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# Introductory Chapter: Ceramic Materials - Synthesis, Characterization, Applications and Recycling

*Dolores Eliche-Quesada, Luis Pérez-Villarejo and Pedro José Sánchez-Soto*

## 1. Introduction

Ceramic materials can be defined as inorganic materials constituted by the combination of metallic and nonmetallic elements whose properties depend on the way in which these elements are linked [1, 2]. Ceramic materials are the most versatile branch of materials. The origin of this versatility lies in the chemical nature of its bonds, since they are mainly constituted by strong ionic and covalent bonds in different proportions. The bonds determine a series of particular properties of ceramic materials among which are relatively high fusion temperatures, high modulus, high wear strength, poor thermal properties, high hardness and fragilities combined with tenacities, and low ductility. In addition to the lack of conduction electrons since they are combined forming chemical bonds, they are good electrical insulators.

Ceramic materials can be divided into two large groups: traditional ceramics and technical or advanced ceramics. Traditional ceramics can be defined as those that are based on silicates, among which are cement, clay products, and refractories. Traditional ceramics are produced in large volumes and constitute an important market. Traditional ceramic materials are made with raw materials from natural deposits such as clay materials. The second group, technical or advanced ceramics, is manufactured with artificial raw materials that have undergone an important chemical processing to achieve a high purity and an improvement of their physical characteristics. Therefore, they are manufactured with more advanced and sophisticated methods. Among them are carbides, nitrides, borides, pure oxides, and a great variety of ceramics with magnetic, ferroelectric, piezoelectric, and superconducting applications, among others. These ceramics possess excellent mechanical properties under extreme conditions of tension, high wear strength or excellent electrical, magnetic, or optical properties, or exceptional strength to high temperatures and corrosive environments, showing high strength to chemical attack [3]. There is a third group that is glasses that, although considered ceramic, are studied separately because they differ from the first group in the order reached by their crystalline structures as glass-ceramics.

The versatility mentioned above also allows ceramics to be used for a large number of end user and applications for the construction and building industry such as clay bricks and blocks, sanitary ware, and wall and floor tiles; in household

goods like tableware (porcelain), cooking ware (glass-ceramics), or pottery; in industrial processing and manufacturing industry for refractories, filters, or cutting tools; or high technology applications as components for solid oxide fuel cells, nuclear ceramics as combustion elements ( $\text{UO}_2$ ), coating reactors ( $\text{AlN-SiC}$ ), and ceramic batteries. Due to their electrical properties, they can be useful as capacitors ( $\text{BaTiO}_3$ ), high transition temperature superconductors ( $\text{YBa}_2\text{Cu}_2\text{O}_7$ ), piezoelectric and ferroelectric, insulators, varistors ( $\text{ZnO}$ ), and integrated circuit substrates. Due to their optical properties, they are used as infrared windows and construction of lasers and high-pressure sodium lamps. For its magnetic properties, the ceramic materials belonging to the family called ferrites stand out. They are usually grouped into two large groups: soft ferrites (spinel and garnets) and hard ferrites (hexaferrites), such as barium hexaferrite, spinel ferrites of Mn-Zn, or Ni-Zn ferrites doped with ruthenium or lanthanides that have a high saturation magnetization value and that have applications for permanent magnets, colored pigments, and electronics (such as interference suppressors, electronic amplifiers, or power inductors) or applications in microwave devices. Due to their hardness, they find utility in applications where abrasion properties such as those exhibited by silicon carbide or tungsten carbide ( $\text{WC}$ ) are required, as well as for cutting tool applications. They can also be used in the defense field as armors or ballistic. On the other hand, many of them are biocompatible and can be used in the health field as 20 ceramic prostheses, dental implants, coatings for tissue ingrowth, access and fixation devices, etc. [4, 5].

One of the most important limitations of ceramic materials in structural applications is the fragility, due to the fact they tend to fracture in a fragile way with hardly any absorption of energy, besides they lack capacity for plastic deformation, especially under traction. This fragility to the fracture can be explained to a great extent due to the presence (something almost impossible to eliminate totally in this type of materials) of defects in the material that intensifies the same, being the ceramic materials much more resistant to compressive forces than to tension forces. This behavior is a consequence of the difficulty of movement of the dislocations by the ceramic structures, even at high temperatures. However, one of the uses that is currently increasing is the structural components that improve the mechanical properties. These uses require materials with high strength in various environmental conditions, capable of withstanding high temperatures and resistant to corrosion and oxidation. In addition, ceramic materials offer a substantial reduction in weight compared to other materials such as metals.

Manufacturing of the ceramic components involves the synthesis of the powder, mixing, shaping, and thermal treatment in which the sintering takes place either by diffusion in solid state or by formation of intergranular-liquid phase [6]. Ceramic powders are obtained either from the treatment of natural raw materials (rock minerals) or through synthetic routes such as sol-gel, self-propagated synthesis at high temperature (SHS), precipitation, etc. Generally the ceramic powders obtained from minerals are going to be used in traditional ceramics, while the particulate systems obtained by synthesis routes will have greater application in advanced ceramics, where the control of impurities and defects is more important in the final application of the piece, since it requires an exhaustive control of the purity of the raw materials and their final microstructure. The starting materials for traditional ceramics need previous processes for the elimination of impurities and the reproducible method to obtain a powder that can be shaped and sintered to obtain a piece. On the other hand, advanced ceramics use high-purity products as starting powders, obtained mostly by synthetic routes. The routes of obtaining ceramic materials are very varied, but the synthetically produced powders have common characteristics, such as high purity, uniform particle size distribution, high specific

surface area, absence of hard agglomerates or aggregates that cannot be broken by grinding, and greater uniformity in the characteristics.

The shaping is the stage of processing by which a ceramic powder, duly prepared by washing processes, homogenization, etc. is compacted and conferred into a desired shape with high porosity and poor mechanical properties. The main existing forming processes are axial and isostatic dry pressing, porous mold or tape molding, or extrusion or injection molding. Each of these forming processes are used depending on the type of piece to be obtained and the time and costs in the production systems. The objective of the forming processes is generally to achieve high particle packing and low porosity (which will be partially or totally eliminated during the sintering process). The packaging, in addition to having a high number of coordination, should be as homogeneous as possible to avoid microstructural defects, which will mean a decrease in the properties of the final material. To do this, a series of parameters must be controlled, such as the particle size and its distribution, the level of agglomeration, and the flow of the powder during the forming process. There are other nontraditional methods for obtaining green parts that do not start from the ceramic powder or that after forming require some type of treatment before sintering, such as the sol-gel method, hot pressed (axial and isostatic), SHS, deposition of molten particles, and deposition in vapor phase (CVD) [5].

Once the green piece is obtained with the desired shape, before the densification of the material, it is necessary to proceed with the drying and the elimination of organics. In the drying step, the solvent used is removed by means of transport and evaporation in an unsaturated gaseous medium. In wet-formed materials, the solvent evaporates after shaping. If left unchecked it can generate defects and break the piece due to two main causes, namely, rapid generation of solvent gases and different contractions in the material. The shrinkage of the piece during drying occurs due to the removal of the liquid between the particles of the shaped material. This should be as uniform as possible, since differences in the contraction generate stresses that produce cracks in the material. The control in the drying of the green piece is done in controlled atmosphere and temperature chambers. In the organic elimination stage, the organic compounds used during the processing are progressively eliminated from the outside to the inside, so that the greater the thickness of the piece obtained, the more difficult it is to eliminate it. The processes of elimination of organic additives are: evaporation, chemical extraction with solvents, catalytic extraction, or thermal decomposition.

Finally the sintering process takes place, in which the compacted material, in green, is subjected to a sufficiently high temperature so that the phenomena of mass transport to the interstices between particles take place and compact densification occurs. As the sintering progresses, the porous phase becomes discontinuous and is eliminated, leaving only the remaining pores occluded in the matrix of ceramic material and that cannot be eliminated. The initial density of the piece in green is usually 40–60% of the theoretical density, while the final density is 85–100%. Sintering can take place through three mechanisms: sintering in solid state, sintering in the presence of a liquid phase, and reactive sintering.

On the other hand, due to the fact that ceramic materials do not corrode, their useful life periods are often much greater than those of other materials. However, the same physical properties that make ceramics so durable also make them extremely difficult to recycle, with the exception of glass. Although recycling is difficult, there are ways to “revalue” them, that is, new uses can be given to certain waste. Thus, ceramic materials (bricks), concrete and bituminous pavements, can be used for the manufacture of secondary products, such as the production of

aggregates, which in turn can be used to manufacture concrete or serve as direct bases for road works.

In addition, the ceramic or cement industry has manufacturing processes that make the recovery of waste especially feasible [7–9], either taking advantage of the calorific power coming from the combustion or incorporating the waste into the internal structure of the materials, forming part of its own matrix and becoming an inert element.

Therefore, it can be concluded that ceramic materials have a great versatility of applications, because they have very characteristic properties that cannot be obtained from any other material.

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