, chrome–magnesite, and magnesite–chrome; they are resisting the basic slags. The third class is neutral refractories which are relatively inert in acidic and basic slags. This type includes carbon, chromite, forsterite, and spinels. The refractories can be applied in the forms of bricks of standard shapes and sizes, tubes, castbles, sheet, cloth, tape, and formable shapes. The recommended refractory properties are low thermal expansion, high thermal shock resistance, and low thermal conductivity, high refractoriness, good cold and hot strength, as well as excellent slag resistance, low porosity, and high bulk density [15–18].

One of the most interesting systems in refractory ceramics is $MgO\text{-}Al_2O_3$. It exhibits highly refractory oxide materials, namely, periclase (MgO), spinel $MgAl_2O_4$, and corundum ($\alpha\text{-}Al_2O_3$). The melting points of these phases are about 2800, 2100, and 2050 °C, respectively. This system includes periclase, spinel-bonded magnesia, spinel, spinel–alumina, and corundum. All of these materials are highly refractory and have a wide range of applications for industrial furnaces lining or for advanced applications as structural, electronic, and biomaterials [15–18].

The known stages for the production of refractory are crushing and grinding of raw materials, mixing, molding/casting, drying, and firing. The raw materials include clay, bauxite, chamote, sand, magnetite, dolomite, etc. Generally, the refractory can be applied in the form of shaped refractories, e.g., bricks, or unshaped refractories as castables/concrete, and mortars [15–18].

3.1.4 Abrasive Material

An abrasive material is a hard and tough grain material that can be produced naturally and synthetic, and utilized as a medium for cutting, grinding, and polishing processes of materials to make a smooth and refractive surface. The natural ones are impure natural materials such as emery, corundum, quartz, flint, garnet, diamond, tripoli, diatomaceous earth, sandstone, pumice, and natural-sharpening stones [19]. The synthetic ones are pure materials since we can control the method of preparation. They are like SiC, Al_2O_3, glass, steel wool, and shot, as well as grit. The abrasive grains must be harder and tougher than the medium in which they are applied; moreover, they must resist thermal and mechanical shock as well as friability. The abrasive processes include grinding, honing, lapping, and polishing.

3.1.5 Glasses and Glass-Ceramics

Historically, glass has been discovered thousands of years ago. It is dissimilar to ceramic, which is mostly crystalline material; glass is an amorphous material fabricated after fusion of its precursors at relatively high temperature, casting, and then annealing at lower temperature. It has attractive properties as optical transparency, hardness and easy for shaping and can be applied for conventional and advanced applications. For example, they can be applied for window glass, light bulbs, TV/computer display tubes, optics, fiber optics, cookware, and biomedical applications. The commercial glass includes soda-lime, lead, borosilicate, aluminosilicate, and high-silica glasses. The soda-lime is the most common one; it is composed mainly of $Na_2O{\cdot}CaO{\cdot}6SiO_2$ in the presence of few amounts of alumina, borate, and arsenic oxide or antimony oxide. The alumina is added to improve the corrosion and crystallization resistances, while borate enhances the workability and arsenic oxide or antimony oxide helps to eliminate the bubbles. This kind of glass is inexpensive and is applied in bottles, electric bulbs, and glazing. Borosilicate glass (Pyrex glass) has good corrosion and thermal shock resistance and could be applied in automobile headlamps, cookware, and laboratory apparatus Alumino-silicate glass can be applied when high chemical durability, strength, and resistance to devitrification are needed, e.g., cookware, fibers, and seals. Lead glass has a high refractive index, so it has a high luster and is named crystal glass. It is applied for high-quality artware and tableware, radiation shielding, lamp envelopes, seals, and optical ware. High-silica glass has high resistance to chemical attack. Fused-silica glass is a special one having >99% silica content. It is used at high temperature cycling as crucibles. Fused-quartz is a high expensive one and is applied in special optical applications.

Comparing to the other types of materials, glass is characterized by larger optical properties which are affected by the imperfection, impurities, stresses inside glass, and surface roughness.

The addition of nucleating agent and thermal treatment of the glass lead to the formation of crystalline materials called glass-ceramics. It is worth to mention that the glass-ceramics are regularly not wholly crystallized; the crystallization percentage ranges between 50 and 95 vol%, and the remaining is residual glass [20]. To obtain glass-ceramic, many parameters should be controlled, e.g., appropriate heat treatment process for the right glass composition since some glasses are highly stable and cannot simply crystallize [21]. Nowadays, there is an emerging mandate for developing the glass-ceramics to be engaged in various applications. These include construction instead of stone [22], optical applications since they have translucency/transparency properties [23–25], and military applications (aircraft and missiles). That is glass-ceramics have excellent properties such as low thermal expansion coefficient, excellent abrasion resistance, high mechanical strength, and high radar wave transparency [26, 27]. Moreover, glass-ceramics have various biomedical application [22, 28].

3.1.6 Ceramics from Waste Streams

A huge amount of solid industrial wastes are produced as by-products from many industries. These wastes might cause environmental pollution for air, soil, and water resources. Recently, a great interest has been directed to use these wastes in the production of traditional and advanced ceramic products [29]. These wastes include silica fume, waste clays, grog, granite sludge, aluminum dross, blast furnace slag, slags from different metals industries, cement dust, glass culets, etc. For example, silica fume is a by-product produced after the production of silicon metal and ferrosilicon alloy in a huge amount. It consists of very fine and active spherical particles, and has been applied in many industrial ceramic products such as cordierite, forsterite, mullite, building concrete, refractory castables, and many other ceramic products. It has an efficient effect on improving the mechanical properties of building concrete and refractory castables. Also, silica fume has been used for the production of foamed and non-foamed geopolymers [30]. Moreover, it has been utilized for the production of advanced ceramics, nanosilicon carbide, and silicon carbide/silicon nitride composites by mechanical alloying and thermal activation method [31–34]. The use of various slags, and tailings in the production of conventional ceramics is also advantageous for both circular economy and virgin resources' preservation [35, 36]

3.2 Advanced Ceramics

These types of ceramics have received a great attention in the recent technologies and they play interesting roles in various industrial applications such as energy and energy storage, transport, life sciences, electronics, and communication. This is due to their outstanding properties which cannot be originated in the conventional materials, such as mechanical, chemical, physical, electrical, optical, and magnetic properties [37–39]. Their name varies according to the society; the Japanese say "fine ceramics", American society says "advanced ceramics" or "technical ceramics", while the European society says "technical ceramics". One of the most important things is that these materials are cheaper and more cost-effective than metallic ones [37]. Advanced ceramics can be classified into structural ceramics, electroceramics, environmental-related ceramics, ceramic coatings, ceramic composites, and nanoceramics for different applications.

3.2.1 Structural (Engineering) Ceramics

One of the most interesting types of advanced ceramics is the structural ceramic. It includes different types such as bioceramics, tribological ceramics, automotive ceramics, and ceramic armors. The demand for structural ceramics comes from their applications to protect and serve human beings; thus, they exposed a higher progressive rate. These types of ceramics include alumina, partially/fully stabilized zirconia, silicon carbide, silicon nitride and boron nitride, ceramic composites, etc. [40]. The following are some examples of structural ceramic materials.

(A) **Alumina (Al_2O_3)**

Alumina is the most common structural ceramic, since it has several attractive properties like high melting point, high wearing resistance, high chemical durability, low density, good hardness, as well as good strength and availability. It is worth to mention that alumina has several crystal metastable polymorphs in addition to the stable form (corundum or alpha-alumina). The metastable forms are classified into two main classes; a face-centered cubic (fcc), or a hexagonal close-packed (hcp) arrangement of oxygen anion. The type of each polymorph depends on the distribution of cations inside it. Fcc packing of oxygen contains γ, η (cubic), θ (monoclinic), and δ (tetragonal or orthorhombic), while the hcp forms include α (trigonal), κ (orthorhombic), and ϰ (hexagonal). Some other monoclinic alumina forms have been recently recognized. The metastable forms of alumina (e.g., γ-alumina) have small particle size, and high surface area, thus they can be applied as adsorbents, catalysts or catalyst carriers, coatings, and soft abrasives. Alumina occurs in nature as alpha-alumina which forms gemstones ruby and sapphire. They contain some impurities of titanium (Ti), iron (Fe), and chromium (Cr), and have blue and red colors and therefore, they can be used in jewelry industry. On the opposite side, leucosapphire is a synthetic and colorless form that has high-strength optical components and is commonly used for cabin windows and active laser components. Polycrystalline Al_2O_3 can be applied for various uses like electrical insulation, wear resistance, mechanical ingredients, biomedical applications, etc. However, it has relatively low fracture toughness along with low fracture strength which leads to the rapid spreading of cracks and consequently it has a negative effect on its performance for some applications [41]. However, this serious drawback can be overcome by preparing composites containing metals to enhance the fracture toughness and strength [42–49].

(B) **Zirconia (ZrO_2)**

Owing to its superior mechanical properties along with its high ionic and thermal conductivity, ZrO_2 has many potential applications [50]. Generally, it has high strength, toughness, hardness, and wear resistance, good frictional behavior, none magnetic, electrical insulation, low thermal conductivity, corrosion resistance in acids and alkalis, modulus of elasticity similar to steel, and coefficient of thermal expansion similar to iron. It is chemically inert and has three polymorphs, i.e., monoclinic, tetragonal, and cubic. The monoclinic transforms into a tetragonal at 1173 °C, the tetragonal transforms into a cubic phase at 2370 °C, these transformations are reversible. The transformation of tetragonal to monoclinic is accompanied by 3–5 expansion and shape deformation. Zirconia can be partially or fully stabilized by magnesia or CaO and Y_2O_3. The main applications of zirconia are pumping components, blade edges, wear resistance parts, nozzles, dies, telecommunications, biomedical, refractories, refractory fibers, thermal barrier coatings, electrolytes, oxygen sensors, fuel cells, furnaces elements, and gemstones [51].

(C) Silicon Carbide (SiC)

SiC is one of the most attractive structural ceramics since it has remarkable characteristics such as good chemical inertness, high hardness, low density, and coefficient of thermal expansion, as well as excellent thermal and chemical stability [52]. It is found in nature as a mineral moissanite which is rare thus most of the silicon carbides are synthetic. One-dimensional (1D) nanostructured materials (e.g., nanowires and nanotubes) are highly necessitated for different potential applications. 1D SiC nanostructure has highly desired physical and electronic properties as a wide band gap semiconductor of band gap energy ranging from 2.2 to 3.4 eV. This variation in band gap is owing to their polytypes with a high electronic mobility and thermal conductivity. Since SiC has a high melting point (2873 °C), it can be applied at high temperature. Due to its chemical inertness, it can resist the harsh environmental conditions. Based upon these outstanding characteristics, SiC is extensively used in different industrial fields such as electronics, heating elements, and structural materials. Another promising usage for such high-strength material is enhancing the thermal and mechanical properties of other ceramics like alumina and mullite via composite fabrication [52]. It could be fabricated industrially by the Acheson method by silica sand with coke (carbon) at high temperature in electric furnaces. The sintering of SiC needs high temperature and inert atmosphere.

(D) Other Non-oxide Ceramics

TiC, ZrC, TaC, Si_3N_4, TiN, BN, AlN, TiB_2, ZrB_2, B_4C, and HfB_2 are also interesting types of non-oxide ceramics having serious properties and applications when applied separately or in composite forms [53–61]. For example, Si_3N_4 is one of the main structural ceramics; it has high mechanical properties and excellent wear resistance. This is due to the developed microstructure that arises after liquid phase sintering in which high aspect ratio grains and intergranular glass phase lead to excellent fracture toughness and high strength. Si_3N_4 was fabricated for the first time in 1955 for use as thermocouple tubes, molten metal crucibles, and also rocket nozzles. It was prepared by nitridition of silicon powder compacts, and attention initiated to rise for possible use in gas turbines. There are reaction-bonded and sintered silicon nitride types. Non-oxide ceramics as carbides and nitrides of group IV transition metals have an interesting mix of ionic, covalent, and metallic bonding. This arrangement of bonding makes the materials having significant valuable properties such as high hardness (about 25 GPa), very high melting points (>2750 °C), good thermal, and electrical conductivity ($\geq 10\ \mathrm{W\ m^{-1}\ K^{-1}}$ and about $200 \times 10^4\ \mathrm{ohme^{-1}\ m^{-1}}$, respectively). For example, TiN could be extensively applied for biomedical and engineering applications since it has excellent hardness and high melting point, high electrical conductivity, and low thermal conductivity. TiN and its composites (as nc-TiN/a-BN/a-TiB_2) have commonly been utilized as super hard coatings to enhance the wear resistance, thermal stability, and oxidation resistance of mechanical devices such as cutting tools and fuel claddings. Most of the TiN composites have an exciting color range so they could be applied as super hard decorative coatings. TiB_2 is one of the high-temperature ceramics which has astonishing characteristics similar to that of TiN; mostly with the same applications, but with some limitations owing to the difficulties of getting full sintered bodies even after applying high pressure and temperature. The high sintering temperature increases the grain growth, which leads to decreasing the fracture toughness. Its high melting point, low self-diffusion coefficient, strong covalent bonding, and presence of oxygen-rich layer on the surface of the TiB_2 powder are the main causes of weak sinterability. One of the most interesting high-temperature non-ceramic oxides for modern structural applications is ZrB_2. It crystalizes in a hexagonal-system with c/a crystal-parameter-ratio of 1.11, this makes it having isotropic properties compared to other classes of high temperature ceramics. It has also high thermal stability (melting point >3240 °C), relatively low density (6.1 g/cm^3), and low coefficient of thermal expansion (6.7×10^{-6} K^{-1}). These properties make it suitable for an extensive range of applications as aerospace and high-temperature industries. The main problem which faces ZrB_2 is the poor sinterability; it comes from intrinsic strong covalent atomic bonds leading to very low self-diffusion. Thus, diffusion-promoting parameters like time, temperature, and pressure are usually required to increase its sintering, but they have some drawbacks as grain coarsening. This grain growth is typically occurred when the grain-boundary diffusion rate is considerably higher than the bulk diffusion rate. This means the diffusing atoms incline to move at grain boundaries rather than in bulk of the crystals. This performance might become leading in materials with stronger atomic bonds. So, the addition of diffusion promoters may improve the overall diffusion through the sintering process. On the other hand, ZrC and ZrN are high-temperature ceramics having interesting applications in exciting high-temperature environments as nuclear applications in generation IV reactors. These materials have required properties as high thermal and electrical conductivities as well as high hardness and melting point. Due to the high melting point and oxidation of these non-oxide ceramic materials, their consolidation methods are a vast challenge. There are many sintering approaches that have been utilized for the preparation of non-oxide bulk ceramics and coatings such as pressureless sintering (PS), hot-pressing (HP), and spark plasma sintering (SPS), chemical vapor deposition, physical vapor deposition, etc.

Bioceramics

A large number of scientists worldwide have exerted much effort on the opportunity to repair and regenerate the diseased/damaged human tissues and organs. This approach is the so-called "tissue engineering" which gained more developments after discovering the biomaterials [62]. This approach depends on the utilization of appropriate biomaterial for proliferation of cells and growth factors to regulate the cellular functions [63, 64]. The selection of the proper biomaterial for accomplishing this purpose is not easy since it should meet numerous requirements. Based on this principle, the main requirements can be presented briefly in the following points:

(i) **Porosity**

Owing to the porous structure of trabecular and cortical bone, which is essential for blood movement, perfect scaffold should have a relatively high porosity with suitable inter-connectivity. The porosity permits the passage of substantial nutrients, osteogenic cells, and molecules that are required for mineralization and vascularization throughout the structure.

(b) **Biocompatibility**

In 2008, biocompatibility has been defined as the ability of the material to facilitate natural cellular and molecular activity within a scaffold without inducing systemic toxicity [65]. Meanwhile, it also involves the osteoconductivity, osteoinductivity, and blood vessels formation around its implantation site.

(iii) **Biodegradability**

One of the most important requirements of optimum scaffold is that it should possess controlled biodegradation rate over time when it is inserted into the human body, taking in mind that the biodegradation rate should be comparable to that of tissue regeneration. It should be noted that this rate is highly correlated to the kind of chosen material and its properties for specific application.

(d) **Mechanical properties**

It is widely accepted that the clinical success of scaffold is based on the matching of its mechanical properties with that of living bones. However, the stiffness of the scaffold should not hinder in-vivo bone growth to help the structural integrity to physically support itself [66].

Recently, tissue engineering approach has been effectively developed for treating several organs like skin [67], bone [68], and cartilage [69]. This wide application for such an approach is accomplished through the great development of biomaterials which are substantial for tissue regeneration [70]. Therefore, it is very useful for the readers of this chapter to get an overview of the biomaterials and their classification.

Generally, a material that is utilized for a medical application is called "biomaterial" [71]. Biomaterials are divided into polymers, composites, metals, and bioceramics. Keeping in mind that they should have many desirable properties such as biocompatibility, stability, and having mechanical properties comparable to human bones [72]. Bioceramics are considered as a large subset of ceramics which are specific for replacing damaged/diseased parts of the human body. They involve crystalline, partially crystalline, or amorphous materials, and they can be divided, according to their behavior when they implanted in the body into three categories as follows [73].

a. **Nearly bioinert ceramics**: Materials that exhibit no reactions within the body, but they are biocompatible and accordingly they are not suffering from body-rejection problems. The most famous examples of such a category are Al_2O_3 and ZrO_2 [49].

b. **Biodegradable materials**: They are able to rapidly dissolve in the body under physiological conditions. Tricalcium phosphate (TCP) and porous magnesium alloys are the common examples of such a type of biomaterials [74, 75].
c. **Bioactive materials**: They show a favorable reaction when they are inserted into the human body through the formation of hydroxyapatite (HA)-like layer on their surfaces which is responsible for the formation of strong bond with the surrounding bone tissues. This category includes bioactive glass [76–78], bioactive glass-ceramic [79], hydroxyapatite [80–84], fluorapatite [85], and silicates compounds [86].

It is substantial to stress that, beside the aforementioned desirable properties of these specific ceramics, they also possess other excellent characteristics such as their high corrosion and wear resistances, thermal stability, high strength, hydrophilicity, and excellent chemical durability [6, 39, 87]. In this regard, in 1970, traditional stainless steel head of hip has been replaced by the sintered Al_2O_3, where the latter material possesses low density which is very beneficial for surgical operations. A great evolution for using ceramics in orthopaedic and dental applications has been approved after the approval of the US Food and Drug Administration in 2003 for ceramic-on-ceramic hip joint replacements. In spite of these amazing properties for such materials, they also have some drawbacks which need to be solved like their low fracture toughness compared to natural bone [88].

Since the bioactive ceramics are the most interesting categories for dental and orthopedic applications, we have to briefly discuss some important information about these promising ceramics.

Bioactive glasses (BGs): Highly bioactive glass compositions form the desirable HA or carbonated hydroxyapatite (CHA)-like layer on their surfaces when inserted in the body within few days or even within few hours, and can also stimulate the proliferation and differentiation of osteoblasts through the release of the leached ions from BGs. Therefore, the past four decades have already witnessed the development of different systems of BGs including silicate, phosphate, borate borophosphate, etc. All these types exhibit biocompatibility, bioactivity, and good bioresorbability. Additionally, some metal oxides like silver oxide (Ag_2O), gold oxide (Au_2O_3), cupric oxide (CuO), zinc oxide (ZnO), and titanium oxide (TiO_2) can be added to glass composition to give the prepared glasses good and even excellent antibacterial behavior against different species. In spite of the brilliant biological properties of BGs, their clinical applications are restricted due to their inappropriate mechanical properties compared to those of human bones. Accordingly, the crystallization of these glasses into their corresponding glass-ceramics or incorporation of another phase, which possesses suitable mechanical properties with the aim of producing biocomposites having the desired mechanical and biological characteristics have been developed. Based on these outstanding properties, this bioceramic type receives great attention from researchers around the world [76, 77].

Bioactive Glass-Ceramics: They are characterized by the abovementioned amazing biological properties for BGs along with better mechanical properties due to that crystallization process is responsible for significant shrinkage in their microstructure giving good physical and mechanical properties [77]. Unfortunately, crystallization process may lead to severe reduction in their bioactivity behavior depending on the starting glass composition, the used sintering conditions, and the resulting phases [79].

Hydroxyapatite (HA; $\mathbf{Ca_{10}(PO_4)_6(OH)_2}$): It is a very promising alternative for damaged/diseased bone where its structure and composition are very similar to those of human hard tissues [89]. Moreover, when HA is in nanoscale range, it exhibits better bioactivity, because of its high surface-to-volume ratio. As a rule, there are two kinds of HA; namely biological and synthetic ones. The biological one is characterized by the presence of many substitutions such as fluorine (F), sodium (Na), zinc (Zn), magnesium (Mg), and carbonates (CO_3) into its crystal structure giving it superior biological characteristics. Notably, synthetic HA can be fabricated by several methods such as sol–gel, hydrothermal, solid-state reactions, mechanochemical synthesis and wet precipitation methods. For a more comprehensive view, it should be noticed that these methods require some cautions during preparation because the characteristics of the final product are strongly correlated to the various conditions. In spite of the aforementioned characteristics, its major limitation for use in clinical applications is its poor mechanical properties and accordingly, its applications are restricted in bone augmentation and middle-ear implants [82].

Fluorapatite (FA): It is commonly utilized as a biomaterial because of its superior biological properties such as high durability, good hardness values, and reduced solubility. It is possible to say that the latter property is very beneficial for biomedical applications where high solubility rate can lead to considerable weakness in the chemical bond between the biomaterial and fresh grown hard tissues. The major reason behind these excellent characteristics is the existence of F^- ions in the center of Ca^{2+} triangle and its crystal structure. Additionally, the presence of F^- ions is favorable for the prevention of tooth decay, and inhibiting bacterial activity. In addition, through bone formation, F^- ions work to promote the mineralization as well as the crystallization of calcium phosphate. Another benefit of FA, compared to HA, is that it shows better cell adhesion, good adsorption of the proteins, and improved effectiveness for alkaline phosphatase [86].

Calcium silicates (CS): They are usually employed for bone regeneration purposes and they include several promising types like wollastonite (β-$CaSiO_3$), pseudowollastonite (α-$CaSiO_3$), and dicalcium silicate (Ca_2SiO_4). All these aforementioned types show an excellent bioactivity behavior and positively affect the mineralization process of hard tissues. On the opposite side, like the abovementioned biomaterials, the major limitations of their broad uses in biomedical applications are their poor mechanical properties and high biodegradation rate [90]. Based on this fact, some other materials encompass Al_2O_3, graphene oxide, carbon nanotubes, and polymers can be added to CS ceramic to give the desirable mechanical properties and control their biodegradation rate.

Amazingly, some bioactive ceramics like HA or FA can be also employed as delivery systems for proteins, genes, vitamins, anticancer, and anti-inflammatory drugs [91–95].

Tribological and Automotive Ceramics

Nowadays, ceramics having high thermal stability, and excellent wear resistance are of great interest for tribological and automotive industry. Some ceramics such as SiC, Si_3N_4, Al_2O_3, AlN, TiN, MgO, and their composites with each other or with metals can be also used for such applications. Generally, aluminum matrix composites (AMCs) have excellent properties as strength, stiffness, and wear resistance. Accordingly, they can be broadly utilized in different applications when mixed with the aforementioned ceramics with the aim of improving their physical, mechanical, and tribological properties. The incorporation of ceramic particles in the alloys leads to increasing the strength and decreasing the ductility of alloys [96].

Ceramic Armors

In the past years, numerous kinds of metals and alloys have been utilized in the production of armors. Recently, ceramics and their composites have been developed to be used as armors due to their excellent mechanical properties. Particularly, boron carbide represents the strongest and lightest ceramic kind utilized in armors. The ceramic plates are hard enough to scatter the bullets considering that the armor pushes out on the bullet with the same force with which the bullet pushes in. Consequently, the bullet is banned from penetrating the body. In spite of the effectiveness of ceramics used for this purpose, the protective value is severely reduced owing to the successive impacts; this still is a major drawback. Hence, one talented strategy to overcome this disadvantage is to reduce the size of ceramic tiles to the smallest possible size, while the matrix substances have a thickness of at least 25 mm [97].

3.3 Ceramic Composites for Different Applications

1. **Aircraft industry**

One of the most significant applications of ceramic composites is the aircraft industry. The famous examples of such composites are fiberglass, carbon fiber, and fiber-reinforced matrix systems [98].

2. **Heat-shield systems**

These systems are crucial for space vehicles since the ambient temperature is elevated throughout the re-entry phase which subsequently, leads to the occurrence of thermal shock and heavy loads. Moreover, they can also be used in the fabrication of brake system components due to their ability to be subjected to excessive thermal shock with high mechanical resistance [99].

3. **Biomedical applications**

Despite the great advantages of ceramics, their biomedical applications are restricted due to their brittleness. Therefore, one of the most promising solutions to counter this problem is the preparation of ceramic-containing composites. Thanks to this solution, the uses of these precious materials were widely expanded to [100]:

A. **Dentistry**

  - Dental restorative materials.
  - Fixed/removable dental prostheses.

B. **Oral and maxillofacial surgery**

  - Dental implants.
  - Temporomandibular joint prostheses.
  - Cranial bone repair.

C. **Tissue Engineering**
D. **Orthopedic**

  - Bone graft.
  - Bone fracture internal fixation devices.
  - Joint prostheses.
  - Artificial tendons.
  - Artificial ligaments.
  - Artificial cartilage.

3.4 Electroceramics

Generally, ceramic materials are attractive materials for optical, electrical, and magnetic applications. The electroceramics with low electric-resistivity are valuable in making integrated circuits. On the contrary, those with high electric resistivity can be employed in the manufacturing of capacitors. Some electroceramics display piezoelectricity property and thus, can be needed in the manufacturing of transducers for microphones. It is significant to note that these ceramics are usually based on (Pb, Ti, and Zr)O_3, and accordingly, they are abbreviated as "PZT" compositions. Moreover, other types of electro-ceramics have good magnetic properties and accordingly, are favorable for transformer cores/permanent magnets. Other types of electroceramics are attractive for optical properties, i.e., luminescence, and lasing. Bearing in mind that the optical properties of these types are changed as a result of applying electric fields and thus used as modulators, demodulators, and switches [101, 102].

3.4.1 Conductive Ceramics

It is well established that the several types of ceramics display high electrical resistivity where they resist the flow of electric current. Based on this fact, they are usually used as electric insulators. Remarkably, some ceramics show excellent electric conductivity. As we know, electric conductivity can be divided into electronic and ionic. The first kind takes place because of the passage of free electrons via the substance. Since the atoms are well bonded with each other due to the ionic bonds, free electrons are forbidden to pass. In some circumstances, the inclusion of impurities can work as donors/acceptors of electrons. Conversely, the second type of electric conductivity depends on the transport of ions, through vacancies in the crystal structure of the material, from one site to another. It is important to underline that ions hopping is very little at normal ambient temperatures, while, at higher temperatures, vacancies become mobile and special ceramics show the so-called "fast ionic conduction". Noteworthy, these ceramics are very desirable in some applications such as gas sensors and batteries [103, 104].

3.4.2 Thermoelectric Ceramics

These ceramics are continuously engaged as semiconductors. For such applications, the ceramic should have a high Seebeck coefficient which is also well known as thermoelectric power or thermoelectric sensitivity of the material. It is the magnitude of produced thermoelectric-voltage due to the temperature difference across that material. For metals, it should have high electrical conductivity with relatively poor Seebeck coefficient. The thermoelectric ceramics can be widely applied in devices that are working at high temperature as combustion engines, gas turbines, power plants including nuclear power plants, furnaces, heaters, or associated with solar cells/solar heaters. However, the energy source for such conversion devices depends on the difference between the temperature inside the chamber and that of external environment. The application of thermoelectric ceramics in these devices makes them cost-effective devices along with their long lifetime, and the produced waste heat can be easily turned into electricity. This means that these devices are deemed as environmentally friendly and economical [105].

3.4.3 Ceramic Coatings

Recently, high-technology applications need the development of materials with superior surface properties to be used in different industries like mining, forestry, construction, cutting tools, electronics, and engineering ceramics for automotive and aerospace industries. In spite of the importance of such industries for economy, they are continuously threatened by many factors such as the price, the erosion, and corrosion of the used raw materials, etc. Thus, one of the best solutions to face the wear, erosion, and corrosion problems is to coat the used materials with super hard ceramics

[106, 107]. In this regard, advanced ceramics can be utilized as coatings for different materials, especially metals and bulk ceramics to be suitable for different technological applications. For example, ceramics coatings on metallic materials received noticeable development in the 1970s, and since then, this field gained more interest for coating of many alloys which need excellent performance in different applications like adiabatic engines [108], and cutting tools. It is important to stress that ceramics coatings exhibit superior properties as they work to improve the thermomechanical performance of metallic substrate [109, 110]. Meanwhile, these coatings are desirable for protecting metallic substrate against corrosion and oxidation. Additionally, they act also to minimize wear damage and decrease the base metal temperature in thermal barrier coatings [111]. There are several approaches for surface modification of metals and ceramics. These include surface modification of ceramic by laser technique [112], and surface coating of metals using different tools such as chemical vapor deposition, physical vapor deposition, and so on [113, 114].

3.5 Environmental-Related Ceramics

After the oil crisis in the 1970s, there is a high demand for the development of advanced energy-efficient engines. The traditional engines are different from the advanced ones; they are working at high temperatures. This means that the ceramics are the most suitable materials that can be applied at higher temperature while keeping their characteristics without noted damage in their functionality. These ceramics include silicon carbide (SiC), silicon nitride (Si_3N_4), and partially stabilized zirconia (PSZ). It is worth to mention that these kinds of engines are cost-effective ones with excellent performance and consequently they are highly recommended for power-generation purposes as stationary gas turbine parts [115]. Furthermore, these ceramics are playing an effective role in preserving the environment from pollution, since they are broadly used in manufacturing of hot gas filter elements that are able to operate at elevated temperatures [38]. Due to their high surface area, outstanding mechanical properties, and their resistances against thermal shock, these filters are very talented for catalyst support.

It is well known that the heat exchanger produced from ceramic can be applied at high temperature like 1500 °C for waste recovery purposes. Thus, it can save 50% of the fuel compared to the metallic one that can save only 20–30% [103]. SiC is characterized by high thermal-conductivity, wear and corrosion resistances, and thus, it is considered as the one of most promising ceramics for such application.

4 Ceramics Processing

There are three essential stages for ceramic processing:

(a) Powder preparation;
(b) Shaping or forming of the needed bodies;
(c) Sintering of the shaped bodies at suitable temperature.

4.1 Powder Preparation Process

For conventional and advanced ceramics, the powder may be prepared by grinding and calcination (solid state route) of natural or synthetic materials like oxides, hydroxides, carbonates, or other salts [116]. Other approaches as chemical precipitation (for single oxides) or co-precipitation (for complex oxides) [60, 117–121], sol–gel [122], gel-combustion [123] and hydrothermal reactions [124] are also accessible for accomplishing this purpose. However, in spite of these altered methods, solid-state route is quite the most promising among the others due to its cost-effectiveness. Unfortunately, this method may give inhomogeneous powder. On the other side, the other wet-chemical methods offer an outstanding homogeneity, but they are fitting only for laboratory studies since they are sophisticated, expensive and give the resulting product in low quantities. Interestingly, wet chemical methods can be combined with solid state where the main materials are solids, while the dopants or additives are added via chemical processes [125].

4.2 Forming (Shaping) Processes

These processes are utilized to convert ceramic powders into the required shapes and bodies. Briefly, powders are firstly well mixed and converted into wet powder by water or suitable mixing agent as polyvinyl alcohol, starch, etc., or into slurry by suitable slurry forming techniques as slip-casting or gel-casting, etc. The wetted powder is compacted in the suitable dies by different techniques. It is worth mentioning that the current forming processes are axial and isostatic dry pressing, hot pressing, porous molding, tape molding, extrusion or injection molding. Of course, the obtained bodies after forming have low mechanical properties, and high apparent porosity. However, the main purposes of forming processes are to accomplish high packing of ceramic particles and removing most of the pores to avoid the possible microstructure defects, which affect the characteristics of the resulting product. This issue depends on several parameters, and should be considered during preparation. These factors are particle-size and particle-size distributions, homogeneity, agglomeration, and the flow of powders during the shaping process. Furthermore, some other advanced routes are available for getting green bodies by thermal treatment prior to sintering process such as hot pressing, deposition of molten particles, and deposition of vapor phase (CVD) [126]. In these methods, obtaining green pieces with the preferable shapes is followed by drying with the aim of removing the organic-parts. In all cases, the shaped products should be dried to remove the solvents by evaporation. Unfortunately, this process can generate defects inside the bodies, and consequently cracking the green sample due to the fast formation of solvent-gases and contractions of the sample. So, the drying process should be completed under a controlled atmosphere and temperature conditions [127].

4.3 Sintering Process

It is well known that the key-parameter for production of final ceramic parts is the sintering process, which is responsible for the solid-state reaction between the grains and elimination of pores scattered in the sintered body. This stage involves applying high temperature on the shaped ceramic bodies, keeping in mind that it should be lower than its melting point. Several phenomena are occurring during this process, which stimulates the consolidation and densification of the shaped part. Also, many reactions can occur and lead to considerable changes in the chemical composition and/or phase composition of the sintered product. Hence; the ultimate properties of ceramics are mostly affected by this process [128]. It is important to highlight that the exact adjustment of essential temperature and time is significantly associated with the required connectivity, porosity, and densification. The main properties of sintered ceramics depend mainly on temperature, time, initial density, particle size, particle size distribution, and the whole process [129].

It is well confirmed that the properties of polycrystalline ceramics are strongly affected by their microstructure. Consequently, in order to improve the properties and the reliability of ceramics, the density, grain size, and microstructure homogeneity should be exactly controlled [130]. Unfortunately, the production of highly dense ceramics having nanometric or submicrometric grain size is difficult through conventional sintering. Instead, other manufacturing routes are available for the preparation of these ceramics such as colloidal powder processing with controlled distribution of particle sizes [131] with or without using sintering additives [132], pressure-assisted sintering [133], spark plasma sintering (SPS) [134] and pulsed electric current sintering (PECS) [135]. However, these methods are not cost-effective due to their expensiveness and complexity [136].

4.3.1 Mechanisms of Sintering

Solid State Sintering

In this type of sintering, a relatively high temperature is required to facilitate the diffusion process. Since the diffusion is a matter of transportation mechanism, it induces both densification and grain growth. According to this aspect, the sintering environments that permit the occurrence of densification without simultaneously encouragement of grain growth are most suitable for microstructural refinement with the production of highly dense ceramics and nanometric grains [137]. As reported in Ref. [126], solid-state sintering can occur through three sequential stages:

a. The powder particles should be compacted to attain the proper connection with each other.
b. The particles begin to form necks between each other when the sintering temperature reaches 2/3 of their melting point, and then they are intensely bonded together after the formation of necks. Furthermore, increasing the contact areas between the grains tends to the successive increase in the density of sintered bodies and decrease in the total void volume (porosity). Remarkably, the particles having small diameter possess high surface area and high surface free energy which are considered as the driving force of sintering process. Accordingly, the surface area is thermodynamically reduced by bonding the particles together, which is responsible for considerable reduction in the energy.
c. The third stage is characterized by full bonding of grains with the completion of solid state reaction. Moreover, the residual porosity becomes closed-off pores which consequently leads to improving the microstructure and mechanical properties of sintered bodies. It should be noticed that the particle size of the original powder greatly affects the pores sizes and their distribution. Examples of materials which have been sintered by this mechanism were published in our recent works [45, 138, 139].

Liquid Phase Sintering

This kind of sintering is highly appropriate for numerous industrial fields like steels, cemented carbides, heavy alloys, bronzes, and silicon nitride systems. This mechanism is intensely dependent upon the presence of liquid phase during all or part of the sintering process to improve the material's densification. There are two different processes:

a. Normal liquid phase sintering in which the original ceramic compressed in situ forms liquid phase, and is accompanied by the formation of one or more components (multi-phase formation) after heat treatment.
b. In this type of liquid phase sintering, infiltration of original ceramic bodies by liquid formed outside the ceramic bodies occurred throughout the early sintering period.

Liquid phase sintering proceeds via three steps as follows:

1. Liquid flow and pore/particle rearrangement.
2. Accommodation or dissolution and re-precipitation.
3. Coalescence and final densification.

It is worth mentioning that these steps typically occur with their approximate sequence and might be overlapped for some systems. The development in liquid phase sintering is responsible for dropping the densification-kinetics. The early densification is enhanced by raising the liquid amount up to closely 35 vol% [140].

Activated Sintering

This kind of sintering deals with the possibility of depressing the sintering temperature by adding various activating agents or sintering aids as certain transition metals and oxides. For example, it is well known that SiC has exciting features owing to strong and stiff Si-C bonds. This makes significant difficulties in its sintering due to low self-diffusion coefficient [141]. Accordingly, the presence of some additives is crucial for facilitating the sintering process. The most utilized aids for this purpose are Al_2O_3 and ZrO_2 [142] which are responsible for reducing the needed temperature for the accomplishment of the sintering process. On the other side, hardness and thermal stability may be negatively affected by these aids [143]. On the contrary, the occurrence of boron and carbon may overwhelm this problem by taking into consideration that sintering should be occurring at elevated temperatures to let the sintered bodies have high hardness values and relative density similar to theoretical one [144]. It is significant to emphasize that the existence of numerous polymorphic structures in SiC, i.e., β and α is considered as another difficulty for obtaining dense structure. Although, β is the major phase that exists during SiC synthesis, it can easily convert to α one [145, 147].

Reaction Sintering

It is a modern sintering type, discovered with production of new materials. Reaction (chemical) sintering is specific for the materials that cannot be compacted under the traditional mechanisms as a result of physical processes, but it occurs due to the chemical reactions. The existence of reagents in the starting materials or their entrance from outside as a result of gaseous medium existence in furnace space leads to the creation of gaseous, or liquid product throughout sintering process. In this process two or more components react together with the possibility of dimension and density changes during densification [146]. In this regard, cold isotactic pressing (CIP) is very useful for accomplishing high densification way during the final sintering process, where it helps to promote the densities of green bodies by 5–10% [145]. On the opposite side, pressure-less sintering process such as vacuum or microwave leads to the enlargement of grains sizes, while pressure sintering such as hot-pressing (HP), hot isotactic pressing (HIP) and spark plasma sintering (SPS) help in suppressing the grain growth [146] and promote the reaction sintering as well as reducing the sintering time and temperature.

4.3.2 Factors Affecting Sintering Process

There are many factors affecting sintering process. Some of these factors are specific to the materials, while the others belong to the process itself. The followings are the brief description of such factors.

Process Factors

A. Temperature: it is a very significant parameter for controlling both the rate and magnitude of the sintering-associated changes.

b. Time: is another effective factor for improving the densification with less effectiveness than temperature.

c. Atmosphere: is crucial for obtaining the desirable results.

Materials Factors

A. Particle size: It is well known that reducing particle size contributes to considerable enhancement of sintering process.

b. Particle shape: Reduced sphericity and increasing macro or micro-surface roughness are responsible for close contacts between particles, and considerable increase in the internal surface area encourages the sintering process.

Particle structure: A fine grain structure within the original particles induces sintering process because of its desirable effect on material transport mechanisms.

Particle composition: It is well known that the presence of additions or impurities within the metals can positively or negatively affect the sintering kinetics. The distribution and the reaction of impurities greatly identify whether this effect is harmful or beneficial. For example, the oxidation is frequently harmful, while dispersed phases within the matrix strongly encourage the sintering by prohibiting the motion of grain boundaries. On the other hand, at high sintering temperatures, the expected reaction between the impurities and either base metal or alloying elements can be highly unfavorable.

Green density: High driving force for sintering can be easily achieved through increasing the amount of internal surface area which arises from the decreased grain density [147].

4.4 Simulation of Sintering Process

It is well known that the sintering process is the key-parameter for ceramic fabrication, and it significantly affects the value, yield, and price of ceramic products. However, it is important to note that the quality of the sintering process depends on the temperature distribution and the experience of researchers. Therefore, sintering of large ceramic bodies leads to a huge economic loss due to the enormous waste of resources. Moreover, from the environmental-protection point of view, and the resources management, the traditional sintering is not suitable for industrial progress. Based on these important facts, the use of computers is beneficial for improving this important process. In this sense, computer-aided sintering (CAS) helps in smart ceramics sintering. CAS technology is a breakthrough for good quality coupled with lower energy consumption [148–151].

Recently, neural network has received a great interest after the revolution of integrated circuits and computer technology. Nowadays, this network is applied in several fields like intelligence control, knowledge processing, robot technology, computer vision, sonar signal processing, etc. In this context, this network has been also applied in the ceramic industries. Neural network is classified into two classes; namely feed network and feedback network. However, Backpropagation (BP) neural network algorithm is the most common algorithm of the first class. Using the neural network, some researchers have successfully built a BP network model to determine some factors such as thermal insulation time, heating rate for different stages, and average of high temperature section. The use of this model was helpful in identifying 20 samples with an accuracy of 90%. It is important to say that the application of the neural network in ceramic industries is very successful for identifying and predicting the materials' properties as well as their defects, etc. So, we hope that scientists will expand their interest toward the application of the neural network for various ceramic materials [148].

5 Novel Processing Ceramic Techniques

5.1 Magnetic Slip Casting

Generally, slip casting is a method used to cast a colloidal ceramic-suspension into a porous mold, dried and consolidated by sintering. This method is very attractive due to the fact that it is a water-based process, which provides a high flexibility of slurry compositions. Therefore, it can be used in the case of slurries made of ceramic powders, metal/ceramic mixtures, etc. Unfortunately, it is not desirable for the industrial scale and therefore must be combined with other technologies. For instance, during casting, pressing/centrifuging can be used. Also, the manufacturing processes can be coupled with magnetic fields to enhance properties of dense bodies through texturing. It is well established that the attractive/repulsive forces of paramagnetic/diamagnetic materials are generated by magnetic fields. In liquid suspensions, magnetic fields are able to manipulate the location and orientation of the particles. By taking advantage of their remoteness as well as tenability, magnetic fields are preferred over other processing techniques. Moreover, when it is generated by passing an electric current through coil or electromagnet, it can be turned on and off. In magnetic slip casting, a magnetic field is applied through the casting process to orient the preferential crystalline axis of the ceramic grains taking into account that most ceramic materials are diamagnetic. Therefore, one can expect that when an external magnetic field is applied to them, an internal magnetic one is induced in the other direction. Thus, a repulsive force is created. It is worth to mention that the strength of the applied external magnetic field must be extremely high to generate such an induced internal magnetic field as the diamagnetic materials are characterized by their low magnetic susceptibility. In order to reduce the strength of the external magnetic field, the magnetic sensitivity of the diamagnetic materials can be increased via transforming the diamagnetic ceramic powder by magnetic elements. Particularly, the crystalline/shape anisotropy of the starting ceramic powder controls the orientation of the ceramic powders [152].

5.2 Laser Surface Texturing

In 1969, LASER (Light Amplification by Stimulated Emission of Radiation) has been discovered by Maiman and since then, this technology is applied in various important industrial and medical fields. In short, if the laser beam hits a material, it is partially reflected, partially transmitted, and partially absorbed. Hence, the electrons in this material are excited, which leads to an increase in thermal energy. The laser beam can be a continuous wave or a pulsed wave. The first type acts to transform uniform energy to the material's surface. On the contrary, the second one allows achieving a higher peak power. Indeed, the pulse duration is short to convey the energy to the desired area before that conveyed by the previous pulse has dissipated.

Laser surface texturing relies on utilizing the laser beam to produce ablation in which the material is selectively removed from the surface. In this respect, a pulsed or high-intensity continuous wave laser is suitable for this purpose. The ablation process can be performed through three mechanisms. They are photochemical (bond-breaking), photothermal (temperature increase), and photophysical (ejection of material from the surface due to a laser-induced shockwave [153, 154].

Laser surface treatment of ceramic materials has also been paid great attention since it is an effective and economical process for improving the surface properties. Re-melting, sealing, or alloying by laser can change the ceramic material into functional materials. It has been reported that tribological properties such as wear resistance, and friction can be significantly improved by laser treatment. Zawrah et al. reported on surface alloying of alumina ceramics using IR-CO_2 laser by adding HfO_2 or HfO_2 with 5 or 10 mol.% SiO_2, CeO_2 and cordierite. They found that the tendency of crack formation and grain growth was significantly decreased after laser treatment. The treated layers exhibited no open porosity, and contained 20–40 vol% second phases homogeneously distributed around the grain boundaries of the alumina matrix. Due to alloying, average grain size, hardness, and elastic modulus of the composite layers have been reduced, but resistance to cracking under the mechanical action of sliding diamond (scratch test) and abrasive wear was significantly enhanced compared with the unmodified dense alumina ceramic [155].

5.3 Cold Sintering

Generally, all bulk ceramic materials are fabricated using green shaping followed by sintering at temperatures usually higher than 1000 °C, so this process is considered as a highly energy-intensive process and high-energy dissipation approach. Most of the energy used for firing dissipates irreversibly through the furnace insulation and lost during cooling. The demand to decrease the consumption of energy and CO_2 produced during firing of ceramics urged the scientists to develop consolidation techniques operating at lower temperatures, ideally not more than 300 °C. Cold sintering is a remarkably low-temperature process that uses a transient transport water phase and an applied uniaxial force to support the densification of powder compacts. The liquid phase can accelerate plasticity, grain boundary/surface diffusion, and mass transport. By utilizing this method, many ceramic powders can be transformed into highly dense monoliths at temperature far lower than the melting point. The existence of water can promote the atomic diffusion at the particle surface without raising the temperature. Using cold sintering process, the researchers succeeded to reduce the consumed energy for consolidation of $BaTiO_3$ powders from 2800 to 30 M kg^{-1}. Other researchers conducted an interesting experiment to compare between hot and cold sintering of 1 Kg of ZnO. In the case of hot sintering, the consolidation required 291 MJ kg^{-1}, while cold sintering required 162 MJ kg^{-1} [156].

5.4 Flash Sintering

As previously discussed, the main disadvantage of conventional sintering process is the high energy consumption along with the release of carbon dioxide. In response to this drawback, the European Commission approved in 2007 the heat consumption required for production of different types of ceramics [157]. The greatest energy needed for sintering process is estimated by some mega-joules per kilogram of resulting ceramic product. Flash sintering (FS) has been discovered in 2010 by Cologna et al. [158]. This technique is based on applying an electric field to the sample powders. Under coupling the electric field and furnace temperature, the densification of ceramic material occurred in a very short time. This time ranges between a few seconds to a few minutes. Actually, the success of Cologna's experiment was based on the previous study by Gosh et al. [159] in 2009. In that work, the effect of applying a weak DC-electric field for 3 mol.% yttria stabilized zirconia (3YSZ) was described. The application of a weak electric current evidently reduced the rate of grain growth.

5.5 3D Printed Ceramics

Three-dimensional (3D) printing is a modern manufacturing and an additive technology. In this technique, the physical parts are fabricated in an additive manner, separated point by point, line by line, or layer by layer are digitally sliced into 2D cross sections using 3D machine. In this context, this technique is a promising one for the flexible preparation of highly fine and sophisticated structures that are extremely difficult to obtain through conventional preparation methods such as casting and machining. Besides this feature, 3D printing technology provides high throughput since many materials can be constructed in one process. Due to these important benefits, 3D technology has attracted the attention of researchers in science and engineering [158, 160]. This technique was first produced by Marcus et al. [161] and Sachs et al. [162] in the 1990s. Depending on the shape of the raw materials pretreated before printing, this technology can be divided into: slurry-based, powder-based, and bulk solid-based methods. In slurry-based technologies utilized for ceramic/polymer mixtures, the viscosities are ranging from low-viscosity (~mPa·s) with a low ceramic loading (up to 30 vol.%) as inks to high-viscosity(~Pa s) with a much greater ceramic loading (up to 60 vol.%) as pastes.

5.6 Porous Ceramics

Advanced porous ceramics "ceramic foams or ceramic filters or ceramic membranes" are used for many applications such as structural, environmental, biological and biomedical ones. Since these types of ceramics possess various advantages over metals and polymers, they gained huge interests from scientists to use them in the above-mentioned applications. Notably, the functionality of these types of ceramics closely depends on the factors related to pore structure such as pore size, shape, distribution, and connectivity. For example, the pores can behave as insulators at elevated temperatures, capture impurities in a filter, expedite tissue ingrowth in a bio-scaffold, or provide the architecture for reinforcement in a ceramic–metal composite. Meanwhile, their properties can be manipulated to suit a specific application through the modification and refinement of processing techniques to control their microstructure. Figure 2 shows the applications of porous ceramics according to their pore sizes [163]. Several processing techniques are responsible for integrating pores into the structure like sintering of coarse powders, and partial sintering of green powders. Other processing techniques are well known for the production of porous ceramics as replica method, the sacrificial phase technique, direct foaming method, paste extrusion, and most recently developed rapid prototyping technique [163].

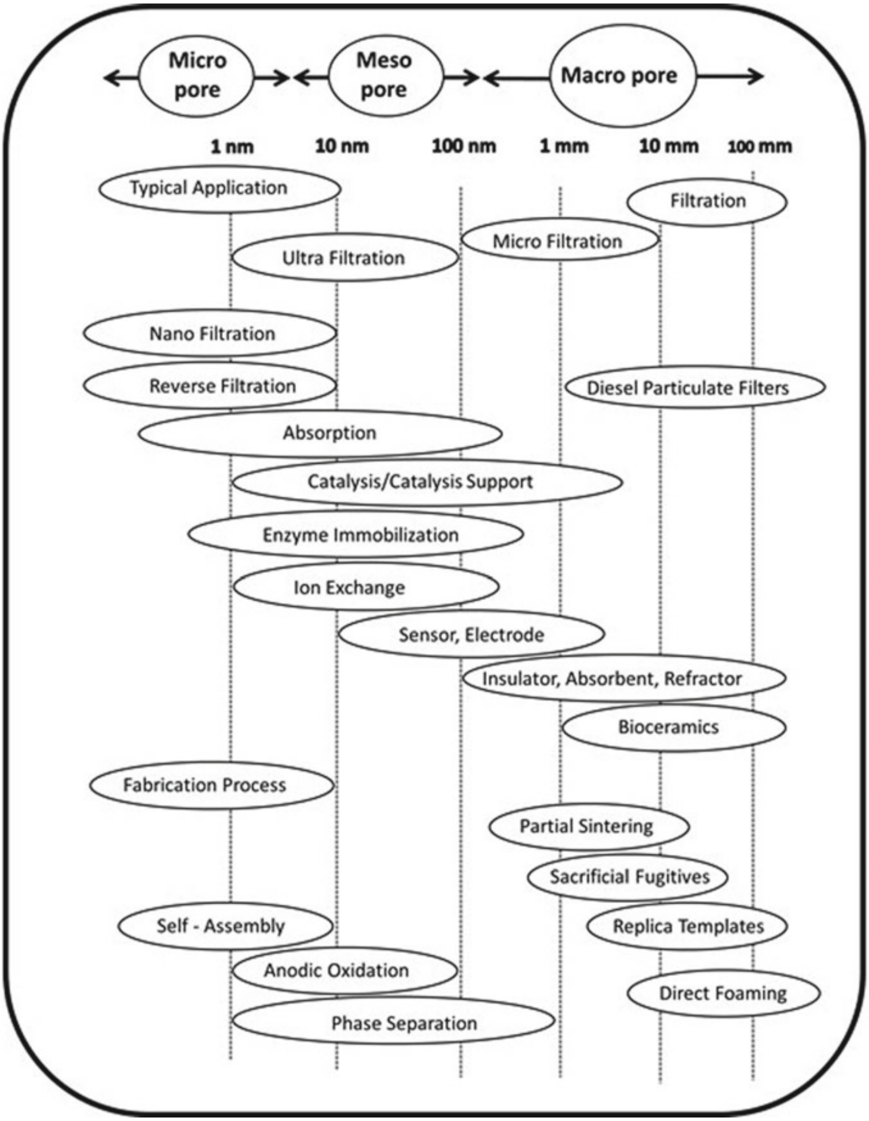

Fig. 2 Schematic of classification of porous ceramic: Redrawn after Ohji and Fukushima [163]

5.7 Functional Ceramics for Catalytic Applications

The ceramics and bioceramics can also play an important role as catalysts of some chemical reactions. About 90% of the new processes undertaken in chemical industry are catalysis-dependent. The catalysts are divided into two categories, heterogeneous and homogeneous. Homogenous catalysis takes place if the catalyst is statically dispersed in the mixture of reactants, whether it is a gaseous or liquid solution. This category includes transition metals, enzymes, and inorganic acids/bases. On the other hand, the second class, i.e., heterogeneous, is characterized by the presence of catalyst in a different phase from the reactants. Therefore, the reaction happens at the surface of solid (catalyst) particle in contact with the gaseous or liquid solution.

Since the ceramic materials resist high temperatures, display chemical-durability and wear resistance, they have unlimited potential as catalytic materials for usage in a variety of reactor structures, and can operate at different conditions. The ceramics catalysts are applied as (i) direct use as catalysts and (ii) use as support materials (substrates) to anchor and disperse a variety of active metals. Ceramic catalysts and catalyst supports are the biggest market sector outside the electronic ceramics. The ceramic catalysts are typically composed of metal oxides that contain at least two different cations. For examples; V_2O_5/SiO_2, $CeO_2/MgAl_2O_4$, CeO_2/ZrO_2, V_2O_5/TiO_2, CeO_2/Al_2O_3, $BaO/SrTiO_3$, Sr/La_2O_3, SrO/Nd_2O_3, Sm_2O_5/MgO, N_2O/MgO, La_2O_3/CaO. When these materials are prepared in nanoscale, they exhibit improved properties. Zeolites are also ceramic catalytic materials composed of aluminum silicates that have cavities or pores with molecular dimensions as part of their crystalline structure. Zeolites are unique among inorganic oxides because of their uniform microporous character, high internal surface area, high thermal stability, and their ability to develop internal acidity [165–171].

Ceramic catalytic converters: Ceramics are applied also in construction of many parts of modern car industry as windows, mirrors, spark plugs, lights and electronics, catalytic converters, etc. With increasing worldwide vehicle usage, the air pollution is increased due to the increasing of exhausts produced by the cars. This has urged the automakers to redesign the car engines and fuel systems using the incorporation of ceramic catalytic converter. Engine exhaust gases consist of a complicated mixture, its composition depends on the type of engine (two- or four-stroke, spark- or compression (diesel)-ignited), driving conditions (urban vs. highway), vehicle speed, acceleration/deceleration, etc. The catalytic converter is located in the downstream of the engine's exhaust manifold and can deal with the exhaust gases by chemical reaction to treat the pollutants as CO, NOx, and hydrocarbons into CO_2, nitrogen, water vapor through the reduction and oxidation actions. A typical catalytic converter unit consists of either a ceramic honeycomb monolithic structure (cordierite) or ceramic beads coated with precious metals (Pt, Pd, and Rh) [165].

Solid oxide fuel cells: In the near future the fuel cell devices will efficiently contribute to power generation. They are classified according to the electrolyte and the fuel used to generate electricity. They include a barrier to select and allow ions to pass as well as pushing the electrons to flow through an exterior circuit to generate electricity. The most important fuel cell that was fabricated from ceramic material as ZrO_2 is the solid oxide fuel cell (SOFC). The basic SOFC unit contains three oxide ceramic units: a fuel electrode; an air electrode; and a solid electrolyte. It operates as follows: the oxygen in supplied air can accept electrons from the external circuit to form O^{2-} ions at the cathode then move via electrolyte to the fuel electrode (anode) and create H_2O and/or CO_2 (depending on the fuel used), liberating electrons to the external circuit. There are several advanced ceramic materials which show greater electrical properties. These materials are known as electroceramics which act as fast ion conductors and are capable to improve a high flux of ions in the solid state. Ceramics which can quickly generate oxygen ions (O^{2-}) are interesting candidates for SOFC developments. Recently, many ceramic materials have been utilized as potential SOFC constituents. The anode can consist of nickel/yttria-stabilized zirconia (Ni/YSZ) cermet (i.e., ceramic/metal composite). The cathode can be formed from a mixed conducting perovskite, lanthanum manganite ($LaMnO_3$). Yttria-stabilized zirconia (YSZ) is used for the oxygen ion conducting electrolyte. To improve the performance of SOFC, it is important to develop materials with elevated electrical conductivity and catalytic performance of the anode. Improved SOFC performance must contain greater energy-conversion productivity, lesser chemical and acoustical pollution, fuel flexibility, cogeneration capability, and a rapid load response [163–171].

6 Properties of Ceramics

It is well established that ceramics possess promising physical, chemical, and mechanical characteristics which enable them to be valid for different industrial purposes. Therefore, we briefly mention these characteristics as follows [147]:

- Low density.
- Low thermal expansion coefficient.
- High hardness value.
- High temperature as well as corrosion resistance.
- High wear resistance.
- High melting temperature.
- Stability of mechanical properties at elevated temperatures.

In spite of these interesting properties, their major drawbacks can be summarized as follows:

- Brittleness.
- Highly demanding processing.
- Joining different ceramic components with each other or with other materials is so difficult.

Tables 1, 2, and 3 illustrate the properties of some advanced oxide and none oxide ceramics [172].

Table 1 Properties of some advanced oxide ceramics (alumina, cordierite, zirconia and mullite) [172]

Property	Ceramic type/value of property				Unit	Test
Physical	Alumina	Cordierite	Zirconia	Mullite		
Chemical formula	Al_2O_3	$2MgO–2Al_2O_3–5SiO_2$	ZrO_2	$3Al_2O_3–2SiO_2$		
Density, ρ	3.7–3.97	2.60	6.04	2.80	g cm^{-3}	ASTM C20
Color	Ivory/white	Tan	White	Tan		
Crystal structure	Hexagonal	Orthorhombic	Tetragonal	orthorhombic		
Water absorption	0.0	0.02–3.2	0.0	0.0	% at R.T.*	ASTM C373
Hardness	9	7	6.5	8	Mohs	
Hardness	2000	–	1600	1450	Knoop (kg mm^{-2})	Knoop 100 g
Mechanical0						
Compressive strength	2070–2620	350	2500	551	MPa at R.T.	ASTM C773
Tensile strength	260–300	25.5	248	103.5	MPa at R.T	ACMA Test #4
Modulus of elasticity (Young's Modulus)	393	70	207	150	GPa	ASTM C848
Flexural strength (MOR)	310–379	117	900	170	MPa at R.T	ASTM F417
Poisson's ratio, υ	0.27	0.21	0.32	0.25		ASTM C818
Fracture toughness, K_{Ic}	4.5	–	13.0	2.0	MPa.$m.^{1/2}$	Notched beam test
Thermal						
Max. use temperature (in air)	1750	1371	500	1700	°C	No load cond
Thermal shock resistance	200	500	280–360	300	ΔT (°C)	Quenching
Thermal conductivity	35	3.0	2.7	3.5	W/m–K at R.T	ASTM C408
Coefficient of linear thermal expansion, α_l	8.4	1.7	11.0	5.3	µm/m °C l (~25 °C through ±1000 °C)	ASTM C372

(continued)

Table 1 (continued)

Property	Ceramic type/value of property				Unit	Test
Physical	Alumina	Cordierite	Zirconia	Mullite		
Specific heat, c_p	0.21	0.35	0.10	0.23	cal/g °C at R.T	ASTM C351
Electrical						
Dielectric constant	9.6	4.7	26 @ 100 kHz	6.0	1 MHz at R.T.	ASTM D150
Dielectric strength	15	5.11	9.0	9.8	kV/mm	ASTM D116
Electrical resistivity	$>10^{14}$	$>10^{14}$	$>10^{4}$	10^{-13}	Ω cm at R.T.	ASTM D1829

[*] R.T: Room temperature

Table 2 Properties of some advanced none oxide ceramics (silicon carbide, silicon nitride, boron nitride and boron carbide) [172]

Property	Ceramic type/Value of property				Unit	**Test**
Physical	Silicon carbide	Silicon nitride	Boron nitride	Boron carbide		
Chemical formula	α-SiC	Si_3N_4	BN	B_4C		
Density, ρ	3.21	3.31	2.28	3.25	g cm^{-3}	ASTM C20
Color	Dark gray	Dark gray	White	White/tan/gray		
Crystal structure	Hexagonal	Hexagonal (α & β)	Hexagonal	Hexagonal		
Water absorption	0.0	0.0	0.0–1.0	Ng	% at R.T.	ASTM C373
Hardness	9–10	9	2	36	Mohs	
Hardness	2800	2200	25–205	Ng	Knoop (kg mm^{-2})	Knoop 100 g
Mechanical						
Compressive strength	1725–2500	689–2760	23.5	2.9	MPa at R.T.	ASTM C773
Tensile strength	310	360–434	2.41 (1000 °C)	155	MPa at R.T.	ACMA Test #4
Modulus of elasticity (Young's Modulus)	476	317	675	445	GPa	ASTM C848
Flexural strength (MOR)	324	679–896	51.8	375	MPa at R.T	ASTM F417
Poisson's ratio, υ	0.19	0.23	0.05	0.19		ASTM C818
Fracture toughness, K_{Ic}	4.0	5.0–8.0	2.6	Ng	$MPa.m^{1/2}$	Notched Beam Test
Thermal						
Max. use temperature (in air)	1400	1500	985	2450	°C	No load cond
Thermal shock resistance	350–500	750	>1500	Ng	ΔT (°C)	Quenching
Thermal conductivity	41	27	20	28	W/m K at R.T.	ASTM C408
Coefficient of linear thermal expansion, α_l	5.12	3.4	1.0–2.0	945	µm/m °C l (~25 °C through ±1000 °C)	ASTM C372
Specific heat, c_p	0.15	0.17	0.19	0.25	cal/g °C at R.T.	ASTM C351

(continued)

Table 2 (continued)

Property	Ceramic type/Value of property				Unit	**Test**
Physical	Silicon carbide	Silicon nitride	Boron nitride	Boron carbide		
Electrical						
Dielectric constant	10.2	7.0	4.08	Ng	1 MHz at R.T.	ASTM D150
Dielectric strength	–	s	374	Ng	kV/mm	ASTM D116
Electrical resistivity	10^{18}	10^{13}	$>10^{13}$	Ng	Ω.cm at R.T.	ASTM D1829

Table 3 Properties of some other important advanced ceramics [145]

Property	Ceramic type/value of property				Unit	Test
Physical	Sapphire	Steatite L-5	Graphite	AlN		
Chemical formula	α-Al_2O_3	$H_2Mg_3(SiO_3)_4$	C	AIN		
Density, ρ	3.97	2.71	2.28	3.25	g cm^{-3}	ASTM C20
Color	White/transparent	Buff	Black	White/tan/gray		
Crystal structure	Trigonal	Hexagonal	Hexagonal	hexagonal		
Water absorption	0.0	0.0–0.2	0.1–1.5	0.0	% at R.T	ASTM C373
Hardness	9	7.5	0.1–1.5	5	Mohs	
Hardness	2200	–	–	1170	Knoop (kg mm^{-2})	Knoop 100 g
Mechanical						
Compressive strength	2000	621	96	2068	MPa at R.T.	ASTM C773
Tensile strength	250–400	62	4.8	–	MPa at R.T.	ACMA Test #4
Modulus of elasticity (Young's Modulus)	250–400	138	4.8	308	GPa	ASTM C848
Flexural strength (MOR)	760–1035	140	50	428	MPa at R.T.	ASTM F417
Poisson's ratio, υ	0.29	–	–	0.25		ASTM C818
Fracture toughness, K_{Ic}	1.89	–	–	3.5	MP a.m.$^{1/2}$	Notched Beam Test
Thermal						
Max. use temperature (in air)	~2000	1425	3650	1600	°C	No load cond
Thermal shock resistance	200	190	200–250	400	ΔT (°C)	Quenching
Thermal conductivity	40	2.9	24	82.3–170	W/m K at R.T.	ASTM C408
Coefficient of linear thermal expansion, α_l	7.9–8.8	7.0	8.39	4.6–5.7	µm/m °C l (~25 °C through ±1000 °C)	ASTM C372

(continued)

Table 3 (continued)

Property	Ceramic type/value of property				Unit	Test
Physical	Sapphire	Steatite L-5	Graphite	AlN		
Specific heat, c_p	0.18	0.22	0.16	0.25	cal/g °C at R.T.	ASTM C351
Electrical						
Dielectric constant	9.3–11.4	6.3	–	8.0–9.1	1 MHz at R.T.	ASTM D150
Dielectric strength	15–50	9.3	–	15	kV/mm	ASTM D116
Electrical resistivity	10^{17}	10^{4}	7×10^{-3}	$>10^{14}$	Ω cm at R.T.	ASTM D1829

7 Conclusion

Nowadays, advanced ceramics are considered as promising materials for different applications such as engineering, biomedical, electronics, energy, and environmental issues. Most of the advanced ceramics depend on pure oxides or non-oxides prepared by new chemical, physical, and mechanical routes. Through their preparation, different parameters such as temperature, concentration of reactants, time of reaction, and atmosphere should be controlled. To convert the prepared ceramic powders into consolidated bodies, sintering processes should be conducted under suitable conditions such as temperature, time, and atmosphere. The sintering process includes solid-state sintering, liquid phase sintering, activated sintering, and reaction sintering. The prepared ceramic powder and sintered ceramic bodies can be investigated by different tools for their physical, chemical, mechanical, morphological, magnetic, electrical, optical, and biological properties according to the needed applications. This chapter dealt only with the most common types of advanced ceramics and their sintering without details on the aforementioned properties.

References

1. https://ceramics.org/about/what-are-engineered-ceramics-and-glass/brief-history-of-ceramics-and-glass. Accessed January 1, 2020
2. D. Eliche-Quesada, Luis Pérez-Villarejo, Pedro José Sánchez-Soto, Introduction to Ceramic Materials: Synthesis, Characterization, Applications, and Recycling, (IntechOpen, 2019), pp. 1–6. https://doi.org/10.5772/intechopen.84710
3. W. Freiman, in *Introduction to Ceramic and Glasses*, Engineered materials handbook, ceramic and glasses, vol. 4 (ASM International, 1991), pp. 41–122
4. R Nathan Katz, Overview of ceramic materials, design and application, in *Mechanical Engineers' Handbook*, ed. by Myer Kutz (Wiley, 2006), pp. 433–449. https://doi.org/10.1002/0471777447.ch12
5. F. Bergaya, G. Lagaly, in *General Introduction: Clays, Clay Minerals and Clay Science*, ed. by F. Bergaya, B.K.G. Theng, G. Lagaly, Handbook of clay science, vol. 1 (Elsevier, Amsterdam, 2000), pp. 1–18
6. W.R. Matizamhuka, Advanced ceramics-the new frontier in modern-day technology: part I. J. S. Afr. I. Min. Metall. **118**, 757–764 (2018). https://doi.org/10.17159/2411-9717/2018/v118n7a9
7. I. Anastopoulos, A. Bhatnagar, E. Lima, Adsorption of rare earth metals: A review of recent literature. J. Mol. Liq. **221**, 954–962 (2016). https://doi.org/10.1016/j.molliq.2016.06.076
8. L. Su, X. Zeng, H. He, Q. Tao, S. Komarneni, Preparation of functionalized kaolinite/epoxy resin nanocomposites with enhanced thermal properties. Appl. Clay Sci. **148**, 103–108 (2017). https://doi.org/10.1016/j.clay.2017.08.017
9. A. Alshameri, X. Wei, H. Wang, Y. Fuguo, X. Chen, H. He, C. Yan, F. Xu, in *A review of the role of natural clay minerals as effective adsorbents and an alternative source of minerals*, ed. by K.S. Essa, Minerals, (IntechOpen 2019), p. 49. Doi: https://doi.org/10.5772/intechopen.
10. A. Bouquillon, in *History of Ceramics*, ed. by P. Boch, J-C. Nièpce, *Ceramic Materials: Processes, Properties and Applications* (ISTE Ltd, 2007), pp. 30–53
11. F. Bergaya, G. Lagaly, ed. *Developments in Clay Science*, Handbook of clay science, (Amsterdam: Elsevier, 2006), p. 1224

12. F. Brigatti, E. Galan, B. Theng, in *Structures and Mineralogy of Clay Minerals, Developments In Clay Science* (Amsterdam: Elsevier, 2006), pp. 19–86
13. L. Black, P. Purnell, J. Hill, Adv. Appl. Ceram. **109**(5), 253 (2010)
14. C. Parr, R. Roesky, C. Wohrmeyer, C N Refractories **5**, 6 (2001)
15. M.A. Serry, S.M. Hammad, M.F.M. Zawrah, Phase composition and microstructure of refractory $MgAl_2O_4$ spinel grains. Brit. Ceram. Trans. **97**(6), 275–282 (1998). http://pascalfrancis.inist.fr/vibad/index.php?action=getRecordDetail&idt=1658021
16. M.F. Zawrah, S. Meky, Ceram Int. **33**, 969 (2007)
17. M.F. Zawrah, N.M. Khalil, Improvement of physico-mechnical properties of self-forming MA-spinel castables. Brit. Ceram. Trans. **100**(3), 110–114 (2001). https://doi.org/10.1179/096797801681305
18. M.F. Zawrah, M.A. Serry, J. Schneider, K.-H. Zum Gahr, Microstructure and mechanical properties of non-stoichiometric $MgAl_2O_4$-spinel bodies, Cfi/Ber. DKG **77**(3), 22–26 (2000). http://pascalfrancis.inist.fr/vibad/index.php?action=getRecordDetail&idt=1330158
19. S.F. Krar, *Grinding Technology*, 2nd edn. (Delmar Publishers, Albany, 1995), p.334
20. G.S. Làzaro, S.C. Santos, C.X. Resende, E.A. dos Santos, Individual and combined effects of the elements Zn, Mg and Sr on the surface reactivity of a $SiO_2{\cdot}CaO{\cdot}Na_2O{\cdot}P_2O_5$ bioglass system. J. Non-Cryst. Solids **386**, 19–28 (2014). https://doi.org/10.1016/j.jnoncrysol.2013.11.038
21. W. Holland, G. Beall, *Glass-Ceramic Technology*, 1st edn. (The American Ceramic Society, Westerville, OH, 2002), p. 372. https://doi.org/10.2298/SOS0403216U
22. E.D. Zanotto, Am. Ceram. Soc. Bull. **89**, 19 (2010)
23. F.C. Serbena, I. Mathias, C.E. Foerster, E.D. Zanotto, Crystallization toughening of a model glass-ceramic. Acta Mater. **86**, 216–228 (2015). https://doi.org/10.1016/j.actamat.2014.12.007
24. E. Kleebusch, C. Patzig, T. Höche, C. Rüssel, The evidence of phase separation droplets in the crystallization process of a Li_2O-Al_2O_3-SiO_2 glass with TiO_2 as nucleating agent—an X-ray diffrraction and (S)TEM-study supported by EDX analysis. Ceram. Int. **44**, 2919–2926 (2018). https://doi.org/10.1016/j.ceramint.2017.11.040
25. I. Alekseeva, O. Dymshits, M. Tsenter, A. Zhilin, V. Golubkov, I. Denisov, N. Skoptsov, A. Malyarevich, K. Yumashev, Optical applications of glass-ceramics. J. Non Cryst. Solids **356**, 3042–3058 (2010). https://doi.org/10.1016/j.jnoncrysol.2010.05.103
26. L. Fu, H. Engqvist, W. Xia, Glass–ceramics in dentistry: a review. Materials **13**, 1–22 (2020). https://doi.org/10.3390/ma13051049
27. G.H. Beall, Milestones in glass-ceramics: a personal perspective. Int. J. Appl. Glas. Sci. **5**, 93–103 (2014). https://doi.org/10.1111/ijag.12063
28. M. Montazerian, E.D. Zanotto, Bioactive and inert dental glass-ceramics. J. Biomed. Mater. Res. Part A **1**, 619–639 (2016). https://doi.org/10.1002/jbm.a.35923
29. H.E.H Sadek, R.M. Khattab, Mahmoud F. Zawrah, Interceram **65**, 174 (2016)
30. R.M. Khattab, A. El-Rafei, M. F. Zawrah, In-situ formation of sintered cordierite-mullite nano-micro composites by utilizing of waste silica fume. Mater. Res. Bull. **47**(9), 2662 (2012)
31. Y. Zhong, L.L. Shaw, M. F. Zawrah, J. Am. Ceram. Soc. **93**(10), 3159(2010)
32. J. Suri, L.L. Shaw, M.F. Zawrah, Ceram. Int. **37**, 3477 (2011)
33. J. Suri, L.L. Shaw, M.F. Zawrah, Tailoring the relative Si_3N_4 and SiC contents in Si_3N_4/SiC nanopowders through carbothermic reduction and nitridation of silica fume. Int. J. Appl. Ceram. Technol. **9**, 291–303 (2012). https://doi.org/10.1111/j.1744-7402.2011.02710.x
34. S.E. Abo Sawan, M.F. Zawrah, R.M.Khattab, A.A. Abdel-Shafi, Mater. Chem. Phys. **239**, 121998 (2020)
35. P.N. Lemougna, J. Yliniemi, E. Adesanya, P. Tanskanen, P. Kinnunen, J. Roning, M. Illikainen, Reuse of copper slag in high-strength building ceramics containing spodumene tailings as fluxing agent. Minerals Engineering **155**, 106448 (2020). https://doi.org/10.1016/j.mineng.2020.106448

36. P.N. Lemougna, J. Yliniemi, A. Ismailov, E. Levanen, P. Tanskanen, P. Kinnunen, J. Roning, M. Illikainen, Recycling lithium mine tailings in the production of low temperature (700–900 °C) ceramics: Effect of ladle slag and sodium compounds on the processing and final properties. Constr. Build. Mater. **221**, 332–344 (2019). https://doi.org/10.1016/j.conbuildmat.2019.06.078
37. L.L. Hench, J.M. Polak, Third-generation biomedical materials. Science **295**, 1014–1017 (2002). https://doi.org/10.1126/science.1067404
38. O.P. Kulik, Powder Metall. Met. Ceram. **38**, 93 (1999)
39. P. Greil, Advanced engineering ceramics. Adv. Mater. **14**, 709–715 (2002). https://doi.org/10.1002/1521-4095(20020517)14:10%3C709::AIDADMA709%3E3.0.CO;2-9
40. R. Riedel, E. Ionescu, I.W. Chen, in *Modern Trends in Advanced Ceramics*, ed. by R. Riedel, I.W. Chen, Cerem. Sci. and Tech. (Wiley-VCH, Weinheim, Germany, 2008), pp. 3–38
41. R.B. Heimann, in *Introduction to advanced ceramics*, ed. by R.B. Heimann, Classic and advanced ceramics: from fundamentals to applications, (Wiley-VCH Verlag GmbH, 2010), pp. 157-174.
42. M.F. Zawrah, R.A. Essawy, H.A. Zayed, A.H. Abdel Fattah, M.A. Taha, Mechanical alloying, sintering and characterization of Al_2O_3–20 wt%–Cu nanocomposite. Ceram. Int. 40, 31-38 (2014). Doi: https://doi.org/10.1016/j.ceramint.2013.05.099.
43. M.A. Taha, A.H. Nassar, M.F. Zawrah, In-situ formation of composite having hard outer layer based on aluminum dross reinforced by SiC and TiO_2. Constr. Build Mater. **248**, 118638 (2020). https://doi.org/10.1016/j.conbuildmat.2020.118638
44. M.A. Taha, M.F. Zawrah, Mechanical alloying and sintering of a Ni/10 wt.%Al_2O_3 nanocomposite and its characterization. Silicon 10, 1351-1359 (2018). https://doi.org/10.1007/s12633-017-9611-4.
45. M.F. Zawrah, M.A. Taha, H. Abo Mostafa, In-situ formation of Al_2O_3/Al core-shell from waste material. Ceram. Int. **44**, 10693–10699 (2018). https://doi.org/10.1016/j.ceramint.2018.03.101.
46. M.F. Zawrah, H.A. Zayed, R.A. Essawy, A.H. Nassar, M.A. Taha, Preparation by mechanical alloying, characterization and sintering of Cu–20 wt.% Al_2O_3 nanocomposites. Mater. Des. **46**, 485-490 (2013). https://doi.org/10.1016/j.matdes.2012.10.032.
47. M.F. Zawrah, H. Ahmed, N.E. El-Baly, Fabrication of Al_2O_3-20 vol% Al nanocomposite powder using high energy milling. Mater. Res. Bull. **47**, 655–661 (2012). https://doi.org/10.1016/j.materresbull.2011.12.023
48. M.M.S. Wahsh, R.M. Khattab, M.F. Zawrah, Sintering and technological properties of alumina/zirconia/nano TiO_2 ceramic composites. Mater. Res. Bull. **48**, 1411–1414 (2013). https://doi.org/10.1016/j.materresbull.2012.12.024
49. M.F. Zawrah, N.M. Khalil, High alumina castable reinforced with SiC. Adv. Appl. Ceram. **104**, 312–317 (2005). https://doi.org/10.1179/174367605X73498
50. M.A. Taha, A.H. Nassar, M.F. Zawrah, Improvement of wetability, sinterability, mechanical and electrical properties of Al_2O_3-Ni nanocomposites prepared by mechanical alloying. Ceram. Int. **43**, 3576–3582 (2017). https://doi.org/10.1016/j.ceramint.2016.11.194
51. M.A. Taha, M.F. Zawrah, Effect of nano ZrO_2 on strengthening and electrical properties prepared by mechanical alloying. Ceram. Int. **43**, 12698–12704 (2017). https://doi.org/10.1016/j.ceramint.2017.06.153
52. J. Silvestre, N. Silvestre, J. de Brito, An overview on the improvement of mechanical properties of ceramics nanocomposites. J. Nanomater. **2015**, 1–13 (2015). https://doi.org/10.1155/2015/106494
53. M.F. Zawrah, H. Abo Mostafa, M.A. Taha, Effect of SiC content on microstructure, mechanical and electrical properties of sintered Al-20Si-xSiC nanocomposites fabricated by mechanical alloying. Mater. Res. Express **6**, 1–11 (2019). https://doi.org/10.1088/2053-1591/ab534e
54. F.S. Moghanlou, M. Vajdi, H. Jafarzadeh, Z. Ahmadi, A. Motallebzadeh, F. Sharifianjazi, M.S. Asl, M. Mohammadi, Spark plasma sinterability and thermal diffusivity of TiN ceramics with graphene additive. Ceram. Int. https://doi.org/10.1016/j.ceramint.2020.12.152

55. M. Sakkaki, F. Sadegh Moghanlou, M. Vajdi, M. Shahedi Asl, M. Mohammadi, M. Shokouhimehr, Ceram. Int. **46**, 4998 (2020)
56. S. Nekahi, F. Sadegh Moghanlou, M. Vajdi, Z. Ahmadi, A. Motallebzadeh, M. Shahedi Asl, Microstructural, thermal and mechanical characterization of TiB_2–SiC composites doped with short carbon fibers, Int. J. Refract. Met. Hard Mater. **82**, 129–135 (2019). https://doi.org/10.1016/j.ijrmhm.2019.04.005
57. M. Vajdi, F. Sadegh Moghanlou, S. Nekahi, Z. Ahmadi, A. Motallebzadeh, H. Jafarzadeh, M. Shahedi Asl, Role of graphene nano-platelets on thermal conductivity and microstructure of TiB_2–SiC ceramics. Ceram. Int. **46**, 21775–21783 (2020). https://doi.org/10.1016/j.ceramint.2020.05.289
58. Stuart Hampshire, in *Materials Science Forum*, vol. 606 (Scientific.Net, 2009), pp. 27–41. https://doi.org/10.4028/www.scientific.net/MSF.606
59. R.W. Harrison, W.E. Lee, Processing and properties of ZrC, ZrN and ZrCN ceramics: a review. Adv. Appl. Ceram. **115**(5), 294–307 (2016). https://doi.org/10.1179/1743676115Y.0000000061
60. P. Karvankova, M.G.J. Veprek-Heijman, M.F. Zawrah, S. Veprek, Thin Solid Films **467**, 133 (2004)
61. M. F. Zawrah, M A Zayed and Moustafa R. K. Ali. J. Hazard. Mater. **227–228**, 250 (2012)
62. M. F. Zawrah, Adel B. Shehata , E. A. Kishar, Randa N. Yamani, Synthesis, hydration and sintering of calcium aluminate nanopowder for biomedical applications. Comptes Rendus Chim. **14**(6), 611–618 (2011). https://doi.org/10.1016/j.crci.2010.11.004
63. J.P. Vacanti, R. Langer, Tissue engineering: The design and fabrication of living replacement devices for surgical reconstruction and transplantation. The Lancet **354**, 32–34 (1999). https://doi.org/10.1016/S0140-6736(99)90247-7
64. J. Elisseeff, W. McIntosh, K. Fu, R. Blunk, R. Langer, Controlled-release of IGF-I and TGF-β1 in a photopolymerizing hydrogel for cartilage tissue engineering. J. Orthop. Res. **19**, 1098–1104 (2001). https://doi.org/10.1016/S0736-0266(01)00054-7
65. J.E. Babensee, L.V. McIntire, A.G. Mikos, Growth factor delivery for tissue engineering. Pharmaceut. Res. **17**(5), 497–504 (2000). https://doi.org/10.1023/a:1007502828372
66. D.F. Williams, On the mechanisms of biocompatibility. Biomaterials **29**, 2941–2953 (2008). https://doi.org/10.1016/j.biomaterials.2008.04.023
67. H.E. Jazayeri, M. Rodriguez-Romero, M. Razavi, M. Tahriri, K. Ganjawalla, M. Rasoulianboroujeni, M.H. Malekoshoaraie, K. Khoshroo, L. Tayebi, Ceram. Int. **44**, 1 (2018)
68. A.F. Black, F. Berthod, N. L'Heureux, L. Germain, F.A. Auger, In vitro reconstruction of a human capillary-like network in a tissue-engineered skin equivalent. FASEB J. **12**, 1331–1340 (1998). https://doi.org/10.1096/fasebj.12.13.1331
69. M. Marcacci, E. Kon, V. Moukhachev, A. Lavroukov, S. Kutepov, R. Quarto, M. Mastrogiacomo, R. Cancedda, Stem cells associated with macroporous bioceramics for long bone repair: 6- to 7-year outcome of a pilot clinical study. Tissue Eng. **13**, 947–955 (2007). https://doi.org/10.1089/ten.2006.0271
70. P.K. Valonen, F.T. Moutos, A. Kusanagi, M.G. Moretti, B.O. Diekman, J.F. Welter, A.I. Caplan, F. Guilak, L.E. Freed, In vitro generation of mechanically functional cartilage grafts based on adult human stem cells and 3-D-woven poly(e-caprolactone) scaffolds. Biomaterials **31**, 2193–2200 (2010). https://doi.org/10.1016/j.biomaterials.2009.11.092
71. M.N. Rahaman, J.J. Mao, Stem cell-based composite tissue constructs for regenerative medicine. Biotechnol. Bioeng. **91**, 261–284 (2005). https://doi.org/10.1002/bit.20292
72. A. Tathe, M. Ghodke, A.P. Nikalje, Int. J. Pharm Sci. **2**, 19 (2010)
73. N.R. Patel, P.P. Gohil, Int. J. Emerg. Technol. Adv. Eng. **2**(4), 91 (2012)
74. L.L. Hench, Bioceramics: from concept to clinic. J. Am. Ceram. Soc. **74**, 1487–1510 (1991). https://doi.org/10.1111/j.1151-2916.1991.tb07132.x
75. P. Palmero, Structural ceramic nanocomposites: a review of properties and powders' synthesis methods. Nanomaterials **5**, 656–696 (2015). https://doi.org/10.3390/nano5020656
76. J. Venkatesan, S.K. Kim, Nano-hydroxyapatite composite biomaterials for bone tissue engineering—a review. J. Biomed. Nanotechnol. **10**, 3124–3140 (2014). https://doi.org/10.1166/jbn.2014.1893

77. R.A. Youness, M.A. Taha, A.A. El-Kheshen, N. El-Faramawy, M. Ibrahim, In vitro bioactivity evaluation, antimicrobial behavior and mechanical properties of cerium-containing phosphate glasses. Mater. Res. Express **6**, 1–13 (2019). https://doi.org/10.1088/2053-1591/ab15b5
78. R.A. Youness, M.A. Taha, M. Ibrahim, A. El-Kheshen, FTIR spectral characterization, mechanical properties and antimicrobial properties of La-doped phosphate-based bioactive glasses. Silicon **10**, 1151–1159 (2018). https://doi.org/10.1007/s12633-017-9587-0
79. S.M. Abo-Naf, E.M. Khalil, E.M. El-Sayed, H.A. Zayed, R.A. Youness, In vitro bioactivity evaluation, mechanical properties and microstructural characterization of Na_2O-CaO-B_2O_3-P_2O_5 glasses. Spectrochim. Acta A **144**, 88–98 (2015). https://doi.org/10.1016/j.saa.2015.02.076
80. E.M.A. Khalil, R.A. Youness, M.S. Amer, M.A. Taha, Mechanical properties, in vitro and in vivo bioactivity assessment of Na_2O-CaO-P_2O_5-B_2O_3-SiO_2 glass-ceramics. Ceram. Int. **44**, 7867–7876 (2018). https://doi.org/10.1016/j.ceramint.2018.01.222
81. R.A. Youness, M.A. Taha, H. Elhaes, M. Ibrahim, Molecular modeling, FTIR spectral characterization and mechanical properties of carbonated-hydroxyapatite prepared by mechanochemical synthesis. Mater. Chem. Phys. **190**, 209–218 (2017). https://doi.org/10.1016/j.matchemphys.2017.01.004
82. R.A. Youness, M.A. Taha, H. Elhaes, M. Ibrahim, Preparation, Fourier transform infrared characterization and mechanical properties of hydroxyapatite nanopowders. J. Comput. Theor. Nanosci. **14**, 2409–2415 (2017). https://doi.org/10.1166/jctn.2017.6841
83. R.A. Youness, M.A. Taha, M.A. Ibrahim, Effect of sintering temperatures on the in vitro bioactivity, molecular structure and mechanical properties of titanium/carbonated hydroxyapatite nanobiocomposites. J. Mol. Struct. **1150**, 188–195 (2017). https://doi.org/10.1016/j.molstruc.2017.08.070
84. R.A. Youness, M.A. Taha, A.A. El-Kheshen, M. Ibrahim, Influence of the addition of carbonated hydroxyapatite and selenium dioxide on mechanical properties and in vitro bioactivity of borosilicate inert glass. Ceram. Int. **44**, 20677–20685 (2017). https://doi.org/10.1016/j.ceramint.2018.08.061
85. R.A. Youness, M.A. Taha, M.A. Ibrahim, In vitro bioactivity, molecular structure and mechanical properties of zirconia-carbonated hydroxyapatite nanobiocomposites sintered at different temperatures. Mater. Chem. Phys. **239**, 122011 (2020). https://doi.org/10.1016/j.matchemphys.2019.122011
86. R.A. Youness, M.A. Taha, M. Ibrahim, In vitro bioactivity, physical and mechanical properties of carbonated-fluoroapatite during mechanochemical synthesis. Ceram. Int. **44**, 21323–21329 (2018). https://doi.org/10.1016/j.ceramint.2018.08.184
87. A. Doostmohammadi, Z.K. Esfahani, A. Ardeshirylajimi, Z.R. Dehkordi, Zirconium modified calcium-silicate-based nanoceramics: An in vivo evaluation in a rabbit tibial defect model. Int. J. Appl. Ceram. Technol. **16**, 431–437 (2019). https://doi.org/10.1111/ijac.13076
88. A.M. Fayad, A.M. Fathi, A.A. El-Beih, M.A. Taha, S.A.M. Abdel-Hameed, Correlation between antimicrobial activity and bioactivity of Na-mica and Na-mica/fluorapatite glass and glass-ceramics and their corrosion protection of titanium in simulated body fluid. J. Mater. Eng. Perform. **28**, 5661–5673 (2019). https://doi.org/10.1007/s11665-019-04296-5
89. T. Kokubo, H.-M. Kim, A.M. Kawashita, in *Ceramics for Biomedical Applications*, ed. by S. Somiya, F. Aldinger, R. Spriggs, K. Uchino, K. Koumoto, M. Kaneno, Handbook of advanced ceramics (Elsevier, 2013), pp. 385–412
90. L.C. Gerhardt, A.R. Boccaccini, Bioactive glass and glass-ceramic scaffolds for bone tissue engineering. Materials **3**, 3867–3910 (2010). https://doi.org/10.3390/ma3073867
91. A. Refaat, R.A. Youness, M.A. Taha, M. Ibrahim, Effect of zinc oxide on the electronic properties of carbonated hydroxyapatite. J. Mol. Struct. **1147**, 148–154 (2017). https://doi.org/10.1016/j.molstruc.2017.06.091
92. Z. Huan, J. Chang, Study on physicochemical properties and in vitro bioactivity of tricalcium silicate-calcium carbonate composite bone cement. J. Mater. Sci. Mater. Med. **19**, 2913–2918 (2008). https://doi.org/10.1007/s10856-008-3423-4

93. F. Martínez-Vázquez, M. Cabañas, J. Paris, D. Lozano, M. Vallet-Regí, Fabrication of novel Si-doped hydroxyapatite/gelatin scaffolds by rapid prototyping for drug delivery and bone regeneration. Acta Biomater. **15**, 200–209 (2015). https://doi.org/10.1016/j.actbio.2014.12.021
94. D. Li, X. Huang, Y. Wu, J. Li, W. Cheng, J. He, H. Tian, Y. Huang, Biomater. Sci. **4**, 272 (2016)
95. S.Y. Wang, H.Z. Hu, X.C. Qing, Z.C. Zhang, Z.W. Shao, Recent advances of drug delivery nanocarriers in osteosarcoma treatment. J. Cancer **11**, 69–82 (2020). https://doi.org/10.7150/jca.36588
96. A. Barbanente, R.A. Nadar, L.D. Esposti, B. Palazzo, M. Lafisco, J.J.J.P. van den Beucken, S.C.G. Leeuwenburgh, N. Margiotta, J. Mater. Chem. B **8**, 2792 (2020)
97. H. Aghaei, A.A. Nourbakhsh, S. Karbasi, R. Javad Kalbasi, M. Rafienia, N. Nourbakhsh, S. Bonakdar, K.J. Mackenzie, Investigation on bioactivity and cytotoxicity of mesoporous nano-composite mcm-48/hydroxyapatite for ibuprofen drug delivery. Ceram. Int. **40**, 7355–7362 (2014). https://doi.org/10.1016/j.ceramint.2013.12.079
98. S. Bhaskar, M. Kumar, A. Patnaik, A review on tribological and mechanical properties of Al alloy composites. Mater. Today **25**, 810–815 (2020). https://doi.org/10.1016/j.matpr.2019.09.032
99. A. William, Jr Gooch, An overview of ceramic armor applications, 35TH International Conference and Exposition on Advanced Ceramics and Composites Daytona Beach, Fl 32118, 23-28 January 2011, 1-15 (2011).
100. B. Alemour, O. Badran, M.R. Hassan, A Review of using conductive composite materials in solving lightening strike and ice accumulation problems in aviation. J. Aerosp. Technol. Manag. **11**, 1–23 (2019). https://doi.org/10.5028/jatm.v11.1022
101. V. kumar, H. Vasudev, N. Kumar, Int. J. Manage. Technol. Eng. **IX**, 2308 (2019)
102. E. Salernitano, C. Migliaresi, J. Appl. Biomater. Biom. 1, 3 (2003)
103. H.L.W. Chan, K. Li, C.L. Choy, Electroceramic fibres and composites for intelligent apparel applications. Wearable Electron. Photonics, 41–58 (2005). https://doi.org/10.1533/9781845690441.41
104. N. Setter, R. Waser, Electroceramic materials. Acta Mater. **48**, 151–178 (2000). https://doi.org/10.1016/S1359-6454(99)00293-1
105. Y. He, B. Ping, L. Lu, F. Wang, S. Hu, Electrically conductive ceramic composites prepared with printer toner as the conductive phase. Adv. Appl. Ceram **116**, 158–164 (2017). https://doi.org/10.1080/17436753.2016.1278339
106. D.M. Smyth, in *Electrical conductivity in ceramics: a review*, ed. by J.A. Pask, A.G. Evans, Ceramic Microstructures ’86. Role of interfaces, vol. 21 (Plenum Press, New York and London, 1987), pp. 643–655
107. M.A. Ryan, J.P. Fleur, Where there is heat, there is a way. The Electrochem. Soc. Interface **30** (2002).
108. R.B. Heimann, *Plasma spray coating, principles and applications*, 2nd edn, (Wiley-VCH Verlag GmbH, Weinheim 2008), pp. 427
109. H. Henke, D. Adam, A. Köhler, R.B. Heimann, Development and testing of HVOF-sprayed tungsten carbide coatings applied to moulds for concrete roof tiles. Wear **256**, 81–87 (2004). https://doi.org/10.1016/s0043-1648(03)00348-x
110. S. Salman, R. Kose, L. Urtekin, F. Findik, An investigation of different ceramic coatings thermal properties. Mater. Des. **27**, 585–590 (2006). https://doi.org/10.1016/j.matdes.2004.12.010
111. Y. Adraider, Y.X. Pang, F. Nabhani, S.N. Hodgson, M.C. Sharp, A. Al-Waidh, Laser-induced deposition of alumina ceramic coating on stainless steel from dry thin films for surface modification. Ceram. Int. **40**, 6151–6156 (2014). https://doi.org/10.1016/j.ceramint.2013.11.067
112. Y. Adraider, S.N.B. Hodgson, M.C. Sharp, Z.Y. Zhang, F. Nabhani, A. Al–Waidh, Y.X. Pang, Structure characterization and mechanical properties of crystalline alumina coatings on stainless steel fabricated via sol-gel technology and fibre laser processing. J. Eur. Ceram. Soc. **32**, 4229–4240 (2012). https://doi.org/10.1016/j.jeurceramsoc.2012.07.012

113. K. Srinivasulu, V.S. Manisha, Int. J. Adv. Eng. Technol. **VII**, 126 (2016)
114. M.F. Zawrah, J. Schneider, K.-H. Zum Gahr **22**(2), 167 (2002)
115. M.F. Zawrah, J. Schneider and K-H Zum Gahr. J. Mater. Sci. Eng. A **332**(1–2), 167 (2002)
116. R. Pompe, Some recent promising developments in industrial application of advanced technical ceramics. Transact. Mater. Res. Soc. Japan B **19**, 709–718 (1994). https://doi.org/10.1016/B978-1-4832-8382-1.50156-7
117. N.L. Wang, X.Y. Zhang, H.T. Jiang, T.T. Dong, D. Yang, Fabrication of $Er^{3+/}Yb^{3+}$ co-doped Y_2O_3 transparent ceramics by solid-state reaction method and its up-conversion luminescence. Mater. Chem. Phys. **135**(2012), 709–713 (2012). https://doi.org/10.1016/j.matchemphys.2012.05.048
118. S. Arabgari, R. Malekfar, K. Motamedi, Parameters effects on the surface morphology and structure of Nd:YAG nanopowders synthesized by co-precipitation method. J. Nanoparticle Res. **13**, 597–611 (2011). https://doi.org/10.1007/s11051-010-0055-7
119. X.B. Ji, J.G. Deng, B. Kang, H. Huang, X. Wang, W. Jing, T. Xu, Thermal decomposition of $Y_3Al_5O_{12}$ precursor synthesized by urea homogenous co-precipitation. J. Anal. Appl. Pyrolysis **104**, 361–365 (2013). https://doi.org/10.1016/j.jaap.2013.06.012
120. K. Guo, H.-H. Chen, X. Guo, X.X. Yang, F.F. Xu, J.T. Zhao, Morphology investigation of yttrium aluminum garnet nano-powders prepared by a sol-gel combustion method. J. Alloys. Compd. **500**, 34–38 (2010). https://doi.org/10.1016/j.jallcom.2010.03.037
121. J. Su, J.H. Miao, L.H. Xu, Y.Q. Ji, C.Q. Wang, Synthesis and characterization of nanocrystalline Nd^{3+}-doped gadolinium scandium aluminum garnet powders by a gel-combustion method. Mater. Res. Bull. **47**, 1709–1712 (2012). https://doi.org/10.1016/j.materresbull.2012.03.039
122. B.T. Huang, Y.Q. Ma, S.B. Qian, D. Zou, G.H. Zheng, Z.X. Dai, Luminescent properties of low-temperature-hydrothermally-synthesized and post-treated YAG:Ce (5%) phosphors. Opt. Mater. **36**, 1561–1565 (2014). https://doi.org/10.1016/j.optmat.2014.04.025
123. Y.H. Sang, H.M. Qin, H. Liu, L.L. Zhao, Y.N. Wang, H.D. Jiang, J.Y. Wang, Partial wet route for YAG powders synthesis leading to transparent ceramic: a core-shell solid-state reaction process. J. Eur. Ceram. Soc. **33**, 2617–2623 (2013). https://doi.org/10.1016/j.jeurceramsoc.2013.04.009
124. C.C. Barry, M.N. Grant, *Ceramic Materials, Science and Engineering*, 1st edn. (New York, NY, Springer, 2013)
125. D. Eliche-Quesada, L. Pérez-Villarejo, P.J. Sánchez-Soto, in *Introduction to ceramic materials: synthesis, characterization, applications and recycling*, ed. by J. Cuppoletti, Ceramic materials: synthesis, characterization, applications and recycling (Intech Open, 2019), pp. 1–5
126. C.H. Leong, A. Muchtar, C.Y. Tan, M. Razali, N.F. Amat, Sintering of hydroxyapatite/yttria stabilized zirconia nanocomposites under nitrogen gas for dental materials. Adv. Mater Sci. Eng. **2014**, 1–6 (2014). https://doi.org/10.1155/2014/367267
127. E. Champion, Sintering of calcium phosphate bioceramics. Acta Biomater. **9**, 5855–5875 (2013). https://doi.org/10.1016/j.actbio.2012.11.029
128. F.J.T. Lin, L.C. De Jonghe, Microstructure refinement of sintered alumina by a two-step sintering technique. J. Am. Ceram. Soc. **80**, 2269–2277 (1997). https://doi.org/10.1111/j.1151-2916.1997.tb03117.x
129. T.-S. Yeh, M.D. Sacks, Low-temperature sintering of aluminum oxide. J. Am. Ceram. Soc. **71**, 841–844 (1988). https://doi.org/10.1111/j.1151-2916.1988.tb07533.x
130. X. Kuang, G. Carotenuto, L. Nicolais, Adv. Perform. Mater. **4**, 257 (1997)
131. Z. He, J. Ma, Grain growth rate constant of hot-pressed alumina ceramics. Mater. Lett. **44**, 14–18 (2000). https://doi.org/10.1016/S0167-577X(99)00289-X
132. L. Gao, J.S. Hong, H. Miyamoto, D.D.L. Torre, Bending strength and micro- structure of Al_2O_3 ceramics densified by spark plasma sintering. J. Eur. Ceram. Soc. **20**, 2149–2152 (2000). https://doi.org/10.1016/S0955-2219(00)00086-8
133. N.J. Lóh, L. Simão, C.A. Faller, A.N. Jr, O.R.K. Montedo, A review of two-step sintering for ceramics. Ceram. Int. **42**, 12556-12572 (2016). https://doi.org/10.1016/j.ceramint.2016.05.065

134. M. Prakasam, J. Locs, K. Salma-Ancane, D. Loca, A. Largeteau, L. Berzina-Cimdina, Biodegradable materials and metallic implants-a review. J. Funct. Biomater. **8**, 1–15 (2017). https://doi.org/10.3390/jfb8040044
135. M.A. Taha, G.M. Elkomy, H. Abo Mostafa, E. Gouda, Effect of ZrO_2 contents and ageing times on mechanical and electrical properties of Al-4.5 wt.% Cu nanocomposites prepared by mechanical alloying. Mater. Chem. Phys. **206**, 116–123 (2018). https://doi.org/10.1016/j.matchemphys.2017.11.058
136. . M.A. Taha, A.H. Nassar, M.F. Zawrah, Effect of milling parameters on sinterability, mechanical properties of Cu-4 wt.% ZrO_2 nanocomposite. Mater. Chem. Phys. **181**, 26–32 (2016). Doi:https://doi.org/10.1016/j.matchemphys.2016.06.030
137. G.S. Upadhyaya, *Powder Metallurgy Technology*, 1st edn. (Camridge International Publishing 2002), p. 68
138. M.-Y. Chu, L.C. De Jonghe, M.K.F. Lin, F.J.T. Lin, Precoarsening to improve microstructure and sintering of powder compacts. J. Am. Ceram. Soc. **74**, 2902–2911 (1991). https://doi.org/10.1111/j.1151-2916.1991.tb06861.x
139. X.-H. Wang, P.-L. Chen, I.-W. Chen, Two step sintering of ceramics with constant grain-size, I. Y_2O_3, J. Am. Ceram. Soc. **89**, 431–437 (2006). https://doi.org/10.1111/j.1551-2916.2005.00763.x
140. S. Chakraborty, P.K. Das, D. Ghosh, Rev. Adv. Mater. Sci. **44**, 182 (2016)
141. M. Suárez, A. Fernández, J.L. Menéndez, R. Torrecillas, H.U. Kessel, J. Hennicke, R. Kirchner, T. Kessel, in Challenges and Opportunities for Spark Plasma Sintering: A Key Technology for a New Generation of Materials, Sintering Applications (In Tech, 2013), p. 319. https://doi.org/10.5772/53706
142. S. Bose, S. Dasgupta, S. Tarafder, A. Bandyopadhyay, Microwave-processed nanocrystalline hydroxyapatite: simultaneous enhancement of mechanical and biological properties. Acta Biomater. **6**, 3782–3790 (2010). https://doi.org/10.1016/j.actbio.2010.03.016
143. K.E. Haque, Microwave energy for mineral treatment processes-a brief review. Int. J. Miner. Process **57**, 1–24 (1999). https://doi.org/10.1016/S0301-7516(99)00009-5
144. N.K. Tolochko, Mechanisms of selective laser sintering and heat transfer in Ti powder. Rapid Prototyping J. **9**, 314–326 (2003). https://doi.org/10.1108/13552540310502211
145. T. Ikegami, J.G. Li, T. Mori, Y. Moriyoshi, Fabrication of transparent yttria ceramics by the low-temperature synthesis of yttium hydroxide. J. Am. Ceram. Soc. **85**, 1725–1729 (2002). https://doi.org/10.1111/j.1151-2916.2002.tb00342
146. Z. Xiao, S. Yu, Y. Li, S. Ruan, L.B. Kong, Q. Huang, Z. Huang, K. Zhou, H. Su, Z. Yao, W. Que, Y. Liu, T. Zhang, J. Wang, P. Liu, D. Shen, M. Allix, J. Zhang, D. Tang, Materials development and potential applications of transparent ceramics: a review. Mater. Sci. Eng. R **139**, 100518 (2020). https://doi.org/10.1016/j.mser.2019.100518
147. J. Zdeněk, A. Evelyn, C. Bolaňos, H. Monika, J. Petr, in *Physical and Metallurgical Characteristics of Fiber Reinforced Ceramic Matrix Composites*, ed. by C. Sikalidis, Advances in ceramics-characterization, raw materials, processing, properties, degradation and healing, (Intech Open, 2011), pp. 281–298
148. X.L. Zhao, Ceramics **102**, 3 (1993)
149. L.K. Zeng, G.Y. Zhang, Chin. J. Mater. Res. **8**(3), 245 (1994)
150. J.H Jeong, K.H. Auh, Modelling. Simul. Sci. Eng. **8**, 541 (2000)
151. B. Lin, F. Liu, X. Zhang, L. Liu, X. Zhu, in *Numerical simulations-applications, examples and theory*, ed. by L. Angermann. (Intech Open, 2010), pp. 401–414
152. H. Le Ferrand, Magnetic slip casting for dense and textured ceramics: a review of current achievements and issues. J. Eur. Ceram. Soc. 41, 24–37 (2021). https://doi.org/10.1016/j.jeurceramsoc.2020.08.030
153. A. De Zanet, V. Casalegno, M. Salvo, Laser surface texturing of ceramics and ceramic composite materials – a review. Ceram. Int. (2020). https://doi.org/10.1016/j.ceramint.2020.11.146
154. T.H. Maiman, Stimulated optical radiation in ruby. Nature **187**, 493–494 (1960). https://doi.org/10.1038/187493a0

155. M.F. Zawrah, J. Schneider, K.-H. Zum Gahr, Mater. Sci. Eng. A **332**, 167 (2002)
156. S. Grasso, M. Biesuz, L. Zoli, G. Taveri, A.I. Duff,D. Ke, A. Jiang, M.J. Reece, A review of cold sintering processes. Adv. Appl. Ceram. (2020). https://doi.org/10.1080/17436753.2019.1706825
157. European Comission, *Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry* (2007), pp. 210–211
158. M. Cologna, B. Rashkova, R. Raj, Flash sintering of nanograin zirconia in <5 s at 850°C. J. Am. Ceram. Soc. **93**, 3556–3559 (2010). https://doi.org/10.1111/j.1551-2916.2010.04089.x
159. S. Ghosh, A.H. Chokshi, P. Lee, R. Raj, A huge effect of weak dc electrical fields on grain growth in zirconia. J. Am. Ceram. Soc. **92**, 1856–1859 (2009). https://doi.org/10.1111/j.1551-2916.2009.03102.x
160. Z. Chen, Z. Li, J. Li, C. Liu, C. Lao, Y. Fu, C. Liu, Y. Li, P. Wang, Y. He, 3D printing of ceramics: a review. J. Eur. Ceram. Soc. **39**, 661–687 (2019). https://doi.org/10.1016/j.jeurceramsoc.2018.11.013
161. L. Marcus, J.J. Beaman, J.W. Barlow, D.L. Bourell, Solid freeform fabrication-powder processing. Am. Ceram. Soc. Bull. **69**(6), 1030–1031 (1990)
162. E. Sachs, M. Cima, J. Cornie, Three-dimensional printing: rapid tooling and prototypes directly from a CAD model. CIRP Ann. Manuf. Technol. **39**(1), 201–204 (1990). https://doi.org/10.1016/S0007-8506(07)61035-X
163. T. Ohji, M. Fukushima. Mater. Rev. **57**(2), 115 (2012)
164. E.C. Hammel, O.L.-R. Ighodaro, O.I. Okoli, Processing and properties of advanced porous ceramics: an application based review. Ceram. Int. **40** (10), 15351–15370 (2014). https://doi.org/10.1016/j.ceramint.2014.06.095
165. M.A. Keane, Ceramics for catalysis. J. Mater. Sci. **38**, 4661–4675 (2003)
166. K. Usami, A. Okamoto, Hydroxyapatite: catalyst for a one-pot pentose formation. Org. Biomol. Chem. **15**, 8888–8893 (2017). https://doi.org/10.1039/c7ob02051a
167. S. ben Moussa, A. Mehri, B. Badraoui, Magnesium modified calcium hydroxyapatite: an efficient and recyclable catalyst for the one-pot Biginelli condensation. J. Mol. Struct. **1200**, 127111 (2020). https://doi.org/10.1016/j.molstruc.2019.127111
168. D. Milovac, I. Weigand, M. Kovacic, M. Ivankovic, H. Ivankovic, Highly porous hydroxyapatite derived from cuttlefish bone as TiO2 catalyst support. Process. Appl. Ceram. **12**(2), 136–142 (2018). https://doi.org/10.2298/PAC1802136M
169. S.C. Oh, J. Xu, D.T. Tran, B. Liu, D. Liu, Effects of controlled crystalline surface of hydroxyapatite on methane oxidation reactions. ACS Catal. **8**(5), 4493–4507 (2018). https://doi.org/10.1021/acscatal.7b04011
170. M. Shokouhimehr, S.M.G. Yek, M. Nasrollahzadeh, A. Kim, R.S. Varma, Palladium nanocatalysts on hydroxyapatite: green oxidation of alcohol and reduction of nitroarenes in water. Appl. Sci. **9**, 1–12 (2019). https://doi.org/10.3390/app9194183
171. J. Xu, T. White, P. Li, C. He, Y.F. Han, Hydroxyapatite foam as a catalyst for formaldehyde combustion at room temperature. J. Am. Chem. Soc. **132**(38), 13172–13173 (2010). https://doi.org/10.1021/ja1058923
172. https://www.ceramicindustry.com/ceramic-materials-properties-charts/. Accessed January 1, 2020