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Ceramics in Dentistry

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Abstract

Ceramics have been used widely used as restorative materials in dentistry because of their chemical stability, excellent mechanical properties, and superior biocompatibility. The utilization of ceramic materials in dentistry has increased with the evolution of new manufacturing processes and innovative materials. However, there are many challenges concerning their performance and design processing. Thus, the control of the manufacturing processes is required in order to achieve the suitable mechanical properties. Additive manufacturing (3D printing) is a very promising technology mainly used for the fabrication of 3D parts, with complex geometries, for biomedical applications. In this paper, the latest research progress on the applications of nanoceramics in dentistry field was reviewed.

Keywords: Nanomaterials; Ceramics; Dentistry; Dental Prosthesis; Composites; Manufacturing; 3D Printing

Abbreviations: AM: Additive Manufacturing; CAD/CAD: Computer Aided Design and Computer Aided Manufacturing; ZAT: Zirconia-Toughened Alumina; RPD: Removable Partial Dentures; HIP: Hot Isostatic Pressing.

Introduction

Nano ceramics or ceramic nanoparticles are a ceramic materials fabricated from nano sized particles. Dental ceramics are generally called inorganic and non-metallic structures principally involving compounds of oxygen with one or additional metallic or semi-metallic elements such as magnesium, silicon, zirconium, lithium, aluminum, etc [1].

Nowadays, ceramics have a significant potential in the biomedical applications because their biocompatibility and high strength and wear resistance. However, ceramic materials are commonly utilized for manufacturing crowns, bridges, denture, models, veneers, and implants with metal as their substructure [2]. Additive manufacturing (AM), also known as 3D printing technology, is a powerful process for producing components by adding materials layer by layer from a 3D digital model [3]. Thus, 3D printing process consists of five stages: acquisition of 3D model (physical or digital), creating design file by using CAD software, preparing for printing, 3D printing, and post processing. Digital dentistry is one of the rapidly areas of the AM technologies [4]. This new technology allows manufacturing pieces of all types of materials such as polymers, metals, composites, ceramics, and materials of biological origin [5]. However, the available literature concerning AM of ceramics constitutes less than 5 % of the all AM published works.

Computer aided design and computer aided manufacturing (CAD/CAM) methods are mainly used for creating 3D complex models in medicine and dentistry. This technique is also known as subtractive manufacturing (SM), which make it possible to obtain dental pieces with desired properties. Several research works have been developed to improve the properties of ceramics, which have many industrial applications such as electronic, aerospace, biomedical, etc.

Although ceramic materials (such as alumina, zirconia, and glass ceramics) have several advantages, they also have some disadvantages. In fact, the advantages and disadvantages of dental ceramic are summarized in Table 1.

Advantages	Disadvantages
Suitable color	Low ductility
High strength	Low brittleness
High hardness	Low tensile strength
Low electrical conductivity	Low fracture toughness
Low thermal conductivity	Poor optical properties
Good biocompatibility	Require specialized equipment
Chemical durability	Cost
Good esthetics	Technique sensitive

Table 1: Advantages and disadvantages of dental ceramic materials.

The main aim of this current review is to provide a detailed description of the results of latest research progress regarding the fabrication of nanostructured ceramics applied in the field of dentistry.

Properties of Dental Ceramics

Ceramic materials are chemically inert in oral cavity and show good aesthetics and biocompatibility. The mechanical and physical properties of dental ceramics are presented in Table 2. In fact, the strength was related to the presence of surface ingredients of the materials. The properties of these materials are strongly dependent on several factors including the particle size, nature, and coefficient of crystalline phases.

Properties	Value
Shear strength (MPa)	110
Compressive strength (MPa)	330
Transverse strength (MPa)	62-90
Tensile strength (MPa)	34
Modulus of Elasticity (GPa)	69
Hardness (KHN)	460
Thermal diffusivity (mm2/s)	263
Thermal conductivity (Cal/s/cm2)	0.003
Coefficient of thermal expansion (/°C)	12.10-6
Specific gravity (gm/cm3)	2.2-2.3

Table 2: Physical and mechanical properties of dental ceramics [6].

Processing Techniques for Fabricating Dental Ceramics

Several processing methods are developed for fabricating ceramic materials in the field of dentistry.

Casting

This technique is based on the solidification of a fluid that has been poured or injected into a mold. The final product is also known as a casting. Thus, casting process consists of three steps: melting, casting, and recovery. Zhou, et al. [7] studied the effects of the rare earth element lanthanum on the metal-ceramic bond strength of Co-Cr alloys prepared by casting. XRD and SEM results revealed the presence of dendritic microstructures with some defects and an island shaped intermetallic compounds rich in Cr and Mo. Atwood, et al. [8] modeled the surface contamination of dental titanium produced by casting. They concluded that the contamination of the wedge sample was established to extended range from 30 to 120 mm. They concluded that the addition of micro- and nano-models revealed the predictions are shown to be in good agreement for the pattern of contamination.

Sintering

Sintering is a heat treatment under pressure applied to a powders compact without melting. The final product is a solid or porous mass with desired properties. Fan, et al. [9] investigated the effect of mechanical properties and sintering temperature on the microstructure of dental zirconia-toughened alumina (ZTA). They concluded that the properties of ZTA ceramic depend on sintering temperature. By increasing temperature, they concluded that the mechanical properties of the samples were improved, the crystal structure of ZrO_2 was changed, and the porosity was decreased. However, the ceramics sintered at 1450°C showed greatest fracture toughness (5.23 $MPa.m^{1/2}$) and also greatest flexural strength (348 MPa). In addition, Ghayebloo, et al. [10] reveled that it is possible to fabricate ZLS glass-ceramics by sintering at 350 °C. The results showed a highest flexural strength of 255.10±15.44 MPa, a fracture toughness of 3.15±0.62 $MPa.m^{1/2}$, a Vickers microhardness of 7.96±0.13 GPa, and a bulk density of 2.63±0.02 g/cm^3.

Partial Sintering

Partial sintering is considered as the most straightforward processing route for macro-porous scaffolds and involves the partial sintering of initially porous powder compacts. A homogenous although closed pore structure can be produced when sintering is terminated before full densification [11]. The pore size and porosity are controlled by the size of the powder particles and the degree of partial sintering, and the size of the raw powder should generally be 2-5 times larger than the desired pore size. Several works have been done on fabrication of ceramics by partial sintering apply for dentistry. Chen, et al. [12] studied the properties of YB_2C_2 ceramics prepared by partial sintering. The results exhibited a high porosity (57.17-75.26 %) and a high compressive strength (9.32-34.78 MPa). Jeana, et al. [13] prepared alumina powder agglomerates by partial sintering. They showed that the final product was characterized by a hierarchical porous network that can contain three levels of interconnected pores: the voids existing between the agglomerates (≥10 μm in size), the porosity remaining inside the agglomerates after partial sintering (100-1000 nm in size), and the pores that may exist within the initial ceramic particles (less than 100 nm in size).

Glass Infiltration

The glass infiltration processing is a powerful technique for the fabrication of ceramic/glass composite with exceptional mechanical properties and low shrinkage. Kocjan, et al. [14] prepared porous Y-TZP nanostructured ceramics, with hierarchical heterogeneities, by partial sintering from meso-porous powder. They showed that the obtained products have a crystallite sizes between 34 and 71 nm for relative densities in the range of 54-81.7 %. They also revealed a surface area of 18 m^2/g, a thermal conductivity of 0.63-1.88 $W.m^{-1}.K^{-1}$, an elastic modulus of 32-156 GPa, and a strength in the range of 70 -540 MPa.

Yang, et al. [15] investigated the effects of process parameters and material characteristics in glass infiltration of gel cast ZTA ceramic for dental applications. They showed that the strength of the obtained ceramic was 291 MPa and the shrinkage was 1.8548 %. Manuel, et al. [16] fabricated biocomposites by infiltrating porous alumina-titania (Al_2O_3-TiO_2) substrates with a lanthania-rich (La_2O_3) glass. Al_2O_3-TiO_2 substrates were fabricated using high energy milled powder mixtures of two different compositions. The sintered substrates presented α-Al_2O_3 and β-Al_2TiO_5 as crystal phases and relative densities in the range of 65.5 ± 2 - 69.4±1.2 %. The obtained products were then infiltrated by lanthania containing glass at 1140 °C for 2 hours. These ceramics revealed a fracture toughness up to 2.6 $MPa.m^{1/2}$, a fracture strength in the order of 218 -254 MPa, a high density of 94-99 %, and a Vickers hardness in the order of 895-1036 HV. Nevertheless, phase identification of the samples by XRD indicated the decomposition of aluminium titanate into alumina and titania besides the formation of lanthanum borosilicate. Moreover, all the compositions presented low chemical solubility (less than 75 $\mu g/cm^2$) and non-cytotoxic behavior.

Slip Casting

Slip was a dispersion of particles of ceramic powders in a liquid like water. The pH of water was then regulated to the desired value to charged particles. Kim, et al. [17] fabricated dense zirconia compacts by slip casting and sintering from zirconia nanopowders. Thus, the green compacts obtained from slip casting were cold isostatic pressed to enhance the close packing and densified by sintering for 2 hours at 1450°C. Highly dense zirconia compacts with a relative density of 99.5 % and grain size of 350 nm were obtained. The microstructure and mechanical properties of the sintered specimen after slip casting were dependent on the yttria content in the 3 mol% yttria-stabilized tetragonal zirconia polycrystal powder and the solid loading within the slurry.

Kim DS, et al. [18] prepared dental zirconia implants by sintering process. They showed that the zirconia blocks have many surface cracks that lead to the deterioration of mechanical strength and the failure of the implant in the body. Thus, highly dense 3Y-TZP samples with a relative density of 99 % and grain size of 200-400 nm were obtained at a solid loading of 50-65 wt%. Alageel, et al. [19] prepared removable partial dentures (RPD) cobalt-chromium alloys using casting process. Thus, new additive manufacturing processes based on laser-sintering has been developed for quick fabrication of RPD metal frameworks at low cost. All Co-Cr alloys exhibited smaller grain size, higher microstructural homogeneity, and low porosity. Laser sintered alloys are more precise and present better mechanical and fatigue properties than cast alloys.

Hot Isostatic Pressing

Hot isostatic pressing (HIP) has been used successfully by manufacturers around the world to increase productivity. This technique was used to eliminate pores and remove casting defects to dramatically increase the material properties. Gionea, et al. [20] produced zirconia powders by HIP at 500°C for 2 h. The results showed that a pure cubic phase, with average particle dimension about 70 nm, was obtained. Thus, the obtained samples presented a mixture of monoclinic-tetragonal or monoclinic-cubic phases. Final dense ceramic materials (density of 94 %) were achieved. ZrO_2-CaO ceramics have high biocompatibility and excellent mechanical properties characterized by strength of 500-708 MPa and Young's modulus of 1739-4372 MPa.

Similarly, Hu, et al. [21] synthesized tetragonal zirconia polycrystalline (3Y-TZP) ceramics by HIP. The grain size of the final products reached about 138 nm. This fine grain size leads to an increase in Vickers hardness to achieve 13.79 MPa. These materials also revealed an elevated transmittance (76-78 %). The result revealed that HIP was an effective process to prepare infrared-transparent 3Y-TZP ceramics with small grain size and with good optical and mechanical properties. Klimke, et al. [22] fabricated ZrO_2 nanostructured ceramics via HIP process. They demonstrated that the particle size was less than 50 nm and the maximum in-line transmission was about 77 %, which observed at IR wavelengths of 3-5 μm.

Computer-Aided Design/Computer-Assisted Manufacture (Cad/Cam) Technology

CAD/CAM method is a powerful tool to improve the design and creation of dental restorations [23]. Leucite-reinforced glass-ceramics involve Authentic and Empress CAD. Both have the identical microstructure and containing feldspathic glass with about 45 wt%. These blocks may characterize utilizing external strains and containing finer leucite crystals (~5-10 µm in size). Hence, the strength behavior of Empress CAD was comparable with Vitablocs. Dental CAD/CAM technology has been used to replace the laborious and time consuming, conventional lost wax technique for efficient fabrication of restorations [24]. This technology enables dentists to produce complex shapes of ceramics.

Typically, CAD/CAM dental restorations are milled from solid blocks of ceramic or composite resin that closely match the basic shade of the restored tooth. Metal alloys including zirconia can also be milled. The software sends this data to a milling machine where the prosthesis was milled [25]. Thus, CAD/CAM complements earlier technologies employed for these goals by enhancing the speed of design and creation, making affordable restorations, reducing unit coast, etc. Nevertheless, chair-side CAD/CAM equipment requires more time on the part of the dentists, and the fee was much higher than conventional restorative treatments.

During the period 2015-2018, the data of 21 patients undergoing fibula free flap reconstructive surgery with CAD/CAM patient-specific reconstruction plates were analyzed, including the applicability of the virtual plan, flap survival, duration of surgery, ischemia time, simultaneous dental implantation, implant exposure, and postoperative complications [26].

Additionally, Okada, et al. [27] fabricated composite crowns using four computer aided design/computer aided manufacturing (CAD/CAM) blanks composed of a resins (named S1) and a lithium disilicate (named S 2), which exhibited distinct tendencies. The results revealed that the flexural strength was in the range of 175 to 247 MPa for S1 and 360 MPa for S2 while the fracture strength was in the range of 3.3 to 3.9 kN for S1 and 3.3 kN for S2, respectively.

Classification of Dental Ceramics

Ceramic dental materials can be divided in four categories. The diagram illustrates the major type of ceramic materials used in dentistry (Figure 1).

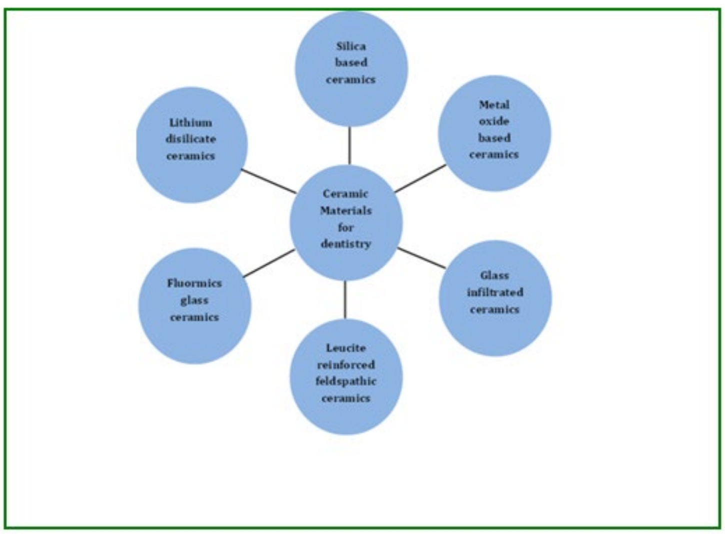

Figure 1: The diagram of the major types of ceramics used in dentistry.

Metal Ceramics

Metal ceramics were dental restorations materials utilized in dental prosthesis. A strong bond must exist between the metal and ceramic, which was capable to withstand the interfacial shear stress caused during manufacturing because of the firing shrinkage of porcelain and to the difference of the coefficient of thermal expansion [28]. There are a number of studies that have been developed concerning the fabrication of these restorations by a number of methods. Campbell, et al. [29] studied the etiology of thermal cycling distortion in metal ceramic alloys. They showed that the heat treatment of the samples led to a remarkable reduction in the thermal cycling distortion. Additionally, Dehoff, et al. [30] investigated the effect of metal design on distribution of residual stresses and metal displacements of metal ceramic crowns. They concluded that the calculated marginal distortions depend strongly on the metal-porcelain combination.

Reinforced Ceramics Core Systems

Reinforced ceramics core systems can be classified into various classes involving high density alumina core, high density zirconia core, alumina-reinforced core, and glass-infiltrated high strength ceramic core.
Kou, et al. [31] studied the surface roughness of five different dental ceramic core materials (Vita In-Ceram Alumina, Vita In-Ceram Zirconia, IPS Empress 2, Procera All-Ceram, and Denzir) after grinding and polishing. They revealed that the surface roughness of the samples Denzir, IPS Empress 2 and In-Ceram Zirconia decreased after polishing compared with after grinding.

Moreover, Al_2O_3/ZrO_2 nanocomposites ceramics were fabricated from the densification of Y_2O_3-stabilized ZrO_2 (10-15 wt%) and Al_2O_3 nanopowders [32]. The results showed that ZrO_2 particles inhibit the densification and delay the matrix alumina grain growth. In addition, the toughness and strength of the samples were 10 $MPa.m^{1/2}$ and 1000 MPa, respectively. Additionally, Ardlin, et al. [33] showed that strength of zirconia was not influenced by aging while the crystalline structure and surface were influenced. Zhang, et al. [34] revealed that the good translucency of the new zirconia ceramics has been reached by microstructural changes, addition of cubic zirconia, and reduce in the amount of defects and impurities.

Resin Bonded Ceramics

Resin bonded ceramics are defined as a full coverage restoration in which an all ceramic crown is bonded to the underlying dentine using a resin bonded with the bond being by using of a micro-mechanically ceramic surface and a dentine bonding system [35]. Derand, et al. [36] studied different surface treatments and resin cements. They revealed that auto-polymerizing resin cement showed the remarkably elevated bond strengths nevertheless of surface treatment. Kern, et al. [37] showed that alone phosphate modified resin cement Panavia 21, after airborne particle abrasion (110 μm Al_2O_3 under 2.5 bar), furnished a durable resin bond to zirconia ceramic. Kramer, et al. [38] investigated the adhesive luting of high strength ceramics restorations. They showed that auto-polymerizing resin cements have fixed setting times and indicated for resin bonding metal based of opaque.

Additionally, Hahn, et al. [39] concluded a remarkably less micro-leakage at the interface of composite when high viscous in place of low viscous resin cements were employed for cementation of ceramic inlays. Chung, et al. [40] studied the shear bond strengths of two resin-modified glass ionomer cements to porcelain. They revealed that the resin-modified glass ionomer cements showed bond strength to etched and silanated silica based ceramics comparable to the composite cements.

Glass Ceramics

Glass ceramics are polycrystalline materials used for dental restorations, which have the same chemical composition as glasses. In the last decades, these materials have attracted great interests from the citizen science community. Glass ceramics are highly interesting for patients and dentists due to their good chemical and physical properties, low thermal conductivity, good biocompatibility, wear resistance, and chemical stability [41,42]. However, there are two manufacturing processes of glass ceramics: (i) the melting-casting-annealing process and (ii) the sinter-crystallization process.

Chenu, et al. [43] prepared glass ceramic by ceramming process. The TEM results revealed that the microstructure of the obtained product exhibit nanoscale phase separation, with the existence of spherical droplets distributed uniformly in the matrix. Similarly, Qin, et al. [44] fabricated a novel glass ceramic, incorporated by calcium mica, by exchange of sodium or potassium ions for calcium ions. They showed that the material exhibited a good machinability. Hence, the microstructure was randomly orientated mica crystals and the strength was 210±14.7 MPa.

Conclusion

Future advances in dentistry have been considered to be dependent on the advancement of material sciences and materials processing technologies. Ceramic materials have been playing a major role in innovation and clinical technological advancements in dentistry. In this paper, the latest research progress on the applications of ceramics in the field of dentistry was provided, which plainly exhibits that several properties of these materials can be enhanced by adding suitable nanomaterials or by the reduction of their size into nanoscale.

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