Review—A Conceptual Analysis on Ceramic Materials Used for Dental Practices: Manufacturing Techniques and Microstructure

Sumanth Ratna. Kandavalli,[1,z] Sunanda Ratna. Kandavalli,[2] Rajesh S. Ruban,[3] Chih Hung Lo,[4] Ravinder Kumar,[5] Abou Bakr Elshalakany,[6] and Catalin I. Pruncu[7,8,z]

[1]Department of Mechanical Engineering, Tandon School of Engineering, New York University, Brooklyn, New York 11201, USA

[2]Department of Electronics and Communication Engineering, Sri Padmavati MahilaVisvavidyalayam, Tirupati Pincode-517502, India

[3]Department of Mechanical Engineering, Karunya Institute of Technology and Sciences, Coimbatore, Tamil Nadu Pincode – 641114, India

[4]Lee Kong Chian School of Medicine, Nanyang Technological University, Singapore 308232, Singapore

[5]School of Mechanical Engineering, Lovely Professional University, Phagwara-144411 India

[6]Production Engineering and Printing Technology Department, Akhbar El Yom Academy, Giza, Egypt

[7]Design, Manufacturing & Engineering Management, University of Strathclyde, Glasgow, G1 1XJ, Scotland, UK

[8]Department of Mechanical Engineering, Imperial College London, London, United Kingdom

[z]E-mail: c.pruncu@imperial.ac.uk; catalin.pruncu@strath.ac.uk; princeratna2017@gmail.com

Abstract: In the era of biomaterials evolution, ceramic materials are playing a notable role in dental practices. Ceramics have been used in dental applications for several decades because of its important properties such as suitable biological incorporation into human body, surface colouration, enhanced surface morphology, mechanical characteristics, physiochemical integration, durability and lifespan. There are numerous complications in the fabrication and production of ceramics by manufacturers. Therefore, many research and development has been performed to further improve and understand the manufacturing mechanism that occurs on the ceramic materials. These efforts are not only able to improve the fundamental understanding of the material but also help to meet the customer satisfaction and quality of production. This review article mainly provides an insight of various ceramic materials with a focus on their properties including stability, strength, and heat resistance. It is corroborated with a detailed account of various ceramic fabrication processing techniques with their applications that include sol-gel casting, hot pressing and phase inversion methods. In summary, some critical suggestions as well as detailed scope of future aspects and frontiers have been outlined to provide robust improvements for research and development platforms.

1. Introduction

The use of ceramics in dental practice has been implemented since the beginning of the 18th century [1]. There are various types of ceramics such as glass ceramics, ceramic composites and bioactive glasses. Ceramics become the best approach in dental practice, due to its reliable precision and cost-effective benefits. All ceramic materials demonstrate a significant potential in engineering applications and high industrial manufacturing capacity due to their excellent biomechanical properties, reliability, antibacterial activity in ceramic glasses, ability to help in healing, restoration, and easy tissue integration. Tissue incorporation continues to be the most important process in surgical techniques and post-treatment effects. Ceramics are desirable for dental clinics and new therapeutic improvements as they possess advantageous properties including excellent esthetic appeal, coloration, low thermal resistance, adequate durability, corrosion resistance, high strength, and high stability. In comparison with the behavior of the inorganic materials, which appear to have structural strength and patterns of antibacterial interaction in medical practice, organic materials show satisfactory compositional enhancement, high microstructure strength, mechanical responsiveness, structural integrity and patterns of antibacterial interaction in tissue engineering [2]–[4]. The ceramic materials are made of precursor powders including metal oxides, hydroxides, carbonates, which are more suitable for large scale production. Ceramics are mechanically solid and brittle, and have the elasticity behavior within the internal bone/implanted area. Ceramic glasses are non-crystalline substances or solid materials that neglect the precision strike alignment, structures and interact perfectly with the surface morphology of the component [5]–[7]. They have symmetrical crystalline structure, including a crystalline cubic structure [8]. Glass-ceramics are preferred for medical implants and restorative dentistry because of their natural appearance and their advantageous properties. Multi-phase dental ceramics also comprise a glass network and a crystalline phase up to 45%, all such dental materials are notably classified as feldspathic, lithium di-silicates, and mica. In these glass-ceramics, feldspathic porcelains are extensively used due to its availability and strength which can be manufactured by laboratory sintered and industrially prefabricated blocks. The structural and physical effects of dental feldspathic porcelain tend to be the worst of ceramics used in dental practice, because Feldspar porcelain is completely leucite-dependent, and porcelain fused to metal crowns, full ceramic crowns, may suffer from progressively decreasing occlusal height reduction as well as unexpected porcelain crack formations in oral cavity after occlusal interactions [9],[10]. There are two types of classifications of glass ceramics in restorative dentistry, including non-metallic and metal-supported [11],[12]. Implantable ceramic materials such as alumina and zirconium dioxide are mostly used because of their mechanical properties, viability, feasibility as well as the ease of production for industrial manufacturers. This explains the frequent use of these materials in Artificial Femoral Head Replacement and Acetabular cups [13],[14]. Replacing various replacements of dental metals with ceramic materials is currently a major challenge for the dental practice, as cosmetic considerations are of particular concerns [15]–[18]. Zirconia is used primarily in dental practices, and also it can be used in industrial productions, which allow massive benefit for manufacturers due to its increased strength, durability, and porosity as well as being non-toxic. [19],[20]. In the case of restorative dentistry, by martensitic development, Yttria-stabilized tetragonal zirconia polycrystalline continues to produce maximum tensile strength and durability than most ceramic materials [21],[22]. The mechanical characteristics of Zirconia are well known among all other metals, as their texture appears to be remarkably similar to the texture of the teeth [23]. Zirconia has a fracturing propensity rate similar to titanium components and also a low Phlogistic reaction same as titanium as well as other restorative materials [24],[25]. The microstructures of Zirconia are much finer, which does not affect the flexural yield strength, and the final color is often limited to a white color. Technological innovation appears to be the coloring method that allows for a wide range of esthetic consequences [26]–[28]. In experimental findings, researchers found that Zirconia shows a reduction in strength after grinding [29]. In restorative dental practices, Zirconia polished or roughened surfaces by polishing or glazing have demonstrated reduced wear of enamel in oral environment [30]–[32]. Glass ceramics and bioactive glasses are found to be interesting research fields due to their cost efficient for industrial manufacturing. Bioactive implants are always preferred and used for main tissue medical practice due to their mechanical and physical properties, while the characteristics of interfacial interactions and connective tissue interactions are positive approach within the implanted area [33]–[39]. Bioactive glasses are being used in biomedical studies from very past 19th century [40]. It may respond to the physical interface layer while embedding into the body part, which creates a close chemical reaction to bone tissue. After long-term implantation, biological apatite is transformed into bone, as this apatite enhances cell adherence and osteogenic cell proliferation [41]–[44]. The antimicrobial activity is compatible with the development of a glass surface layer and it has high biocompatibility similar to bone strength. Bioactive glasses can be placed directly in the area of defect, followed by surface ion-exchange interactions, as well as biochemical fluids throughout the area, which contribute to the formation of a bone-like apatite surface layer. Bioactive glasses and some crystal-structured ceramics, including HA and TCP, appear to be highly biocompatible and bone-bound, but no interaction between fibrous tissues [45]–[47]. Bioactive glasses with enhanced heat treatment showed a crystallized phase with enhanced physical and mechanical properties compared to normal ceramic glasses, while glass-ceramics have showed crystalline phases in the amorphous matrix. [50]–[53]. The requirement of the engineered product is assessed based on crack formation or deformation, but also based on its integration/incorporation techniques [54],[55]. The data for bio glasses and different ceramic materials is presented in Materials (section 2). Ceramic materials/glasses can act as nanoparticle reinforcements that can be used in dental practice, bone tissue engineering for porosity, and heavy scaffolding in clinical dentistry [56]–[59]. In the year 1953, Li–alumina silicates and Mg–Alumina silicates have been developed for dental practices. Sintered ceramics for tough dental implants using computer-aided design (CAD) or computer-aided manufacturing (CAM) processing operations that require feldspar, leucite and lithium-di silicate ceramics, which are the strongest and toughest ceramic materials [60]–[63]. Lastly, the manufacturing techniques are discussed with their detailed parameters. As in most similar sectors, the theoretical foundations for restorative dentistry are gradually increasing. In addition to the fact that the cost of producing dental research projects becomes a major determinant in clinical practice as well as in medical treatments, computerization production may allow for more efficient outputs. The various fabrication techniques include Tape Casting, Gel Casting (direct foaming), Slip Casting, Sol-gel Casting, Hot Pressing, Extrusion Process, Phase Inversion Method. Conventional methods such as gel-casting techniques were used in past decades. Other significant techniques have been introduced in the recent years such as 3D printing techniques like 3D Binder based printing technique, Selective Laser Melting technique, Stereo-lithography technique, Powder bed fusion, Vat photo-polymerization, Material jetting, Material extrusion, Sheet lamination, Binder jetting, Electro-phoretic deposition, Electro-photographic printing, Fused Deposition Modelling technique, direct inkjet printing, and Additive manufacturing technologies have been used to construct dental implant structures employing various innovative techniques [63]–[65]. These techniques have attracted researchers to do more research and industrialists to invest more in its production due to its various characteristics such as reliability, viability, less-time more production, mechanical properties, ecological efficient andbeing cost-effective for industrial processes. They allow the enhancement of the design potential with solutions that are feasible and sustainable through these approaches. Crystallization plays a critical role during the production process of multi-functional ceramic materials, synchronizing their surface interface, restore ability, antimicrobial properties, and also cytotoxicity. Facilitated design and enhancement of the crystalline structure of ceramics proves to be an essential component of the adaptability of medical treatment. Also some investigations have been conducted to achieve accurate bio ceramic glass coatings using a variety of methods, including enamel coating, magnetron sputtering, laser adhesive, and heat treatment[70]–[72].

This review focuses on dental ceramic materials and manufacturing processes; hence the work provides a comprehensive review of the past, the current state of the art of ceramic glasses for dental applications, materials used during manufacturing processes, mechanical properties, biocompatibility and also outlines important research focuses that can be used in the years to come. This review also presents an in-depth sight of parameters with various experimental findings of these techniques. Furthermore, this review paper gives an overview of the most common challenges and current status in the use of lasers for surface texturing of zirconia-based ceramics for dental applications, such as texturing of zirconia implants to improve osseointegration, texturing of zirconia abutments to reduce peri-implant inflammation, and texturing of zirconia restorations to improve bonding retention[389].

2. Classification of ceramic materials and their history

The term ceramic material was originated from the greek word called "Keramicos," first ceramics has been produced from China in the year 1700BC-1027 BC of Shang dynasty period, which are called high-fired glazed ceramics, but later on it came into existence which can be utilized by common man in the 13^{th} -17^{th} BC. In detail Ceramics are classified into 3 types they are earthenware, stoneware and porcelain, which can be made from a type of form of clay [73]–[97]. Due to its compositional bond formation, integration and incorporation, etc., that demonstrated significant characteristics of its thermal conductivity, feasibility, viability, light-in-weight, durability because of all these attractive listings, it found researcher interest. **Figure 1** provides classification of the Materials and Ceramics, specifically in dental practices in which the ceramics have demonstrated good mechanical properties. It was noted that the ceramic materials have been used as an alternative for implant materials in restorative dentistry. Oxidative stress is the primary reason for this. Mostly, porcelain will be preferred, high-tech-engineered-quantitative ceramics can even be called high-quality ceramic materials. They are essentially crystalline structured components for real practice development and produced from specially formulated and categorized materials that generate precisely predefined significant characteristics [73], [74], [76], [85]. Current generation ceramics may include borides, oxides, nitrates, silicates, carbides, which are used because of its implementing behaviour of the removal of metal ions and allergic reactions which are feasible. Formulation of ceramic materials usually involves in the heat treatment of ceramic powder particles, which require considerable processing for to stabilize the variability of the ceramics, material composition, hardness, particle size, particle distribution, surface morphology, and specific crystalline structure. Certain features have a crucial role to play in the characteristics of the final ceramics. In practice, it is quite simple to distinguish between final ceramics derived from typical materials and perfectly synthesized materials. Various ceramics materials like Magnesium (Mg), Silicon (Si), Calcium (Ca), Iron (Fe), Cobalt (Co), Copper (Cu), Zinc (Zn), Gallium (Ga), Strontium (Sr), Niobium (Nb), Silver (Ag) are being used as dental materials [73]–[97]. Enhanced ceramic glasses are also preferred as high-performance ceramics, competent ceramics, attenuated ceramics that provide crystal structure, with absolute manufacturing regulations for well-characterized ceramic materials. Most-recent ceramics are carbides, borides, oxides, nitrides, silicates which includes and other various types of ceramics also available in the market [73], [74], [85]. **Figure 2** provides a list of ceramics availability in the market. Modern ceramics which includes chemical proportions, particles arrangement, homogeneity, heterogeneity, and particle size distribution, The deep and depth insight about bio glasses also various types of bio glass systems including the SiO_2-CaO-P_2O_5-Ag_2O [98], P_2O_5-CaO-Na_2O-Ag_2O [99], B_2O_3-Na_2O-P_2O_5-Ag_2O [100], SiO_2-Ag [101], Ag_2O-B_2O_3-SiO_2-CaO [102], SiO_2-CaO-P_2O_5-Al_2O_3-Na_2O-K_2O-Ag_2O [103], CaO-SiO_2-Ag_2O [104], CaO-Na_2O-P_2O_5-Ga_2O-Ag_2O + Ag-Zn [105], Ceramic doped with Ag-Zn [106], SiO_2-CaO-P_2O_5-Ce [107], Na_2O-CaO-P_2O_5-Cu [108], bioactive glass S53P4 [109], 45S5 Bio-glass [110], MgB_2 ceramics [111], SiO_2-Zn NPs [112], SiO-SrO-CaF_2-MgO [113], SiO_2-B_2O_3-Na_2O-MgO/SrO[114], Na_2O-MgO-CaO-B_2O_3-P_2O_3-SiO_2/K_2O/Al_2O_3[115], Na_2O-K_2O-MgO-CaO-P_2O_3-SiO_2[115], Na_2O-K_2O-MgO-CaO-B_2O_3-P_2O_3-SiO_2[116], P_2O_5-CaO-Na_2O [99], SiO_2-P_2O_5-CaO-Na_2O-SrO [117], SiO_2-B_2O_3-Na_2O-CaO-K_2O-Al_2O_3[118], SiO_2-CaO-Na_2O-K_2O-P_2O_5/MgO[119], SiO_2-Na_2O-CaO-P_2O_5-Al_2O_3 Fe_2O/B_2O_3/K_2O/MgO[120], SiO_2-Na_2O-CaO-B_2O_3/K_2O-Al_2O_3[121] is provided. When the real ceramic materials which are commonly used in dental implants like, Aluminum tri-Oxide or Aluminum has been discussed; Alumina is the first ceramic material to be used in ceramic industry production. The entire material shown is substantial Osseo integration, but does not have sufficient mechanical characteristics [122],[123]. The particle arrangement, uniformity, homogeneity, distribution of particles, etc., play a vital role in the properties of ceramic glasses, most likely Aluminum / Silicon dioxide, which can be produced by non-oxidative ceramics as well as various synthetic techniques. In most cases, the reactive solid-state reaction is ultimately used because of its lower cost in the industrial production of low molecular and organic or inorganic precursors. The liquid state can be used in the manufacture of analogous fine powders by means of a co-precipitation technique that also includes hydrothermal synthesis, and the gas state can also be used to synthesize ultra-fine powder. Various binary ceramic oxides, such as Silicon dioxide or Alumina, are produced using non-oxidative ceramics, even when natural materials and more sophisticated oxides are extracted using complex manufacturing techniques. Ceramics including calcium phosphate, tri-calcium phosphate, tetra-calcium phosphate, alumina, silica, and zirconia have been investigated for clinical applications such as dental implants. Nano-materials such as calcium phosphate have been used in a wide range of dental ceramics and can be used in various biomedical applications, including concrete and adhesives in dental implants. One of the critical limitations of Titanium is plaque improvement which could results in the development of bacterial concerns [124], [125]. An experimental study with one-decade life span of a ceramic study has found that Yttria partially stabilized tetragonal zirconia polycrystal and is a material with the highest quality of mechanical and physical properties as well as fracture stress in comparison with other ceramic materials [126].

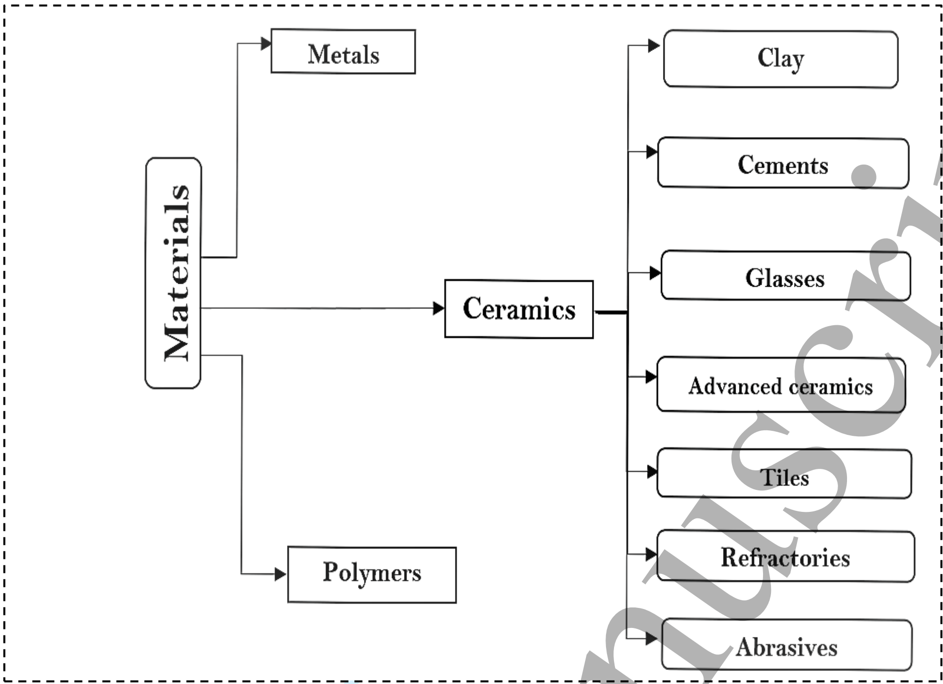

Figure 1. Classification of the Materials and Ceramics

TCP -Tri-calcium phosphate	**TiN -Titanium nitride**
BN -Boron nitride	**Ti_3SiC_2 -Titanium Silicon Carbide Powder**
B_4C -Boron carbide	**TiB_2 -Titanium di-boride**
SnO_2 -Tin(IV) oxide; stannic oxide	**TiO_2 -Titanium dioxide**
GaN -gallium nitride	**AlN -Aluminum nitride**
CdS -cadmium sulfide	**Al_2O_3 -Aluminum oxide; Alumina**
MoS_2 -Molybdenum disulfide	**Al_2TiO_5 -Aluxminum titanium oxide**
WO_3 -Tungsten(VI) oxide; tungsten trioxide; tungstic anhydride	**$MgAl_2O_4$ -Spinel Powder; Magnesium aluminum oxide**
V_2O_5 -Vanadium pentoxide	**$Mg_2Al_4Si_5O_{18}$ – Cordierite**
ITO -Indium Tin Oxide	**$MgTiO_3$ -Magnesium titanium trioxide**
Cu_2O -copper (I) oxide; cuprous oxide	**$MgTi_2O_5$ -Magnesium di-titanate**
CuO -copper(II) oxide; cupric oxide	**$ZnTiO_3$ -Zinc titanate; zinc titanium oxide**
Cu_2S -Copper(I) sulfide	**$CaTiO_3$ -Calcium titanium oxide**
$YBa_2Cu_3O_{7-\delta}$ -Yttrium barium copper oxide	**$SrTiO_3$ -Strontium titanate**
TiC -Titanium carbide	**SIALON -Silicon aluminiumoxynitride**
TiCN -Titanium Carbo-Nitride; Carbo-Nitride	**$BaTiO_3$ -Barium Titanate**
$PbTiO_3$ -Lead titanate	**ZrO_2 -Zirconium dioxide**
$BiFeO_3$ -Bismuth ferrite	**ZrB_2 -Zirconium diboride**
$LiNbO_3$ -Lithium niobium trioxide	**ZrC -Zirconium carbide**
$ZrSiO_4$ -Zirconium silicate	**$Ca_3ZrSi_2O_9$ -Calcium zirconium silicate; Baghdadite**
ZrW_2O_8 -Zirconium tungstate	**SiO_2 -Silicon dioxide**

SiC -Silicon carbide	**SiOC -Silicon Oxycarbide**
Si_3N_4 -Silicon nitride	**BaO -Barium oxide**
MgALON -Magnesium aluminium oxynitride	**MgO - Magnesium oxide**
BeO -Beryllium oxide	**NiO -Nickel oxide**
MnO -Manganese(II) oxide	**ZnO- Zinc oxide**
CoO -Cobalt(II) oxide	**$LaCrO_3$ -Lanthanum Chromite**
LaB_6 - Lanthanum Hexaboride	**$LiCoO_3$ -Lithium cobalt(III) oxide**
$LiTaO_3$ -Lithium tantalite	**Y_2O_3 -Yttrium oxide**
Co_2O_3 -Cobalt oxide	**Er_2O_3-Erbium oxide**
Nd_2O_3 -Neodymium(III) oxide	**$Ca_7Si_2P_2O_{16}$ - (Nagelschmidtite)**
HAP - (Hydroxyapatite)	**$BaAl_2Si_2O_8$ - (Barium aluminosilicate)**
3Y-TZP - (tetragonal zirconia polycrystal)	**[(Si_3N_4)–hBN] – (Silicon nitride-hexagonal boron nitride)**
GDC-NiO - (Gadolinium doped ceria- Nickel(II) oxide)	**Y-TZP - (yttrium tetragonal zirconia polycrystal)**
CCTO - (Calcium copper titanate)	**$Li_2O_5Si_2$ - (Lithium di-silicate)**
BN-SiO_2 - (Boron nitride- Silicon dioxide)	**$CaSiO_3$ - (Wollastonite)**
Ca_2SiO_4 - (Di-calcium silicate)	**$CaMgSiO_4$ - (Monticellite)**
Mg_2SiO_4 - (Di-magnesium silicate)	**$Ca_2MgSi_2O_7$ - (Akermanite)**
$Ca_3MgSi_2O_8$ - (Merwinite)	**(Sr,Ca)SiO_3- (Hardystonite)**
$Ca_7MgSi_4O_{16}$ - (Bredigite)	**Zn_2SiO_4 - (Zinc silicate)**
$Ca_5P_2SiO_{12}$ - (Silicocarnotite)	**Mg-PSZ - (Magnesia partially –stabilized)**
K[$AlSi_2O_6$] - (Leucite)	**$Mg_2Al_4Si_5O_{18}$ - (Magnesium –Aluminosilicate)**
ZTA/ZrO-Al_2O_3 - (Zirconia Toughened Alumina)	**$BaAl_2Si_2O_8$ - (Barium aluminosilicate)**
$Sc_2W_3O_{12}$ - (Tungsten acid scandium)	**α-Al_2O_3 - (alpha - Alumina)**
3YTZP - (yttria-stabilized tetragonal zirconia polycrystalline)	**Al_2TiO_5 - (Aluminiumtitanate)**
Al_2O_3*TiO_2 - (Aluminum titanate)	**PFM - (Porcelain-fused-to-metal)**
γ- Al_2O_3 - (Gamma-alumina)	**CNT - (carbon nanotube)**
HCA - (hydroxyl carbonated apatite)	**YSZ - (Yttria-stabilized zirconia)**

Figure 2. The list of ceramics availability in the market

3. Fabrication of dental-ceramics

The preparation of ceramics will play a significant role in dental applications. Fabrication of engineered ceramic materials will cover common phases, including the heating phase of powder particles, which can be treated precisely to regulate consistency, chemical characteristics, durability, and industrial production quality. Because of massive interest in the research community and frequently the use of material properties in bioengineering processes is growing rapidly. Dental practices are being facilitated in the development and implementation of new ceramic materials. Ceramic materials used in dentistry have a variety of beneficial physical characteristics such as biocompatibility, buildability, poor thermal conductivity, wear resistance, or color sustainability. Ceramic material processing is carried out using a number of methods and techniques. Fabrication techniques of bio-ceramics has attracted research interests and various techniques are used to reduce the porosity of the ceramic and increase the durability and surface coatings property. Ceramic products can traditionally be designed in a variety of geometric shapes, such as porous fibers, pipes, disks, various frame works. The preparation, refining, sintering, and finishing of different ceramics can be made in various phases/routes. Nanomaterials, which are widely used for the restoration or replacement of lost parts, are classified as three categories: metals, ceramics and polymers.

Nanomaterials which demonstrates certain characteristics, including stiffness-strength, durability, toughness and microbial effect to its implementations. Dental ceramics have always been categorized by the temperature range, the various types of dental ceramics are fusing, medium fusing, low fusing, and extremely low fusing approach. The thermal treatment methods utilized, including the solid-state process, appear to be easy to manufacture with cost-effective ceramic materials. Consequently, glass-nanomaterials are being manufactured by a conventional molten metal-quench or sol-gel methods, in which a range of compounds can also be combined to solidified like glass [127], [128]. These were alternative approaches to the manufacture of ceramic materials and structures, including Tape Casting, Gel Casting (direct foaming), Slip Casting, Sol-gel Casting, Hot Pressing, Extrusion Process.The flowchart of **Figure 3** lists the major techniques which are discussed in the paper. Phase Inversion Method and 3D printing technology has become fully configurable innovation technologies and transformative approaches to porous ceramic production [129], [130]. In order to enhance the production of high-purity ceramic structures with significant properties, certain technological advances, such as polymer pyrolysis, sol-gel methodology and chemical vapor deposition, are injected into a heated reaction chamber in a relatively low molecular and volatile state where a solid reaction product is produced but also extracted as a clear amorphous product. The two significant advantages of the use of massively processed ceramics produced by Sol-Gel are the lower grain size, including lower sintering costs. The production of ceramic material could be configured into a number of geometric shapes, such as fibers, canals and flat surfaces. Pressurization and depressurization processes can be considered for the purpose of intercepting stress reduction damage which can be manufactured in four distinct phases, they are preparation of materials, refining, sintering and finishing. For fabrication of the dental ceramic materials, various techniques will be employed such as Wet-foaming, gel-casting, freeze casting, thixotropic-casting and phase inversion methods. Wet foaming technique has shown significant shape complexity, pessimistic drying / binder removal effects due to cracking phase, drying time and also drying cost, fine particles in order to improve sintering techniques. Gel casting (Dry-foaming) technique is also one of the best promising techniques in the production of ceramic-glasses, consisting of uniaxial die pressing and cold isostatic pressing, as well as no requirement for dry precursors. Tape casting technique is one of the new trends and has proved versatile nature in manufacturing the thin and thick film components. It has been introduced in 1940s and classified in two types i.e., aqueous and non-aqueous casting [131],[132]. Slip casting technique is most frequently used advanced technology for ceramics that allows consistent microstructure in casted part (porous space) porosity and enhanced dispersion of ceramics [133]–[135]. Powder injection molding becomes the premier technique, which integrates polymer-binders, waxes with amorphous ceramics. Extrusion is also an effective selection in which the ceramic mixture is extruded through a die and produces semi-infinite objects with such a specified cross-section, rather than injection molding, which also includes various techniques such as blending, mixing, sintering, and drying. The Diamond Anvil Cell (DAC) technique can also be used to fabricate high-pressure ceramics [136],[137]. Lower liquid originates less precision of the mold filling, which needs high forming pressure, and drying also helps to reduce cracking failure, while increasing the size of the substance also increases the risk of cracking failure. The sintering operation is performed by combining the inter-connective bonding of all ceramic particles when heat treatment with the primary objective is actually to achieve a dimensionally accurate dense product. The interactive compositional bonding that develops a pre-existing bond within the component with its sintered particles will be the same. Sintering techniques including solid-state sintering, pressure-less technique and also liquid-phase sintering technique are employed in the ceramic industry. Various non-conventional techniques used in manufacturing processes like Field Assisted Sintering, Microwave sintering and Spark plasma sintering. Manufacturing of nanoparticles will result in enhanced mechanical properties, including the ultimate tensile strength and the ultimate porous aspects. However, several improvements in engineering and science have been made. Traditional production techniques still have problems, developing interconnected porosity, inadequate elimination of excess particles within these polymers, uneven pore size, inadequate porous integration and poor configuration, including issues of reduced reproducibility, and also more time in manufacturing and human workload. 3D printing technology has been successively used for some clinical applications, driven by improvements in background information, accuracy, and surface integrity. Specific porous scaffolds that incorporate the formation of healthy bones, peculiar in size and thickness, have been developed in recent years. Sol-gel technique, gel-casting technique, solid-state sintering, polymer foam impregnation are the various porous ceramic methods used in manufacturing, and 3D printing technology provides increased speed, flexibility, economic viability, commercial feasibility and reduces equipment limitations [138], [139]. Temperature and pressure appear to be the principal reaction influencing ceramic synthesis variables. More prior techniques are being developed to supplement high purity ceramics with excellent properties, including the polymer pyrolysis process, the Sol-Gel method, and chemical vapor deposition. During the gas process in which the product is manufactured as a powder a relatively low molecular and volatile solid material was put in a hot environment. The overall rate of deposition is determined according to the rate of diffusion, nucleation rate, and reaction. Diffusion and reaction are aspects that significantly improve rates at low and high temperatures. Applications usually involve specialized medical devices, patient-implants, scaffolds, porcelain, including porous ceramics in all these recent years, various techniques such as 3D Binder based printing technique, Selective Laser Melting technique, Stereo-lithography technique [66], [140], [141]. Fused Deposition Modeling technique, Selective Laser Sintering technique may be used for the manufacture of dental ceramics due to its particle distribution, homogenization. Additive manufacturing has become an evolving technology that exhibits tremendous potential control over full design details, such as porosity, which significantly influences coating, providing a precise and complex design accuracy [142]–[145]. Stereo-lithography (SLA) has become one of the best modern techniques available for making dental products.

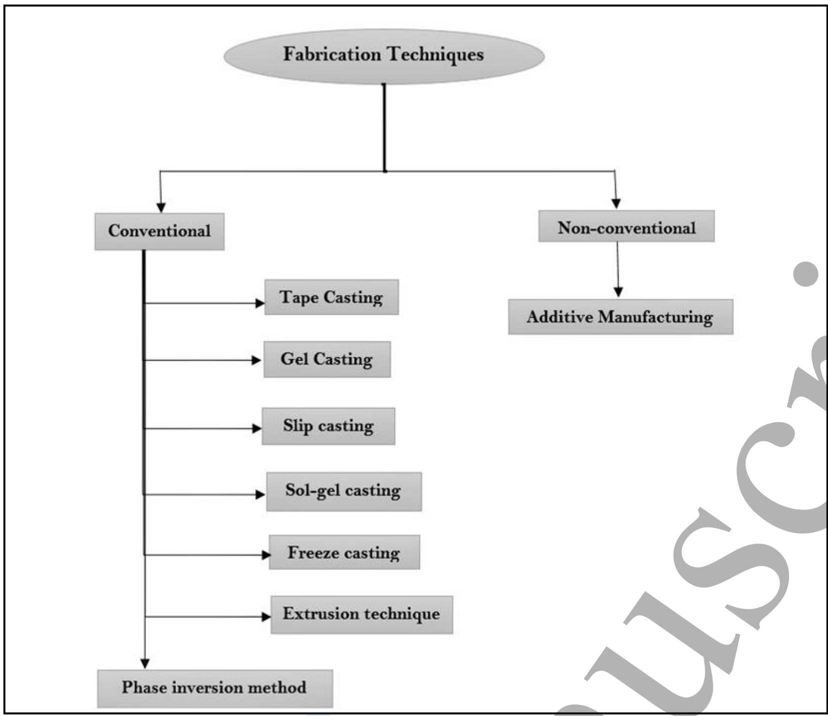

Figure 3. List of Fabrication Techniques addressed in the paper

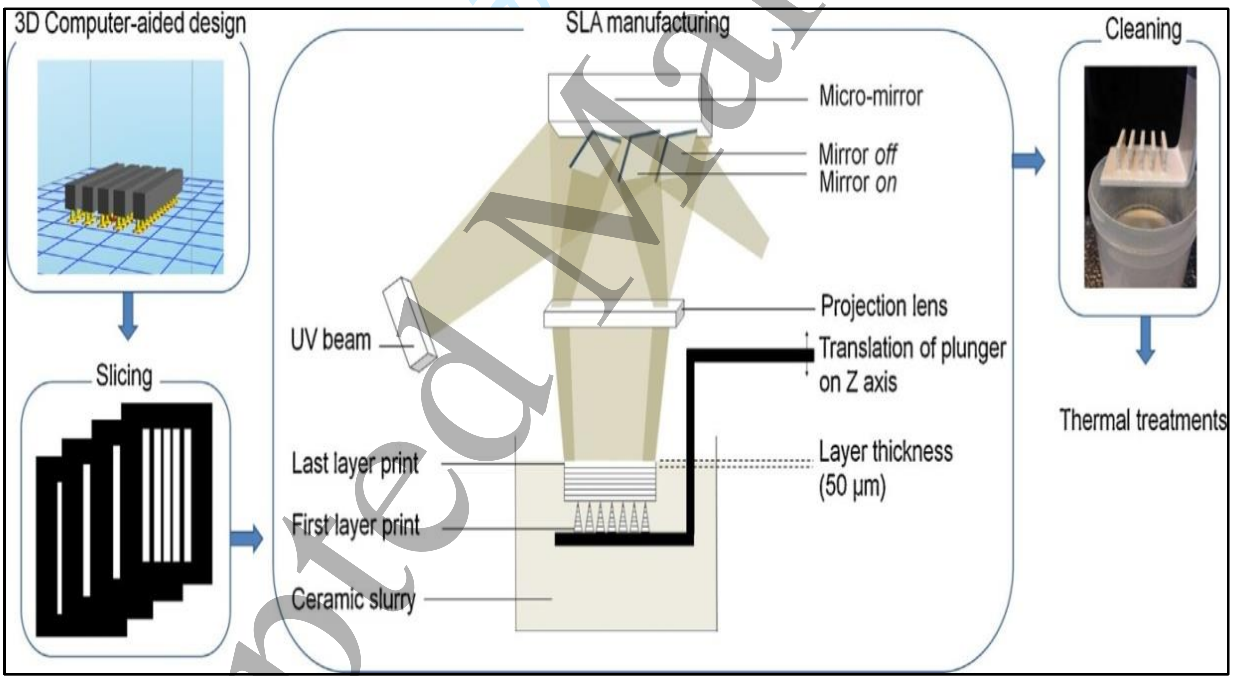

Figure 4. Stereo lithography manufacturing process [146].

Figure 4 demonstrates the overview of the SLA process from the incipient stage of manufacturing to the end part of product.

Figure 5 clearly revels the microanalysis of SEM with magnification about 90× of a rectangular SLA-manufactured alumina sample. During the SLA-manufacturing process, the high viscosity of the S75 slurry causes macroscopic and microscopic deformations of the printed layers. (Fig. 5C,D) which generally do not occur with the S70, L70, L75, and L80 slurries (Fig. 5A,B).

Figure 6 shows the external and internal views of SLA-manufactured alumina dental crown framework [146] inserted on an all-ceramic crown preparation (L80 slurry) (Fig. 6C). The crown framework could be placed on the all-ceramic crown preparation, but excessive oversizing resulted in a large marginal gap. The residual pillars and marginal gaps can still be seen (Fig. 6A). Based on this, the hypothesis that dental crown frameworks can be produced using SLA manufacturing is confirmed.

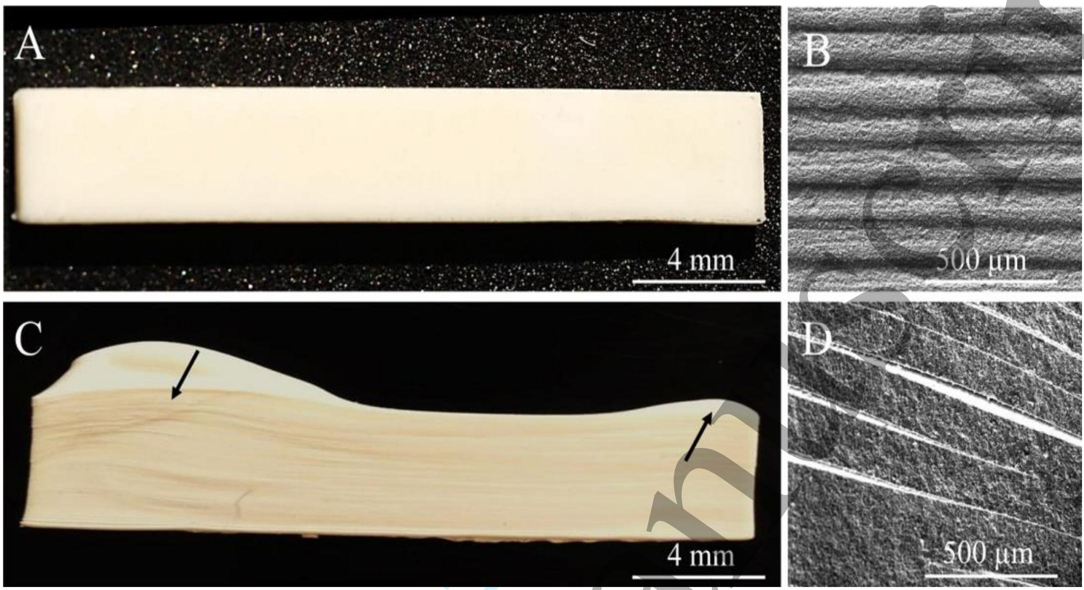

Figure 5. Representative photograph (A) and scanning electron micrograph (B) (magnification: 90×) of a rectangular SLA-manufactured alumina sample made from the S70 slurry. The photograph and micrograph are also representative of the L70, L75, and L80 slurries. Representative photograph (C) and scanning electron micrograph (D) of a rectangular S75 sample (arrows = macroscopic deformations) [146].

A detailed indication of transposition of orientations of printed layers from specimens are shown in **Figure 7**, where it specifically explains that ZY and ZX-oriented frameworks which help to create a perpendicular orientation to the occlusal surface of the printed layers and thus parallel to the direction of the principal masticatory stresses applied to the occlusal surface[147]. However, the complexity of a crown shape that represents both the ZY- and ZX-oriented from experimental conditions and clinical extrapolation are revealed. These findings need to confirmed in future studies replicating a highly more complex masticatory stresses that ceramics and other materials like zirconia are subjected to. This method may allow to determine the maximum layer surface of a complex crown framework, and other layer orientations.

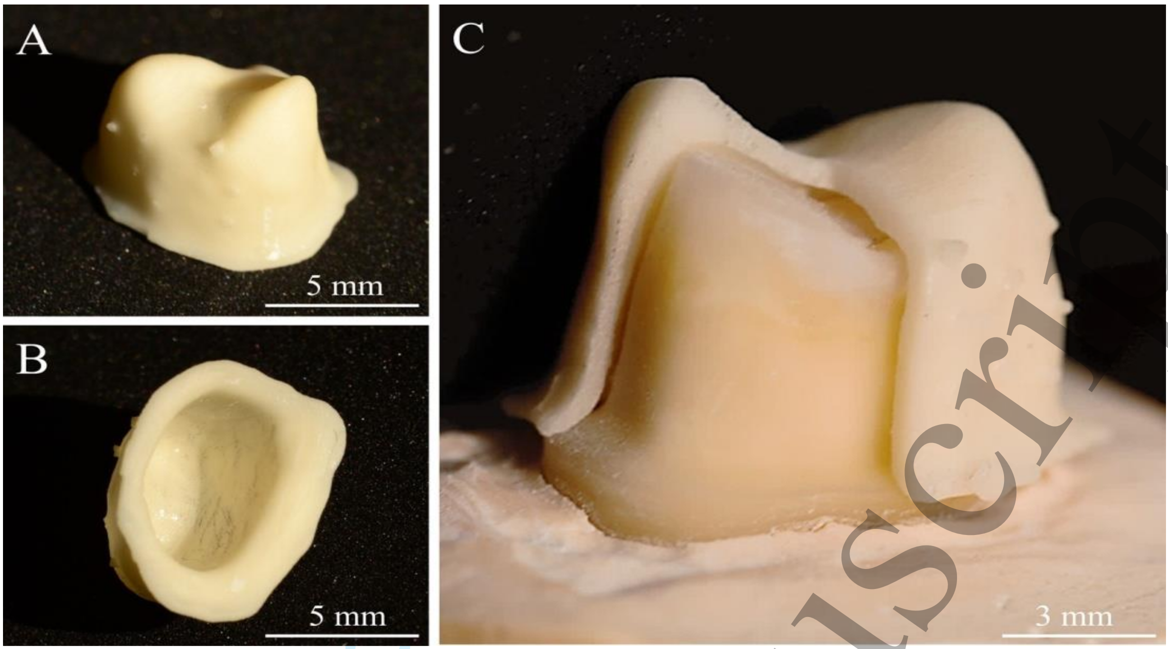

Figure 6. Photographs of an SLA-manufactured alumina dental crown framework: external (A) and internal (B) views. Crown framework in place on an all-ceramic crown preparation (C) [146].

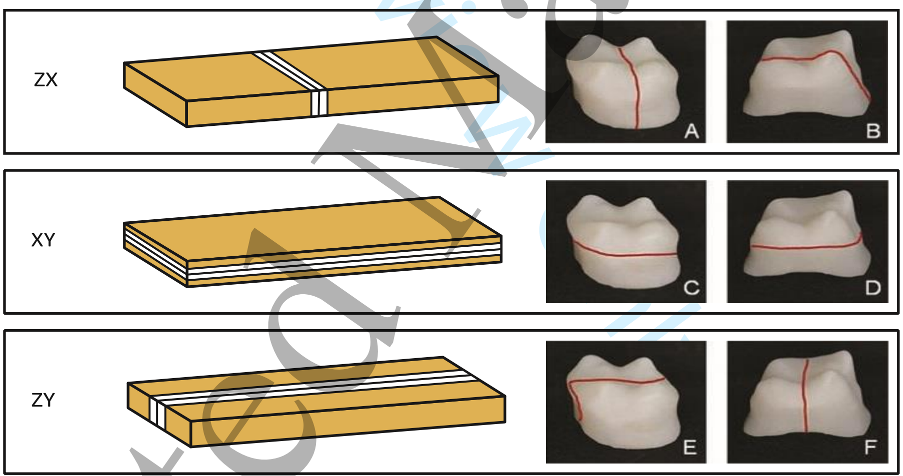

Figure 7. Transposition of orientations of printed layers from specimens studied to complex crown framework shapes: ZX, XY, and ZY. A, C, and E are in buccal view. B, D, and F are in mesial view [147].

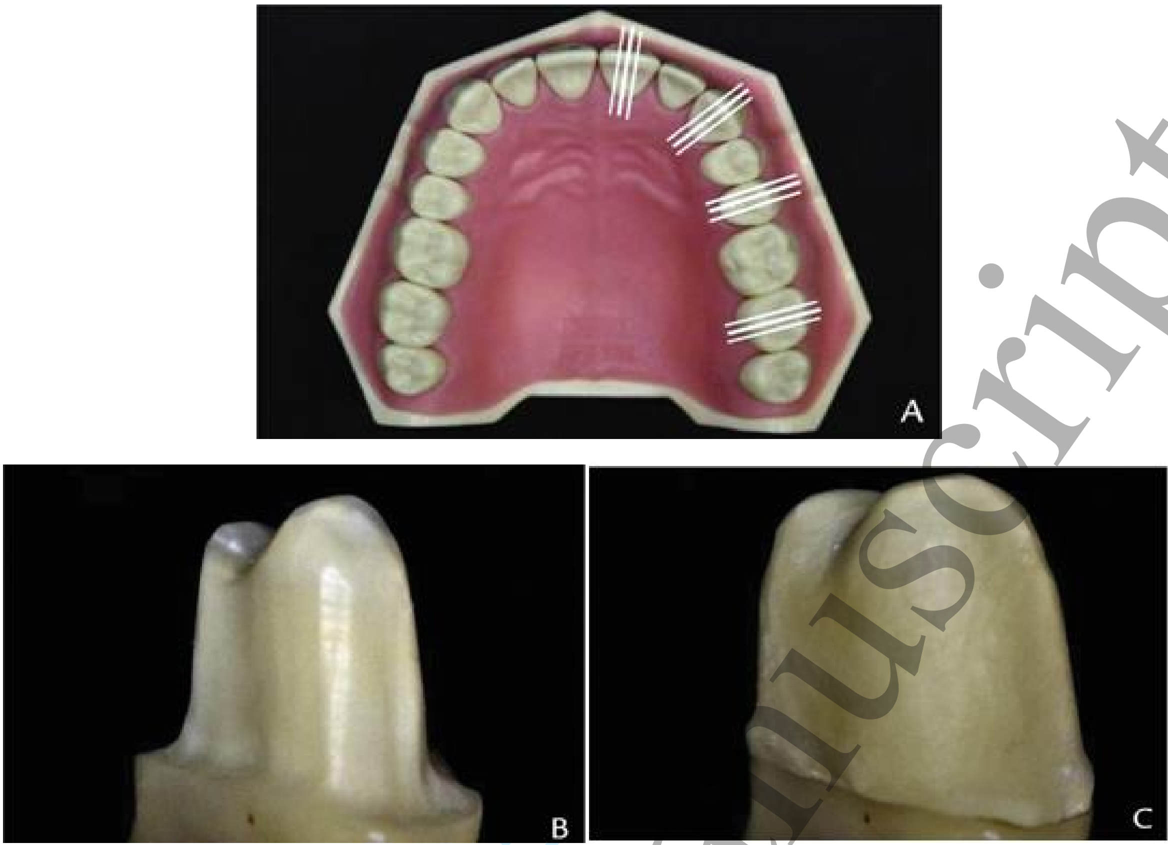

Figure 8. A) Recommended SLA orientations to manufacture complex frameworks (white bars: orientation of successive layers). B) Preparation of first right maxillary premolar for ceramic crown. C) SLA-manufactured alumina dental crown framework on first right maxillary premolar. SLA, stereo lithography [147].

There are different types of techniques used in the manufacture of additives, including powder bed melting technique, material jetting technique, sheet metal lamination technique, material extrusion technique, vat photo-polymerization technique, direct energy deposition technique, and binder jetting technique. High-purity amorphous (ultra-fine) powders have been produced using various ceramic processing techniques. Formulation of the liquid phase, which helps to produce relatively homogeneous fine particles, includes hydrothermal synthesis as well as co-precipitation techniques. With the use of CAD software, each layer is formed has been determined by mixing materials and printing objects and the direct-digital output is popularly referred. However, in the recent years three dimensional printing technology has become a commonly applied method, including enhanced medical equipment, prosthesis implant, design processes for scaffolding, porcelain and porous filters also a manufacturing technology layer-by-layer to develop unique geometrical structure by means of material deposition [148]. Concerns about incorporating the use of 3D printing technology for nanostructures may facilitate the effective use of each porosity of ceramic glass, in particular for biomedical applications by incorporative various ceramic materials. The most complex research in medical practice prefers adequate production techniques to obtain the right implants. Scaffolds production techniques involving electro-spinning, solvent-casting and particulate leaching, chemical oxidation and molten-metal integration [36], [37], [39], [51], [53]–[55], [149], [150]. In this section, the summarized key outlines about manufacturing parameters and approaches, is detailed in **Table 1**.

Type of Ceramic-material	Type of manufacturing approach	Time	Temperature	Heating rate:	Cooling rate:	Ref
	Gel casting / Direct foaming technique.	120 min	1400°C	----	----	[151]
	Phase inversion technique.	120 min	1400°C	----	----	[152]
	Slip-casting technique.	240 min	1400°C	----	----	[153]
	Phase inversion technique.	----	----	----	----	[154]
	----	----	1000°C	----	----	[155]
Aluminum oxide (Al_2O_3)	Phase inversion technique.	----	----	----	----	[156]
	Uniaxial die-pressing technique.	----	650°C	----	----	[157]
	Slip casting technique. Uniaxial die-pressing technique.	----	1400°C	----	----	[158]
	Direct foaming technique.	120 min	1400°C	----	----	[159]
	----	----	----	----	----	[160]
	Gel casting / Direct foaming technique.	120 min	1400°C	----	----	[161]
	Gel casting / Direct foaming technique.	120 min	1550°C	----	----	[162]
	Gel casting / Direct foaming technique.	120 min	1400°C	----	----	[163]
	Uniaxial die-pressing technique	120 min	1400°C – 1550 °C	30C/mm	----	[164]
	Slip casting technique.	180 min	800°C - 1500°C	----	----	[165]
	Phase inversion technique.	120 min	1200°C -1600°C	1 °C/min	----	[166]
Alpha-Alumina (α-Al_2O_3)	Phase Inversion technique.	120 min	1200°C -1600°C	2 °C/min	----	[167]

	Phase inversion technique.	----	----	----	----	[168]
	Phase inversion technique.	----	1350°C	5 °C/min	----	[169]
	Phase inversion technique.	----	----	----	----	[170]
	Phase inversion technique.	120 min	1200°C -1600°C	1°C/min	----	[171]
	Phase inversion technique.	60 - 120 min	800°C -1250°C	2 °C/min	----	[172]
Gamma-alumina (γ-Al_2O_3)	Phase inversion technique.	----	----	----	----	[173]
Gamma-alumina (γ-Al_2O_3)	Uniaxial die-pressing technique.	120 min	1000°C	----	----	[174]
Silica ((fused) (SiO_2))	Freeze casting Technique.	240 min	1100°C	----	----	[175]
Silica ((fused) (SiO_2))	Freeze casting Technique.	----	1150°C	1 °C/min	----	[176]
Zirconium dioxide (ZrO_2)	Non-aqueous tape casting Technique.	60 min	1480°C	N/A	----	[177]
Zirconium dioxide (ZrO_2)	Cold isostatic pressing Technique.	----	----	----	----	[178]
Mesoporous Alumina (α-Al_2O_3 + γ-Al_2O_3)	Sol-gel technique.	180 min	400°C	0.5 °C/min	0.5 °C/min	[179]
Silicon nitride (Si_3N_4)	Hot pressing Technique.	----	----	----	----	[180]
Silicon nitride (Si_3N_4)	Freeze casting Technique.	----	1350°C	----	----	[181]
tetragonal zirconia polycrystal (3Y-TZP)	Freeze casting Technique.	180 min	1400°C	5 °C/min	5 °C/min	[182]

	Uniaxial die-pressing Technique.	120 min	900°C	----	----	[183]
Barium aluminosilicate ($BaAl_2Si_2O_8$)	Uniaxial pressing Technique.	180 min	850 °C – 1425 °C	3 °C/min	----	[184]
Alumina+ Silicon dioxide (Al_2O_3 + SiO_2)	Non-directional freeze casting technique.	180 min	1350 °C	5 °C/min	----	[185]
Aluminiumt itanate (Al_2O_3*TiO_2)	Uniaxial pressing technique	----	----	----	----	[186]
Alumina/ tetragonal zirconia polycrystalline (Al_2O_3/3Y-TZP)	Uniaxial die-pressing Technique.	120 min	1400 °C -1600°C	3 °C/min	----	[187]
silicon nitride-hexagonal boron nitride ((Si3N4)–hBN)	Hot pressing Technique.	----	----	----	----	[188]
Gadolinium doped ceria-Nickel(II) oxide (GDC-NiO)	Uniaxial die-pressing Technique.	480 min	900°C	----	----	[189]
yttrium tetragonal zirconia polycrystal (Y-TZP)	Extrusion Technique.	120 min	1050°C	----	----	[190]
Boron nitride-Silicon dioxide (BN-SiO_2)	Cold isostatic pressing Technique.	60 min	1400°C-1700°C	----	----	[191]
beta- Silicon nitride (β-Si_3N)	Uniaxial die-pressing Technique.	10 min	750°C-880°C	10-20 °C/min	5 °C/min	[192]

Table 1. Various types of Ceramics and their Fabrication Techniques

3.1 Tape casting

Tape casting is a well-known approach in the production of ceramics which has been introduced in the year 1952, that also patented by scientist named Howatt. Ceramic materials are a rigid, brittle in nature and dense solid, where pores are usually considered to be defective/ defect in ceramic industry [144], [214]. However, Advances in ceramic particle technology production coupled with technological and research competition for porous thermal conductivity, integration of chemical-mixes, and highly engineered materials have increased interest in porosity ceramics. **Figure 9** provides details of the preparation procedure of ceramic by tape-casting method [196]. The CRN method was used to create highly crystallised AlON powder as the starting material. Plasticizers included butyl benzyl phthalate and polyethylene glycol. For the preparation of slurry, green tape, and ceramics, polyvinyl butyral was used as a binder, and menhaden fish oil was used as a dispersant agent. Dental ceramic materials processing has contributed greatly to the introduction of modern approaches to ceramic material processing. The microstructure may be changed by adjusting the particle size, the porous structure, and the parameters of the sintered material. In the case of tape casting, thickness change is essentially a significant parameter for the physical activation of membranes and substances with a complex framework to sustain them. In comparison with conventional dental ceramic materials fabrication, the process of forming an alumina structure by tape-casting has demonstrated outstanding mechanical properties. This methodology is more difficult and time-consuming to achieve accurate thickness, and a specialist is needed, and some dental laboratories will face difficulties during the process. When implemented, the use of thermo-compressed alumina tapes with a dental ceramic frame to improve adaptive response has demonstrated a forming technique [197]. Tape casting technique has become an effective method mainly used during the high-temperature manufacturing capacity of straight ceramic products. Ceramic products/components are formed by pouring the slurry consisting of powdered ceramics dissolved in solvents on a moving surface beneath the knife-side of a blade known as a Doctor blade, with the addition of dispersants, binders, and plasticizers. Interestingly, tape casting is performed by utilizing non-aquatic organic substances to synthesize the organic materials such as dislocation, additives and surfactants. Potential medical risks are the main issues related to the use of a non-aqueous substance, thus minimizing these challenges by using methods such as slow drying of tape casting techniques, powder agglomeration due to hydrogen bonding and low water-binding pressure necessitating elevated slurry levels. In that study the effect of the dispersant and binders in alumina aqueous tape casting slurries were characterized with electrophoretic mobility and rheological measurements. In aqueous medium, a 4, 5-dihydroxy-1, 3_benzenedisulfonic acid, was found to be a very effective dispersant for alumina. The best conditions to obtain a homogeneous stable slurry with a high powder loading suitable for tape casting were determined in terms of order of component addition, rheological behaviour and ageing of the suspensions. Acrylic binders should act through a cohesive mechanism and lead to green tapes with good mechanical strength. [198], [199]. In addition to therapeutic benefits, medical implementations and ceramic repairs prerequisites are realistic manufacturing of different geometry with a precise fit to adjacent teeth and enhanced corrosion and resistance. All-ceramic technique is used for accurate and consistent, limited-shrinkage. Growing demands in dental practice for regenerative treatment and metallic bacterial infections have recently greatly contributed to the growth of various ceramics. PFM systems consisting of a metallic load-bearing system and a ceramic adhesive for architectural aspects but account for about 80 percentage of all long-lasting tissue regeneration compared with PFM reconstruction in general and specifically [200]–[202]. Tape-casting leads to the development of dense ceramic materials by means of powdered ceramic slurry, typically non-aqueous particles containing different superplasticizers, additives and coatings to produce a dry tape that is very durable in processing of all ceramic types, analysis and thermal compression for greater responsiveness of dental implants [203],[204]. The mixture of tape casting can be modified to yield bands that meet certain quality criteria, such as (I)no drying deformities, (ii) cohesion to allow drying of sheets, (iii) microstructural stability, (iv) effective thermo-pressing (lamination) capability, (iv) efficient pyrolysis (de-binding) and also (v) superior mechanical hardness to heat treatment [205]. In general, the method of preparation takes place in various stages. The formulation of its slurry for tape casting is heavily dependent on the solids concentration, the order of the additives being added, and the binder quantity. All of these parameters can affect the final properties of ceramic tape, including density, thickness, porosity, surface quality, and mechanical behavior. The dispersants are used to produce a slurry with a well-dispersed powder. The binders retain the particles after molding until the tape is sintered, and the particles are eliminated by thermal treatment. Plasticizers add versatility to green tape. The formulated mixture begins to pour into a container as well as the band is positioned on such a mobile polymer band, the green band is monitored and laminated to include denser components to enhance mechanical stability and density [206]. The pseudo-plastic properties of slurry mixture are preferred to stabilize homogeneity, and during the casting process and also viscosity has been reduced but improved after casting [207]. The slurry would be reduced to a semi-rigid, versatile tape that will eliminate the drying phase of the solvent. Artificial drying or drying at low temperatures and thermal conductance can be achieved by including the boiling point of the lowered solvent that enhances the drying process [208]. It prevents the formation of cracks in green tape due to stress and heterogeneous-shrinkages [209]. The dry tape is used for lamination which enhances surface roughness and architectural cohesion. The multi-layer green surface is formulated by pressing the 10Mpa – 30 MPa layered tape at the heating rate above the nominal temperature of the binder mixture as well as the plasticizer frame. Thermo-pressure makes ensure that the surrounding particulate matter is interpenetrated and therefore also improves its green density. In addition, lamination can be done with lower pressure about 2.5 MPa – 5.0 MPa at room temperature [210]–[212]. Furthermore, organic solvents need to be phased out of tapes to stop disintegrating, such as laminate de-lamination. Slow drying, low tape green power, improved crack sensitivity, increased hydrogen bonding agglomeration and possible material reactions with H_2O are the disadvantages of the aqueous medium. It also significantly restricts their applications in the real world, while simultaneously reducing health problems and possible risks, with a much more controllable procedure and lower prices. Superfine waterproofing tape casting provides an increased variety of choices, a unified green structure, reduced surface tension, and limited boiling points. Hence, the tape casting technique is one of the conventional techniques in manufacturing the ceramics or bio-glass ceramics.

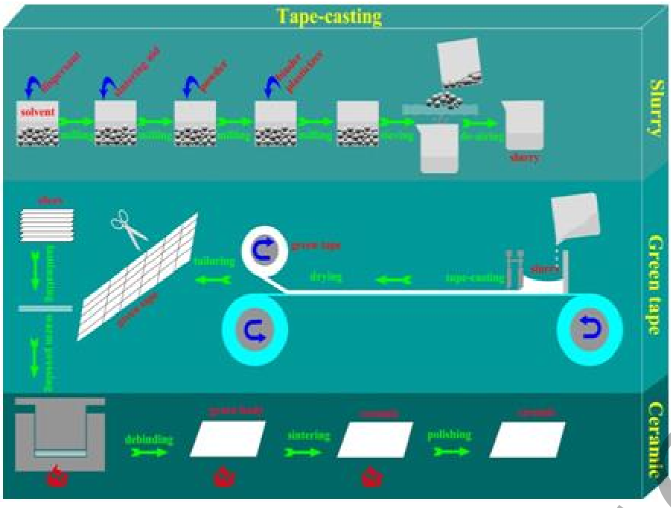

Figure 9. Preparation procedure of ceramic by tape-casting method[196].

3.2 Gel casting (direct foaming)

Gel-casting appears to be a fascinating technique in ceramic industry for producing high-quality ceramic components with a complex/complicated shape. Gel casting is a relatively new methodology for ceramic powder molding constructed based on conventional ceramics and polymer chemistry definitions. Gel-casting is a novel colloidal formation of ceramics, initially introduced by the Oak Ridge Laboratory, Tennessee, USA. This method is simple to implement, which significantly improves performance, and budget-friendly engineering and manufacturing technologies for the ceramic industry and the finest quality complex porous components have been included in the development. But to produce high-quality, complex ceramic components through the in-situ production of a macromolecular matrix to retain ceramic aspects. **Figure 10** shows the detailed description about the gel casting technique [213]. TBA (Tert-butyl alcohol) is frozen from top to bottom, forming complete unidirectional crystalline prisms that penetrate the entire body and serve as the template for pore channels. (Fig. 10c). The frozen bulks may be easily removed from the molds at 3 C (Fig. 10d), and then heat-treated at 85 C. (Fig. 10e). These freeze and gelation phases produces green ceramic bodies with excellent strength, and the final ceramic pieces that are made using the drying, de-binding, and sintering processes. (Fig. 10f). **Figure 11** demonstrates the microstructures of porous ceramics via gel-casting process. The freeze-gel casting technology is used to create porous ceramics with unidirectional pore channels. Unidirectional pore channels structure depicted in **Figure 12**. By combining the gel casting and freeze drying technologies, porous ceramics with unidirectional pore channels is fabricated, as well as porous ceramics with very good unidirectional pore channel structure, as shown in Fig. 12. Gradient porous ceramics is also fabricated using the freeze gel casting of an alumina/TBA/AM slurry. Molds containing slurry and packed by heat barrier layers are placed under conditions with a temperature gradient. One end is set below the freezing point of TBA and the other end is exposed to air at the temperature in its melting range. As a result, the slurry froze from the cold bottom, forms the TBA crystals. Solidification and volatilization, on the other hand, occurs near the hot surface. These two procedures acts in opposite directions at the same time, resulting in a novel pore gradient structure. **Figure 13** reveals the formation of full densification without defects in the porous region near the bottom (Gradient pore alumina)[213]. Sintered parts showed nearly complete densification with no visible defects, either in the dense region near the top surface or in the porous region near the bottom, where alumina walls were present (Fig. 13d). Unlike the circular cross-sections in aqueous or camphene-based freeze casting, a green body with pore channels is fabricated using TBA as a template in its frozen state. Gel-casting has been used since its invention in the production of thick, porous, and complicated ceramic components. And Near Net Shape is a very interesting technology for Gel-casting. The macromolecular gel membrane is the result of the in-situ polymerization of synthetic monomers applied to hard ceramic compact formulations. This gel particle size is capable of generating sufficient strength to maintain its weight so that it can be treated without structural modification [214]–[216]. Similar to a relatively homogeneous microstructure, the gel-casting process has the potential to reduce costs and durability employing a standard dry pressing technique. There are two categories of solvent used for gel-casting which are aqueous and non-aqueous. The aqueous method is favorable despite being ecologically responsible [213], [217]–[220]. The traditional approach of the gel-casting technique which is used to prepare suspensions of higher loading and lower viscosity, thereby increasing the suspension of the non-porous mold. Replication of insights into conventional ceramics and polymers is based on which the gel-casting approach focuses, and its theory is that monomers responds to the polymers and also as required to build a 3D structure that freezes suspended solids. Green structures that are processed using a gel-casting technique demonstrated similar homogeneous surface morphology including the suspension of the substrate, thus enhancing the consistency of its formation as well as the strength of ceramic products. It is also very important and essential to prefer the gel casting procedure. Every gel-casting component tends to be chemically resistant in most polymeric products, including oxidizing, highly radioactive, explosive, harmful, and environmental activation of organic substances, while some monomeric units are capable of sensitizing exposed workers and, ultimately, are all unpleasant [221], [222]. Ceramic particles are dispersed in an aqueous mixture consisting of a monomer, a cross-linking agent, free-radicals and solvent to produce a mixture that is then poured into the sufficiently configured in-situ molding and polymerized to form a polymer-water gel that helps to move its dispersed ceramic particles into the molding cavity. The gel casted component of equal thickness, when the chemical is extracted from the molding even it will be warm/hot condition, but then the wet-gel component is separated into a dried green body under experimental conditions, and the dried-up green plate is ready for the machining process. The processing and sintering of binders begin with a number of ceramic formation techniques [223]. Ecological emission techniques for gel casting are made from low-and non-toxic gel castings. Certain methods for controlling and eliminating internal stress and thermal decomposition in ceramic gel-cast green bodies are purely for ceramic colloidal-molding processes. In comparison with gel casting, wet foaming processing route appears to be the most viable method of ceramics production. Due to its dry phase, wet processing can effectively balance interactions between particles and improve their consistency, while at the same time reduces defects across ceramic microstructures. Colloidal production has been one of the most successful approaches to improve the durability of ceramics. In recent years, several studies have focused on work with an opinion to modify the processes to improve ceramic reliability [224]–[226]. Normally, solvents consist of Ca^{2+} ions are reacted with sodium-alginate to produce gels. The rate of gel formulation between calcium salts and alginate is difficult to control, making it impossible to complete well-casting processes in a timely manner by changing the temperature of the outlet [227]. Colloidal forming involves a gel-casting technique, a tape-casting technique, a direct coagulation technique, and an injection molding technique. A colloidal formation can strengthen particles in green glass ceramics, greatly enhance its crystalline structure as well as the homogeneity of green ceramics and reduce the cost of manufacturing ceramic materials [228], [229]. A few investigations had all of its slow release of the aluminum coagulation factor hydroxyl-aluminum diacetate particles in a liquid state in which the ceramic particles were coagulated by compacting the electrical dual-layer by inducing the gel formation of alginate compounds introduced in aqueous phases [230]. Gel formation continues to evolve through rapid casting gelatinization, resulting in a variety of cross-linked volumes and a heterogeneous nature within the casting. A controllable reaction of calcium salts with sodium alginate must be used to complete the casting technique. However, with its lower liquid solubility, Hydroxyaluminum(2+) diacetate is likely to be used to gradually remove acetate ions as well as aluminium in aqueous phases, reducing its pH while increasing ion strength. For most manufacturing industries, gas filtration, liquid metal filtration, and medical devices have high thermal conductivity. In the manufacturing process of ceramic products, short-chain amphiphilic acids typically used carboxylic acids to create globules that were distinct due to chain lengths for particle stabilization. Additionally, because of high electrostatic forces, short-chain carboxylic acids are added to the ceramic composite coating. These surface treatments will allow both the particles lyophobic and binding liquid-gas interaction to control the globules. Over a long time, particle stabilization of the foam produced with surfactants is relatively stable. Ceramic porosity is still made from particle-stabilized foams that can also minimize the effect of foam source and foam formation. For most of the gel-casting processes, engineered Optimized suspension deformation due to various factors including changes in temperature or particle distribution has always been stable. Simultaneous solidification causes the suspension to decrease in non-homogenized size in internal stress and crack formation during the Green Ceramic body manufacturing process. Ceramic foams are transformative materials with characteristics including high aspect ratio, relatively high longevity, low density, conductivity, as well as high resistance to corrosion and stress. The porosity of all ceramics emerged in the natural binder burned out of the micro-space of polymers within the green body during the gel-casting process. When the added natural polymers are distributed and spread in the liquid phase, the suspension phase, then the micro-pores form uniformly in ceramics. Some Ceramics are produced by an in-situ synthesizing procedure [231]. With the formation of a macromolecular structure to hold the ceramic particles around each other. The same slurry can be used in the gel-casting methodology, which could result in a lower viscosity of large solid particles than organic monomers, which are made of polymerized binding material in the presence of a dried body, cross-linking polymers can be machined to produce more complex shaped ceramics. As a result, this method has been used in electronics, automotive, and defence industries to produce more complex, sophisticated ceramic materials. The gel-casting process uses liquid solvents as well as gel-formers, while the manufacturing sector has reduced the usage of gel-casting techniques for clear benefits, due to newly existed monomers such as acrylamide, a light neurotoxin portion. This issue may be partially addressed by the production of less harmful monomer solutions that make the industry more likely to use gel-casting approach. However, essential integrated elements are fabricated by gel-casting [232],[233]. Effective developments and challenges must be addressed until gel-casting is a prerequisite. The toxic effects of its monomers, which have also been used in a time-consuming and repetitive dry phase. The use of organic gel-formers in micronutrients and small amounts of drugs is crucial to the successful implementation of their metrics [234]–[237]. Recent developments and their implementations for the widespread use of possible gel-formers exemplify research into natural gel-forming categories of products. Two key aspects must be taken into account in the manufacture of ceramic materials with gel casting especially for the production of highly complex structures. First, the optimum frost speed must be assessed, which must be sufficiently fast to prevent foam from collapsing. Second, gel thermal conductivity must allow the formation of all mold cavity details and higher flow ability gels [215]. Many industrial perspectives have to be taken into account in order to produce more products in less time with less price.

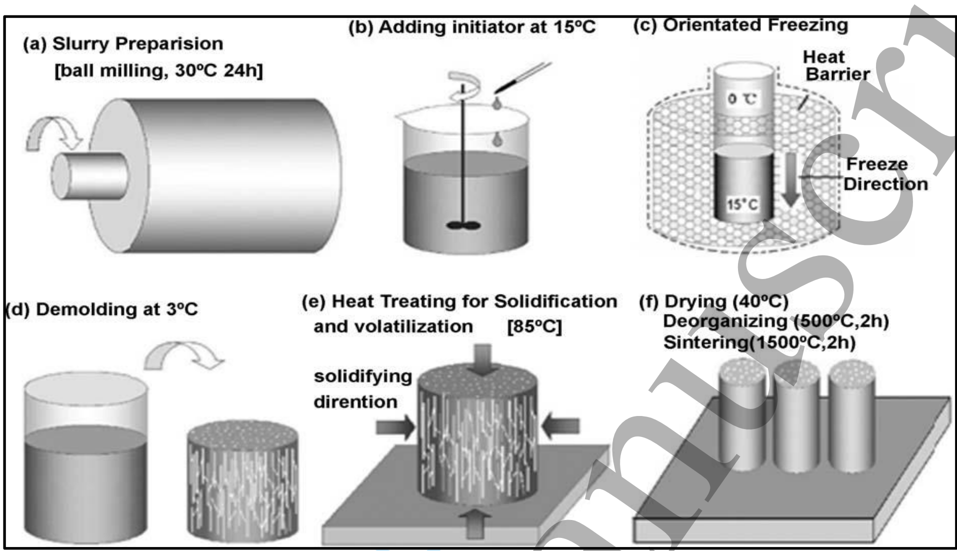

Figure 10. Full process for fabricating ceramics with long-range ordered porous structure by freeze-gel casting technique: (a) slurry preparation (ball milling, 24 h); (b) adding initiator at 15 ◦C; (c) orientated freezing; (d) de-molding at 3 ◦C; (e) heat treating for solidification and volatilization (85 ◦C); (f) drying (40 ◦C), de-binding (500 ◦C, 2 h) and sintering (1500 ◦C, 2 h).[213]

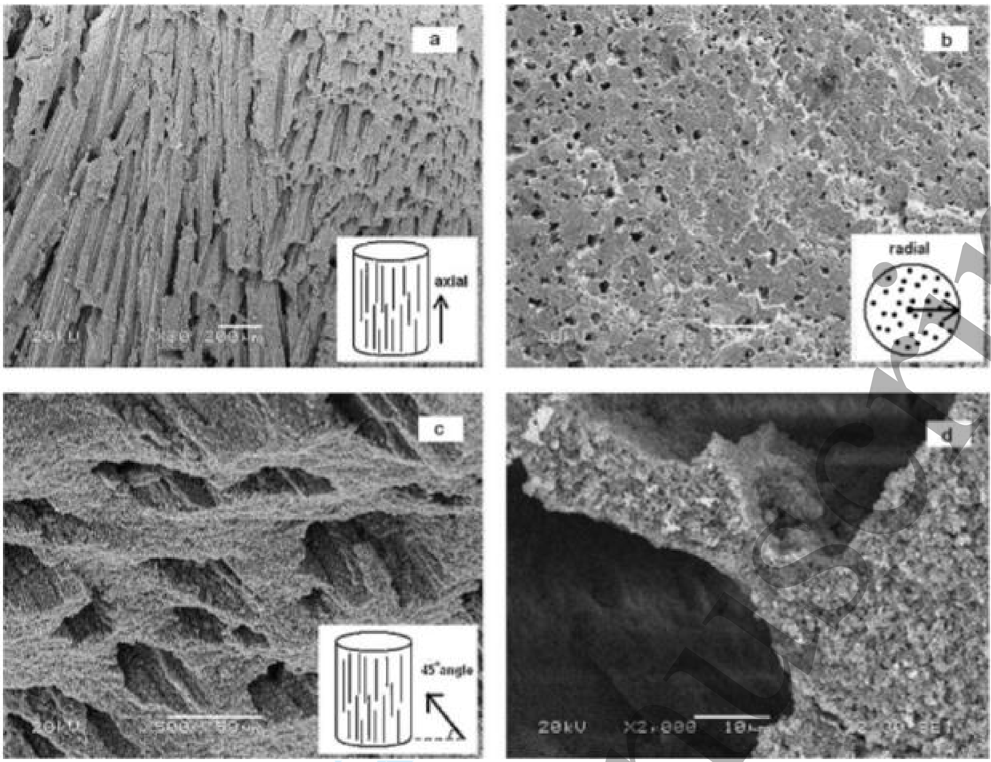

Figure 11. Microstructures of porous ceramics with long-range unidirectional pore channels fabricated by the freeze-gel casting method observed in different orientations: (a) vertical to freezing direction, (b) parallel to freezing direction, (c) at 45◦ angle direction and the dense walls formed between pores (d). [213].

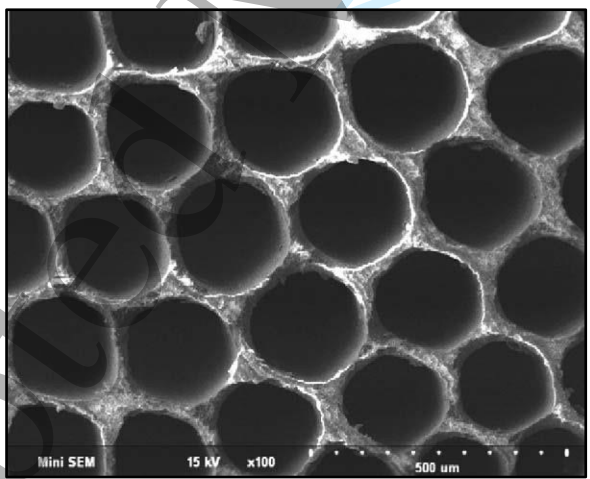

Figure 12. The ceramics with very well unidirectional pore channels structure[213].

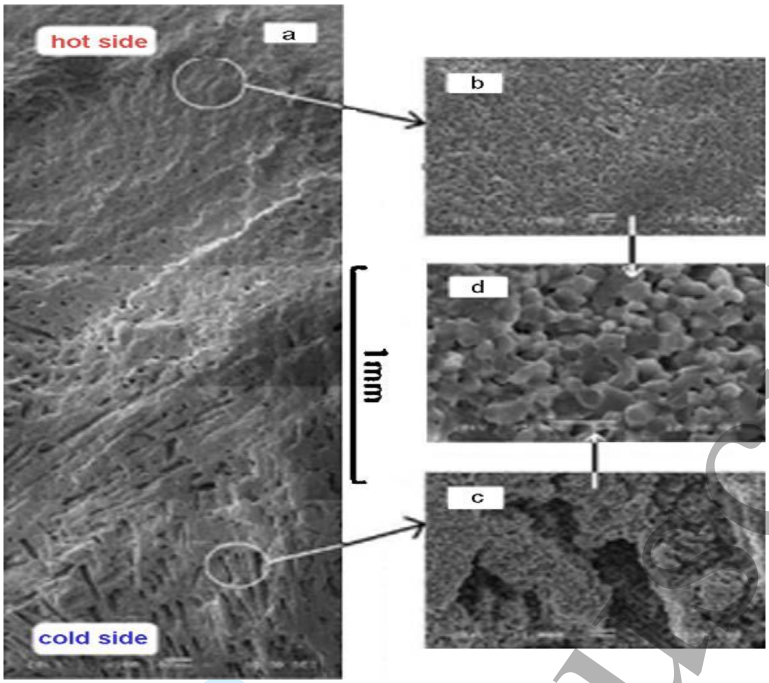

Figure 13. Gradient pore alumina ceramics fabricated by the freeze-gel casting technique under the freezing temperature gradient of 12 ◦C/mm [213].

3.3 Slip casting

The technique for fabrication of the ceramic materials by slip casting technique suggested an approach that combines the ceramic mixture with de-ionized water and feasible additives. Actually, the particles are not integrated with an aqueous mixture like water but are transformed mostly into agglomerates and the sediments. One of the most common forming techniques used in the ceramic industry is slip casting. This technique is an effective approach for producing accurate structure and dense ceramics. Due to its ease of manufacturing complex components and having large surface area, fine ceramic particles often tend to form agglomerates during manufacturing, resulting in effective viscosity suspensions but subsequently poor packaging properties. For both the homogenization and the rheological interaction of their suspensions, green structures have been shown particularly for hybrid or complex frameworks. It is therefore widely known that an effective approach to fine particulate matter depends heavily on a decision to disperse. In order to achieve effective casting results, ceramic particles should be completely de-agglomerated and concentrated mixtures achieved by effective rheological behavior [238]–[240]. Ceramics are formed through sintering the aluminum components by employing the slip-casting technique which has demonstrated enhanced flexural strength, resistance, and considerable ceramic porosity dispersion which also improved the strength of the fractures [241],[242]. There is also a wide range of methods used to manufacture silicone particles together with slip-casting, die-pressing, isostatic pressing but slip casting would be used to create a complex-shaped frame over its porosity base. The strength of different ceramics is lies between 45 MPa-470 MPa in the slip casting technique, but all-ceramic production techniques are used for efficient and cost-effective, limited-shrink parameters [242]–[245]. Interestingly, colloidal methods, including slip-casting approaches, are commonly used for manufacturing ceramic cordierite materials or glass-ceramics. The combination of its microstructure and finished product characteristics are important factors in the production of slip casting [246]. This technique was widely acknowledged due to its ability to meet the requirements of pore size distribution. It is the most common manufacturing approach in the ceramic industry is to provide an interactive porous structure which also appears to be processing organic polymers with ceramic modernization. Some of these techniques aimed to allow the manufacture of ceramic components with precise positioning over the entire micro-porous structure and macro-porous structure, as well as a satisfactory topography, although it is conventional. Limiting the specific quality of the scaffold has become one of the major challenges, especially in engineering and manufacturing including varying scaffolds such as β-TCP scaffolds, attracting researchers to improve the mechanical properties of bio-ceramics [247],[248]. In an experimental evaluation, the integration of the mixtures into the mold cavity occurs by separating the liquid porosity capillary of the slurry, which absorbs the dispersing material and ends up leaving the formed thick green body [249]. It is an advantageous approach to incorporate this technique with dual slip-casting techniques that develop a nano-porous structure that results in a final bio-scaffold macro-porous structure and particle distribution, including its improved mechanical characteristics. However, a foaming agent was used to achieve microstructure pores in the experimental results. In particular, a special technique incorporating a double polymer foam casting technique as well as a foam replica was used, which is an excellent Nano-porous β-TCP scaffold for biomedical applications [250],[251]. Polymer replication is one of the first techniques proposed for the production of structural porcelain within the regulated macro-porosity as well as the preferred micro-structure, but macro-pores remain manageable in size and maintains the required porous structure as well as high inter-connectivity. In recent years, pressure slip-casting has become the advance of slip-casting. But traditional slip casting uses Paris plaster and can be used roughly several times. The capillary pressure of the pore spaces in the mold cavity also the casting layer shaped at its mold interface which absorbs dispersion as if it slipped out. Slip casting can be defined as a filtering process, which is why even vacuum here on the sides of the mold or excessive pumping pressure mostly on the slippery side increases the filtering product deposition. The Paris plaster was modified by a porous structure in the polymer mold at a capillary pressure of less than 200KPa, which also allows for an optimum casting pressure of up to 4 and thus reduces the casting time; these plastic molds are often quite flexible, which is used for thousands of dental practices component textures. Glass dense structures may also be formed with a pressurized casting at acceptable processing times, which could also allow the possibility of automation. This is one of the main reasons why it is more cost-effective than conventional slip casting [252]–[255]. In the slip casting technique, the configuration of green particles with porosity and large pore size distribution is improved. The highly deflocculated powdered slurry is produced with a relatively high percentage of particle density. By changing the characteristics of the powdered surface, a strong repulsive force is successfully achieved between the particles, and electrostatic repulsion is significantly higher than the attractive body [256]. Recently, slip casting has become a phase-of-the-art process for the production of all ceramics, including various clay materials, certain sanitary wares, cooking utensils. Also, significant progress has been made in the manufacture of advanced ceramics employing pressure slip casting. Slip casting techniques are ideal practices for the production of visible YAG ceramic materials too, as they are safer to overcome defects, including aggregate particles and agglomerates, through segregation and dispersion methods [239], [257], [258]. The production of fine-grain porcelain by pressure-slip casting has been given limited attention in recent decades. The incorporation of grain into ceramic particles has several advantages for applications at high temperatures including some improvements in thermal conductivity, corrosion, and creep resistance. In addition, the sintering shrinkage is also reduced, the thermal conductivity and the mechanical properties are mostly due to micro-structural cracks forming. Furthermore, in some cases the thermal gradient disparity of various stages may cause this crack development to be sintered better from smaller particles than from equi-axed grain fractions [259]–[261]. Slip-casting must be filled in with a slurry (slip) into a porosity mold to form the final product. There is a high potential in using slip casting to easily and efficiently produce molds. The molds are typically low in tensile strength but high in porosity which reduces hardness. To maximize strength there has to be a certain porosity. In an investigational analysis it was revealed that the total no. of pores in single slip casting was higher than the double slip-casting with heating temperature of 1200 ^{0}C [262].The number of pores in a specimen obtained with single slip casting was greater than that of the samples obtained by double slip-casting followed by heating at 1200 ^{0}C, which agreed with the porosity. Slip casting has become one of the most widely used ceramic processing methods, providing both an excellent microstructure for porous casting media and a high degree of ceramic phase distribution. Gypsum molds of reduced strength appear to be worn over time, while the water flowing through them weakens the spaces on the pores. These molds are typically excellent for producing complicated structures because when the green body loses water and then begins to dry out, the outer edge of the mold shrinks for an effective removal procedure. It is a good thing because it is the best way to get rid of equipment failures. Slip casting is mainly aimed at the development of cost-effective porous materials and also for the integration of flexible material versatility, especially in comparison with all other material manufacturing methods.

3.4 Sol-gel casting

Sol-Gel method is a type of wet-chemical technique requiring a lower pH value as well as a temperature that is too high for sintering which has been introduced in early 1846. Sol-gel technique is an advanced technique for the processing of powdered particles due to the presence of a strict limitation of the processing conditions. Sol-gel casting product is either characterized by a nanoscale dimension, including its particle size and appears to be a very significant criterion for improving interaction and even stabilization at unnatural/new bone formation interfaces but sol-gel powder results in a significant reduction in its temperature and degradation effects during sintering. This approach provides for a chemical mixture of calcium phosphate-based compounds that would be effective in enhancing biological, chemical consistency for various engineering and ceramics manufacturing industries, it may also produce a mixture of calcium and phosphorus that can improve chemically in a homogeneous way [263],[264]. Also suggested among the synthesizing techniques for the production of ceramics were sol-gel techniques due to its economic response rates, most notably for the formation and manufacture of aluminum-based ceramic matrix composites with carbon nanotubes. The objective of achieving homogeneous distribution through rapid, regulated gel formation, liquid precursors, pH influence as well as high-power support including carbon nanotubes which also enhance the carbon nanotubes' intra-granular positioning which can be seen in the formation of ceramic particles. Eventually, the Sol-Gel method will also strengthen the bond structure between its carbon nanotubes and ceramics, which can also improve the bonding between their CNTs and ceramics by using synthesized carbon nanotubes and hydroxides or alkoxides as by-products [265]–[267]. In addition, Sol-gel methods may have been integrated with supramolecular surfactants, resulting in improved development of advanced surface modification materials in clinical research and industrial productions. Mesoporous materials appear to be particularly suitable for drug delivery applications, and they have also been a valuable research commitment to this particular issue over the past few decades [268],[269]. Sol-gel technique which can provide a possible structural, chemical and textural treatment and also the increased concentration of its sol-gel particles resulted in reduced operating temperatures throughout the sintering process as well as any degradation process in its application [270]. It is interesting that many functionalized components can also have a greater influence on the phosphor components within that sol-gel technique.

Due to its versatility, improved purification, lower thermal conductivity, and the ability to check the dimensions and structure and function of grain sizes, the sol-gel method used in which all cations in the mixture are transferred initially to sol, then to dried gel, and finally to ceramic powders, in conjunction with the citrate sol-gel method [271],[272]. Another important thing is that Nd:YAG is a crystal clear ceramics which have been synthesized using the citrate sol-gel method [273]. Sol-gel cast silicate structure synthesizing was extensively researched due to its huge availability of structural silicone resources including mild reactive materials such as tetra-alkoxysilane. Hydrolysis and polycondensation of tetra-alkoxysilanes create silica gels that can also be integrated at temperatures of around 1000 ° C–1500 ° C at relatively low temperatures without melting into silica glass [274]. Wet-gels can easily create cracks during the process, making it difficult to produce amorphous. On the other hand, dried gels are better suited as by-products of silica glass as well as for the synthesis of monolithic silica glasses and integrated silica-based glass. The gel formation or the gelling phase occurred mostly in the sol-gel method at low or room temperatures. Various types could also be produced, including such aerogels, oxides, gels, bio-glasses Using the sol-gel casting technique, which allows the integration of chemical and inorganic molecules into cell types between silica matrices during the process [275]–[279]. The use of this technique can increase doping concentrations, strengthen compositional and microstructural capacity and develop custom organic solids that can facilitate the production of ceramic industry. This method is suitable for the development of bio-glass ceramics which would have been difficult to achieve through conventional melt-quenching and vapor-phase methods.

3.5 Freeze casting

Another ceramic fabrication technique, Freeze casting which was introduced by Maxwell in 1954, which has become an impressive technique for the development and manufacture of porous materials with complex structures and morphologies, and in recent years has attracted a lot of interest. A simple approach, in which the material suspension is merely processed, that will provide materials with homogeneous porous structures, where the pore size appears to be a specific replica of frozen substrate particles, that also produce distinctive mechanical characteristics and have successful load-bearing applications, and also has led it to a significant number of studies in recent years. Alternative techniques for controlling pore space were employed. **Figure 14** reveals the freeze casting system during which the pore structure was formed [280]. The TBA ice prism, ceramic walls, and liquid particle suspension make up most of the system. This method takes advantage of the fact that when TBA is solidified at a specific freezing temperature, it forms long, straight ice prisms with no branches. TBA gradually crystallizes into unidirectionally aligned ice prisms that ran from the bottom to the top, parallel to the freezing direction during the freeze casting process. The ceramic particles is repelled by the growing TBA ice prisms and bound by PVB, causing them to cohere and form strong pore channel walls. The solidification process usually took about 30–60 minutes, yielding a solid green compact. The green compact is then de-molded and vacuum-sealed at 50°C for 24 hours to allow TBA to sublimate. Because the saturated vapor pressure of TBA (8–10 kPa) is high enough to allow sublimation in a vacuum, solid TBA gets converted into a gaseous state. TBA crystals that are unidirectionally aligned sublimed and left one-dimensional channeled pores. Notably, regardless of the change in pore channel size under different freezing temperatures, the pore channels tends to align with increasing pore channel size in the freezing direction. The solidification velocity decreases with increasing layer thickness due to the thermal resistance of the solidified layer, in turn increasing the thickness of the solidified layer.

Freeze casting appears to be one of the most widely known techniques for enhancing the solidification rate, which may result in a decreased pore space. Because of its versatile nature and ease of handling, it is also possible to use certain types of ceramic materials to keep their structural design interdependent and also to facilitate the structure of the materials to be modified for a specific oral dental application. Biodegradable bio-glass scaffolding may also be modified by the biodegradability process by employing this approach. The complete accurate synthesis of the composition of the glass is ecological, especially where water can be used as an organic solvent. The average compressive strength can also be achieved through biologically low ceramic materials, including calcium phosphate which is considerably higher production control performance [281]. The dispersed particles are kept away during freezing, although the finished microstructures of porous materials and the stabilization composition have often influenced by the interaction between the surfactant particles and the solvent in the mixture. Regulation of its porous structure is necessary throughout the solidification process since it affects the strength properties significantly.

The ultimate porosity can also be modified by adjusting both the particle load-bearing solids in suspensions and the pore space thickness. As the particle size is larger than the nanoscale, there is a considerable amount of fracture bonds on the particle surface. The amount of surface energy increases dramatically as the particles appear to be more important for agglomeration. Mostly as a consequence of this, solid particles containing nano-particular suspension are much more crucial for localization [282]. In an experimental study, processed porous YSZ ceramic materials are treated with uni-directionally aligned pore channels using a freeze casting technique with all −30◦C, −78 ◦C and −196 ◦C. This shows that a reduction in pore size by lowering the three temperatures of each sample and low thermal conductivities, due to the limitation of mold and other considerations as well as its influence on specific freezing methods, has been minimally taken into account [280].

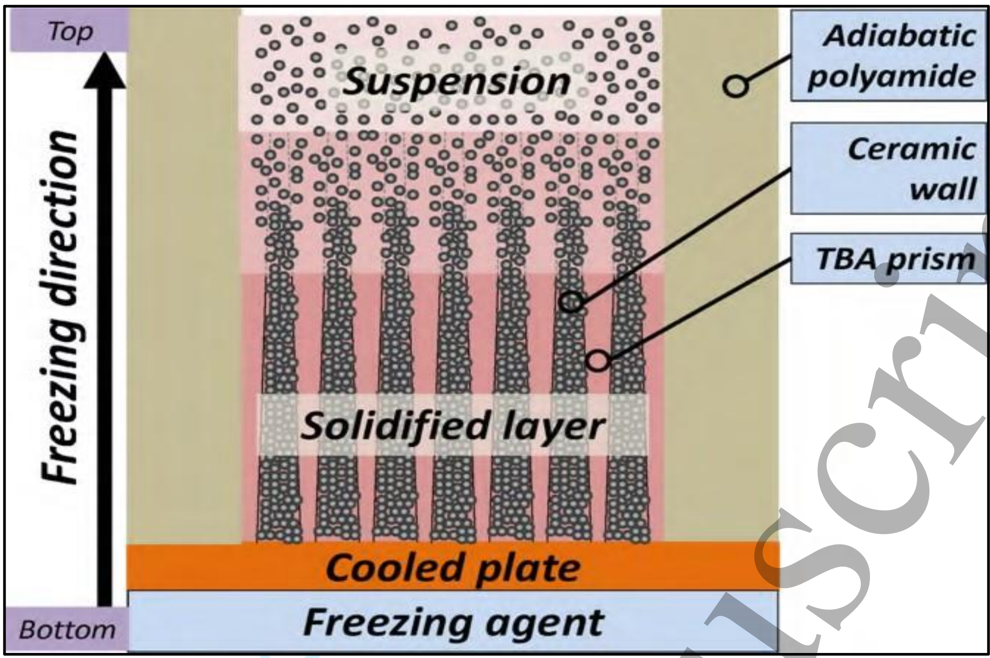

Figure 14. Schematic illustration of freeze casting system and pore structure formation during freeze casting [280].

The composition of the specific structure of ceramic materials has a beneficial impact across several other developmental phases. The nature of its structural activity and all its diverse interactions and synthetic materials seem to be of great interest. The distribution of pores may also be adapted to the range generally considered essential for biomedical applications. Porous ceramic scaffolds are effectively synthesized and characterized by the incorporation of nanoparticles from the very first stage. There is enough evidence on the market that the frozen products are mixed [283]. The freeze-casting technique was applied to different materials, including polymeric ceramic materials and metals, due to their flexible character. The formulation also concerned primarily the direct physical contact for the application of the porous structure and the removal of the particles from the solvent matrix and substrate material used. Much of the initial freeze-casting technique is performed under gelation or drying on polymeric materials [284]–[286]. Ceramic porosity is based on various freezing techniques rates is increased by 70%. Highly complex as well as unstable, the porous structure of the specimen formed by homogenous freezing also has high compressive strength. By comparison, the porous structure seems to be more structured and it has a high porosity as formulated ceramics using the bi-directional freezing method [287],[280].

The association within the particle size leading to synthetic ceramics is crucial for the high slurry concentration and for a small percentage of the particles to be locked into the microscopic particles via tip splitting and modification. The distribution of fined particles of pore size is always a key factor in the characteristics of different applications. While its porosity of micro-structured porous ceramics is indeed a version of the preceding ice-crystal structure, it is possible to adjust the finished porous structure of ceramic materials using different production needs [288]. The process of high anisotropic solvent solidification typically refers to the uni-directional solidification method and this approach is favoured as compared to isotropic solidification techniques.

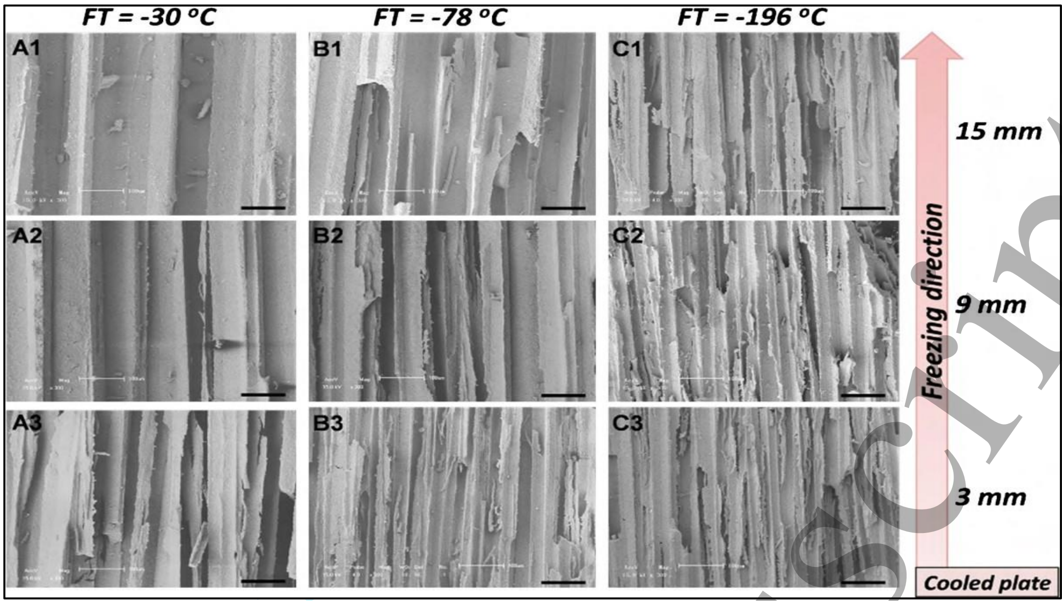

Figure 15. Microstructure of uni-directionally aligned pore channels in the porous YSZ ceramics at different locations from the cooled end of 15mm (A1, B1 and C1), 9mm (A2, B2 and C2), 3mm (A3, B3 and C3) and under different freezing temperatures of −30◦C (A1, A2 and A3), −78◦C (B1, B2 and B3) and −196◦C (C1, C2 and C3). FT: freezing temperature[280].

Figure 15 shows the microstructure of uni directionally aligned pore channels in porous YSZ ceramics at different distances from the cooling plate of 15 mm (A1, B1, and C1), 9 mm (A2, B2, and C2), 3 mm (A3, B3, and C3) and at different freezing temperatures of 30°C (A1, A2, and A3), 78°C (B1, B2, and B3), and 196°C (B1, B2 and (C1, C2, and C3). Regardless of the microstructure details in the individual samples, pore channel size decreased significantly with decreasing freezing temperature. The authors believe that as the solidification velocity increased, freezing temperature dropped, resulting in reduced prism spacing and thus pore channel size. Under different freezing temperatures of 30, 78, and 196 C, there are variations in pore channel size with distance from the cooling plate in porous YSZ ceramics with unidirectionally aligned pore channels. Pore channel size is determined by measuring the size of pore channels in a section parallel to the cooling plate's microstructure. On each sample, the microstructure at four random locations is taken. Lower freezing temperatures reveals larger pore channel sizes and a wider size range in the samples. Regardless of the location, the pore channel size shrank as the freezing temperature drops. In samples frozen at 30°C, the pore channel size is 31.6, 51.8, and 80.4m at 3, 9, and 15 mm away from the cooling plate, respectively. The corresponding values in samples frozen at 196°C decreases with decreasing the freezing temperatures to 16.4, 26.3, and 37.8 m, respectively. The pore channel size increased with distance away from the cooling plate, regardless of the freezing temperature. As shown in Fig. 15, the results are consistent with observations of microstructure development. Due to their thermal conductivity, copper and Teflon are typically made in the freeze casting base (down part) and top (upper part) of the mold easily to enhance surface morphology and solidification process. Also, porous ceramics with cylindrical pores closely connected uni-directionally displayed a typical gradient structure with increased pore sizes from tens in the bottom up to hundreds in the top. The development of porous morphologies using freeze casting is fully justified towards removing both the breakdown of solidification into non-planar morphology and the distribution and displacement of particles within the specimens, both affected by solidification [289]. Isotropic casting techniques are commonly employed in freezing gel production. Although ceramic materials do show a range of microstructural variations, the composition of which is almost isotropic. Under other conditions, precursors and suspension of the mixture may cause cross linking or the formation of gel until it is frozen.

Fortunately, porous structures vary widely from closed structural morphology, including the incorporation of space-holding techniques with an isotropic freezing method for equi-axial cells to an open structural morphology, with the use of highly conductive frozen molds from the bottom as well as radially from the front of the freezer [175], [290]–[292]. Freeze casting is an interesting process of transformation that should be used by freezing and extracting solvents from ceramic suspension to form stable porous material. This approach has several beneficial effects including flexibility to adapt the porous structure by adjusting production conditions, employing a wide range of ceramic materials, low tooling costs, and energy efficiency. Both have significant applications in various areas, including dental practice, orthopaedics, thermal or electrical implementation, purifying, and pain control. Because this type of technique can still be customized, it can rapidly advance its crystalline structure throughout the entire production process. A valuable contribution to the structural interface can also be made by laboratory conditions for the production of ceramic materials with a good understanding of the future large-scale micro-structural structure using freeze-casting. Closely related porous materials will be useful for the industrial production of both material science and engineering applications [293]–[295]. In this context, a comprehensive analysis of the various ceramic materials used in freezing methods is carried out, mostly on the properties and applications of porous materials. Freezing methods also make a significant contribution to the morphology, microstructure, and durability of porous ceramic materials.

3.6 Extrusion technique

The extrusion technique is used conventionally in to manufacture of honeycomb ceramics first introduced by John Etherington in the year 1619. Honeycomb ceramics have a highly porous structure, smooth grids, crystalline structures and effective surface morphology in engineering applications is also about > 1 mm in size, and it would be too large for regenerative bone implants. The extrusion method will considerably increase the output of relatively affordable Honeycomb ceramics [296]. The new technique of extrusion as a ram extrusion is widely used due to its significant advantages, including the ease of implementation and the versatility. The ram extrusion method is an advanced production approach that includes enabling benefits in engineering, ceramic industry to maintain dimensional accuracy with ideal surface integrity and long-lasting cross-section area, affordability, customizability, and efficiency [297],[298]. Porous ceramic materials formed by other techniques show good microstructures, although there are some complications including such as massive production problems, structural ceramic disadvantages, and microporous uniformity uncertainty. On the other hand, the extrusion method is commonly used for the widespread processing of honeycomb structures and porcelain in the manufacturing industries, including for the processing of ceramic reinforced glass fiber composites [299],[300]. The extrusion method has been confirmed as an effective method of combining Whisker-shaped structured ceramic particles with implant material to create a Unidirectional crystalline structure after sintering [301]–[303]. The technique of extrusion is particularly beneficial since it eliminates the difficulties of mass production, pore size distribution, and matrix modification. Integration errors can occur through extrusion techniques with high surface area particles. The regulation of the alignment of their pores can help to enhance the permeability of porous alumina ceramic materials. Due to the extremely structured microstructure, the resulting porous aluminum ceramic materials have higher flexural strength than traditional porous materials [304],[305],[306]. The homogeneous sequential flow of the compositional matrix results in a functional microstructure that stimulates the modification of the glass fibers in the extruder. Thus, flame retardant fibers are often used as pore-forming components, porous ceramics with uni-directionally positioned pore space may need to be formed by extrusion [300],[307]. A new type of extrusion technique called Thermoplastic Extrusion typically requires de-binding, which can be considered is among the most time-consuming, complex, and fragile phases in ceramic thermoplastics production. A significant volume of synthetic bonding material that is used inside feedstock for thermoplastics. The 40–50% binder is generally used to achieve the maximum rheological activity for the framing process. It is hard to extract such a large amount of binding agent without disrupting the composition of its particles. The blending process regulates the slurry mixture by combining ceramic powders with suitable plasticizers, lubricants, binders, coagulants, lubricants, deflocculants, surfactants, and preservatives. Several lubricants are widely used for lubrication purposes including silicones and crude oils. The extruder cycle is advantageous at lower speeds and high temperatures due to the high flow stress as well as the weak compressive strength of ceramic materials, as it reduces the capacitance on the flow.

3.7 Phase inversion method

The phase inversion technique seems to be regenerative for the manufacture of porous ceramics, particularly with very void fiber. It has been introduced in the year 1900. Phase inversion technique for the processing of anode substrates or compounds requires several phases of powder systemization using a solid-state or wet-chemical procedure. The process is time-consuming and energy-consuming, resulting in the emission of toxic gases [308][309]. A recent manufacturing approach, based mostly on phase inversion phenomena, has also been developed for the manufacture of functional ceramics, in particular with a very ceramic membrane configuration. This process was originally designed for the formation of a polymer membrane. The phase-inversion concept aims to convert the liquid form of polymer into a solid form of the polymer. Ceramic particles are dispersed as aqueous polymer solutions for the preparation of ceramic porous fibers. However, they are extruded into boiling water similar to a coagulation pool from a tube orifice spinneret. Mixing its water extraction liquid by immersion in water results in precipitation [310]. Phase inversion tape casting is also to be an efficient and easy method for the preparation of porous ceramic materials. It is also widely accepted that polymer solutions are being developed by the crystallization and development techniques as well as the production of finger-like macro voids. Diffusion-controlled aqueous streams are influenced by a mixture of polymers that surrounds the nucleus [311]. Phase inversion usually involves de-mixing procedures that transform the immediately thermodynamically sensible solution from liquid to solid state in a sensible manner. Its denser liquid phase can be reinforced by forming a dense framework at some point in de-mixing. All of these transitions are carried out in a variety of ways, including regulated solvent evaporation in three-component networks, submerged precipitation by incorporation into a non-solvent system, vapor precipitation and thermal expansion segregation [290], [309], [312], [313]. One major challenge that controls effective casting in phase inversion appears to be the lack of a structured and effective process for selecting a solvent mechanism. Both submerged precipitation and thermal phase inversion, as described in the studies, are commonly used in ceramic industrial applications. Ceramic particles containing aqueous phase are milled for one day approximately 24 hours as a standard precursor material for suspension, complemented by even more stirring for more than 24 hours after polymer addition. The suspension would then be compacted by a dual-cylinder nozzle positioned near the non-solvent water [314]. In fact, this method is the main technique for the preparation of ceramic membranes.

4. Dental-ceramics properties

Ceramic glasses are also preferred as high-performance ceramics, competent ceramics, attenuated ceramics that provide crystal structure, with absolute manufacturing regulations for well-characterized / classified ceramic materials. The microstructure of some alloy powders, in which **Figure 16** specifically shows the spherical geometry of the Co-Cr-Mo alloy and opaque porcelain powders.[315]. A CoCrMo dental alloy was used in this study in two forms: ingot and powder. The powder was produced by air atomization and supplied by Nobilmetal, the alloy's manufacturer. The alloy powder particles have spherical shape (Fig. 16) and the particle size distribution is the following: D10 = 4.44 µm; D50 = 8.27 µm and D90 = 12.76 µm. An opaque porcelain powder was used in which the composition is shown in micrograph in Fig. 16(b). The measured specific surface areas of four groups of powders are 12.46 (P0.4), 6.10 (P0.9), 5.01 (P1.5), and 3.46 (P2.0) m^2/g, which corresponds to the median particle size D50 sequence. As a result, the powders can be classified into four groups based on their median particle size: fine, medium-fine, medium coarse, and coarse powder. The SEM images of four AlON powders show the particle size characterization (Fig. 17). The AION is one of the hardest polycrystalline transparent ceramic materials as shown in **Figure 17**. The particle size characterization of four AlON powders from SEM images and fracture analysis of AlON powders are shown in **Figure 19**. The AlON sample has a relative density of up to 99.83 percent (using a theoretical density of 3.688 g/cm3), contributing to its high transmittance. As a result, using coarse AlON powder in direct aqueous slip casting to prepare green bodies for pressure less sintering of highly transparent AlON ceramics is a feasible option. For the better understanding about the microstructure of ceramic composite $Bi_4Ti_3O_{12}$, in research findings it has been revealed that both powders are in pure BIT phase. The SEM images and XRD patterns are exhibited in Figs. 18 However, after ball milling, BIT-1 powder contains equiaxially shaped particles with a diameter of 1–2.5 m and has a normal random XRD pattern. Because of the plate-like particle shape, BIT-2 powder contains single-crystalline plate-like particles with diameters of 0.5–3 m and a thickness of 0.2 m. The XRD pattern indicates a c-plane orientation (with stronger (0 0 l) peaks). The down surfaces which are in the two samples have the same random microstructure are clearly showed in **Figure 20**. It is worth noting that both samples bottom surfaces have the same random microstructure. The large c-plane of the BIT grains can be seen clearly in the top surfaces of the sample without magnetic alignment (as indicated by the arrow). However, it is difficult to find in the magnetically aligned sample.Ceramic materials which actually possess attractive properties such as corrosive behavior, strength, thermal conductivity and heat resistance, and good stability with a wide range of bioactive solvents, Stabilizing the glass structure and Nontoxic substance release. Due to the present of porous space and its chemical inertness, especially in aquatic environments, it does not always have harmful effects. Non-metallic inorganic solids include plastic fibers, feldspar, and silica, consisting of oxides, nitrates, carbides, and non-silicate ceramic glasses [316],[317]. The oxide compositions, though also involve both the crystalline structure and the amorphous forms of the macroscale and the larger porous structure. As a result, conventional ceramic glasses, such as floor tiles, porcelain, can also be considered due to their ductility and durability, thermal conductivity as silica provides a significant temperature gradient in its melting state and feldspar. In addition, this nanomaterial will have good biocompatibility and limited temperature-dependent enamel adhesion occurring in three phases, Monoclinic, Cubic, and Tetragonal. The monolithic phase appears to be brittle at the temperature of the cellar, requiring stabilization in order to avoid the transition of the Tetragonal-to-Monoclinic in engineering fields [124], [318]–[321]. In the recent decades, Zirconia has attracted researchers and industrialists (for large scale industrial productions) because of its significant range of desired characteristics than Alumina. Zirconia has shown that, in dental practice, poly-crystal tetragonal zirconia is partially stable despite higher fracture resistance, which increases crack formation [322]. Yttria-stabilized tetragonal zirconia polycrystalline which has shown excellent biocompatibility, high strength, extreme durability, good biological integration into the body easily [323],[324], and microstructural consistency to match rugophilic surface as well as cell proliferation development [325]. In dental practice one of the most common used materials is Titanium, which has been considered as one of the best implant materials in dental practice due to its built-in capacity, durability, strength ratio, biocompatibility, easy and rapid integration into the body. It also has excellent morphology layer stabilization oxides, which are also used in intraosseous applications, and easy engineering in the ceramic industry [324], [326]–[328]. Using various research and review articles, the physical and mechanical properties for various ceramic composition, compounds are listed as shown in **Table 2.**

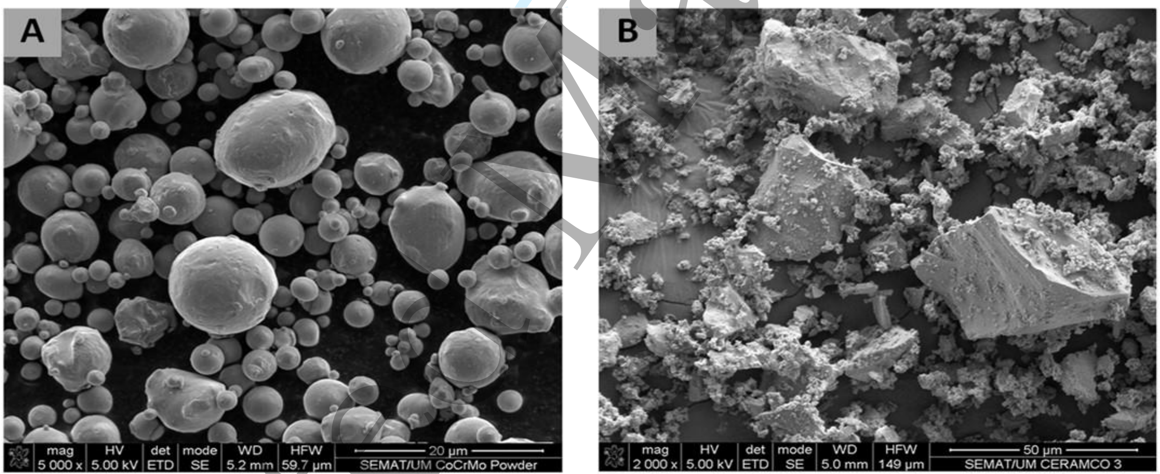

Figure 16. SEM micrographs of (A) CoCrMo alloy powders and (B) opaque porcelain powders (Ceramco3) [315].

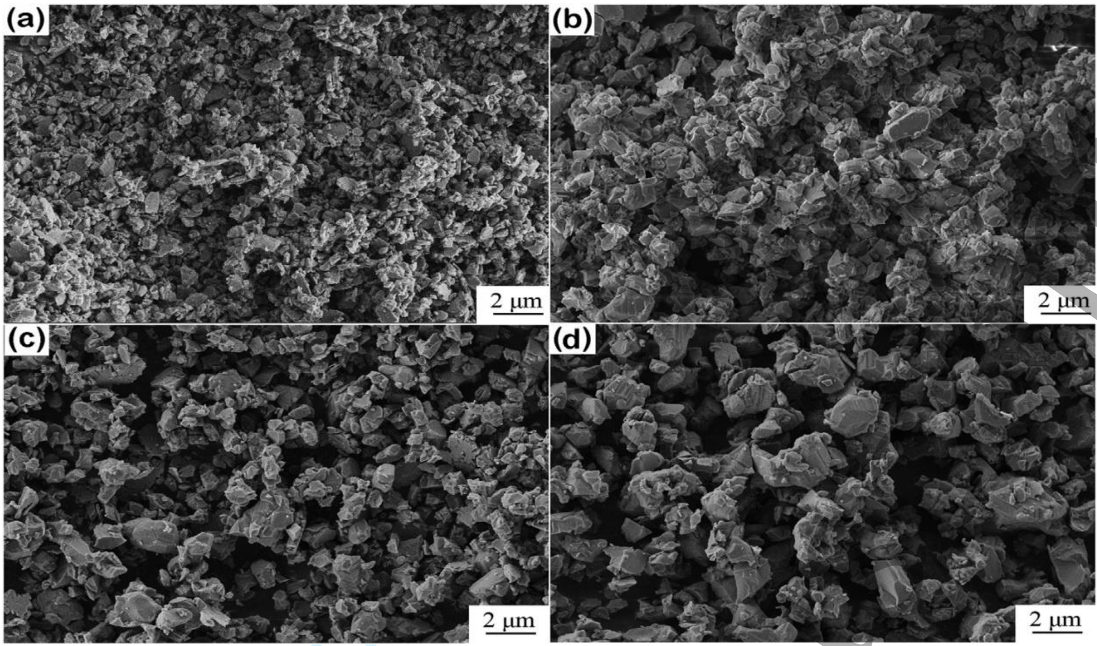

Figure 17. SEM images of the ball milled AlON powders: (a) P0.4, (b) P0.9, (c) P1.5, (d) P2.0 [329].

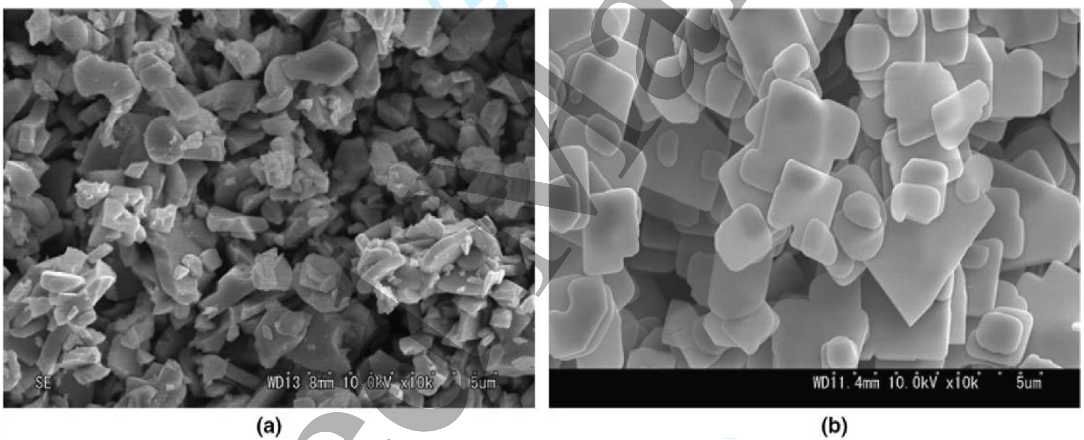

Figure 18. SEM images of starting BIT powders (a) BIT-1with equi axial shaped particles (b) BIT-2 with plate-like shaped particles [330].

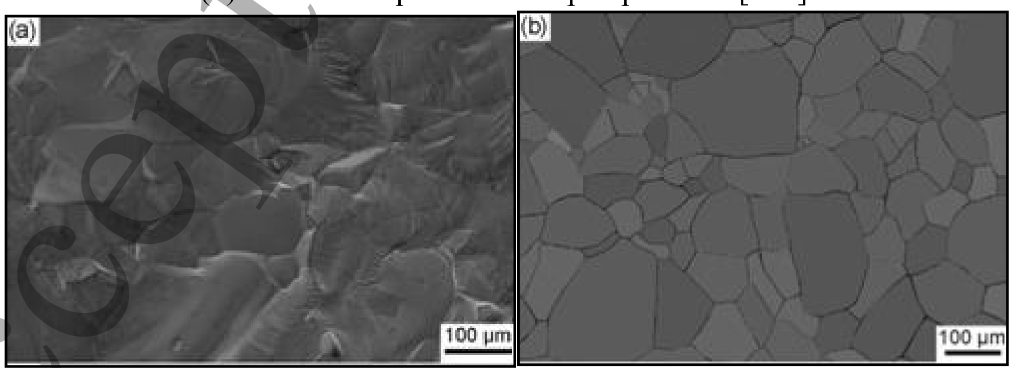

Figure 19. Fractured surface (a) and hot etched surface (b) of the direct coarse powder aqueous slip casting AlON ceramics [329].

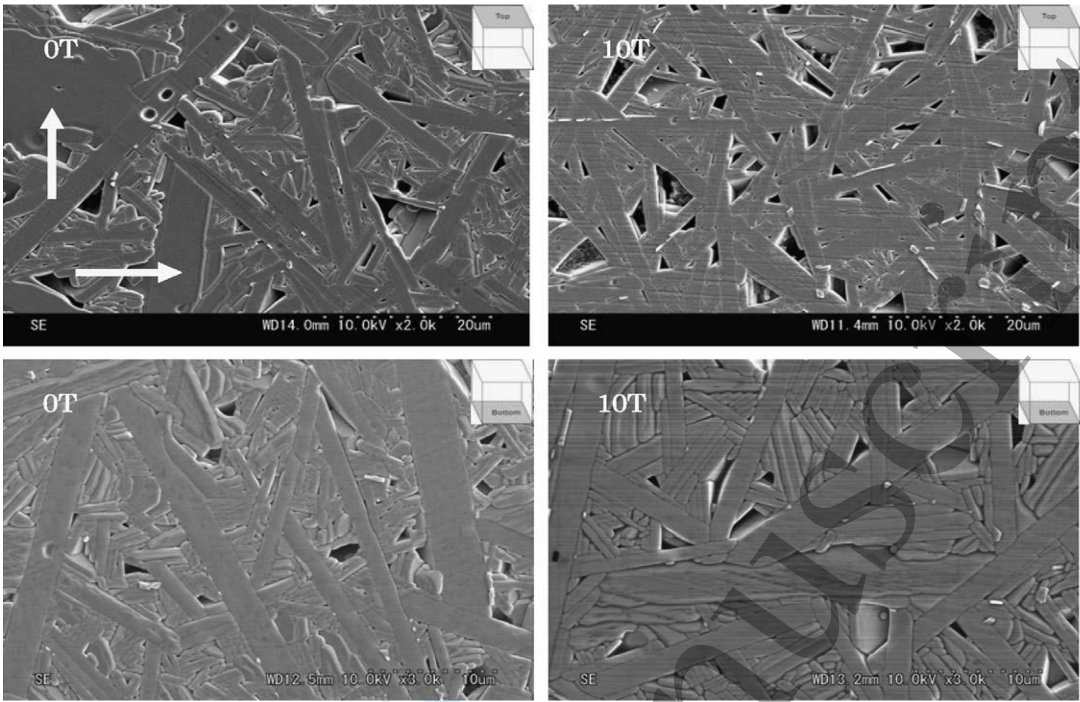

Figure 20. Microstructures of sintered BIT samples using BIT-1 powder with and without magnetic alignment. The observed surface was shadowed [330].

Table 2. Properties of Various ceramic materials [126], [134], [136], [137], [150], [331]–[363].

Type of ceramic	**Flexural /Bending strength (MPa)**	**Young's Modulus (E)**	**Fracture toughness (MPa.m1/2)**	**Compressive strength (MPa)**	**Hardness (GPa)**	**Tensile strength (MPa)**	**Co-efficient of thermal expansion**
	365	----	2.80	----	5.3	----	----
	350-450	70	0.8– 1.5	----	4–6.5	----	10.2 ±0.4 × 10−6 K−1
	350-450	70	0.8– 1.5	----	4–6.5	----	10.6 ± 0.35 10^{-6} K−1
	250-365	90–100	2-3.5	----	----	----	----
	740.8	----	3.30	----	----	----	----
Lithium di-silicate	740.8 ± 79.7	----	3.30	----	----	----	----

($Li_2O_5Si_2$)							
	249 ± 16	----	2.1 ± 0.2	----	----	----	----
	215 ± 18	----	2.2 ± 0.2	----	----	----	----
	165 ± 16	----	1.8 ± 0.1	----	----	----	----
	185 ± 241	----	1.9 ± 0.2	----	----	----	----
	164	----	1.03	----	6.5	----	----
	80–120	70	0.7–1.2	----	6.5	----	16.6 × 10−6 K−1
Leucite($K[AlSi_2O_6]$)	80–120	70	0.7–1.2	----	6.5	----	17.5 × 10−6 K−1
	55-134	65–67	0.8–1.3	----	5.3–7.9	----	----
Wollastonite ($CaSiO_3$)	294	46.5	2	60	----	----	----
Di-calcium silicate (Ca_2SiO_4)	26–97	10–40	1.1–1.8	----	----	----	----
Tri-calcium silicate (Ca_3SiO_5)	93.4	36.7	1.93	----	----	----	----
Magnesium silicate ($MgSiO_3$)	32	8.5	----	----	----	----	----
MagnesiumAluminosilicate ($Mg_2Al_4Si_5O_{18}$)	----	70	1.5	350	----	----	1-2×10^{-6} °C^{-1}
Di-magnesium silicate (Mg_2SiO_4)	203	----	----	----	----	----	----

Monticellite ($CaMgSiO_4$)	159	51	1.63	----	----	----	----
Merwinite ($Ca_3MgSi_2O_8$)	151	31	1.72	----	----	----	----
Diopside ($CaMgSi_2O_6$)	300	----	3.50	0.2–1.36	----	----	----
Mullite ($Al_6Si_2O_{13}$)	180	151	2	1310	----	----	5.4×10^{-6} °C^{-1}
Akermanite ($Ca_2MgSi_2O_7$)	----	----	0.63–1.72	0.53–1.13	----	----	----
Bredigite ($Ca_7MgSi_4O_{16}$)	156	43	1.57	0.233	----	----	----
Hardystonite ($(Sr,Ca)SiO_3$)	136	37	1.37	----	----	----	----
Silicocarnotie($Ca_5P_2SiO_{12}$)	65	80	----	----	----	----	----
	90–130	70	0.8–1.5	----	4–6.5	----	6.4–7.2 × 10−6 K−1
Mica ($AB_{2–3}(X, Si)_4O_{10}(O, F, OH)_2$)	140–160	48–164	0.6–2.2	----	3.2–4.5	----	----
Zin silicate (Zn_2SiO_4)	91	37.5	----	----	----	----	----

Zirconia Reinforced lithium silicate (ZrO_2 / Li_2SiO_3)	444 ± 39	70 ± 2	2.31 ± 0.17	----	6.5 ± 0.5	----	----
Zirconia(ZrO_2)	177–1000	100–250	1-8	----	5–15	115–711	----
Zirconia Toughened Alumina(ZTA) (ZrO-Al_2O_3)	----	330	7.3	2500	----	----	8 x 10−6 $^oC^{-1}$
Magnesia partially – stabilized Zirconia (Mg-PSZ)	----	205	6	1700	----	----	10 x 10−6 $^oC^{-1}$
Zirconium silicate($ZrSiO_4$)	----	----	2.1	----	7.5	----	2.5-4 x10^{-6} °C^{-1}
Zirconium di-boride (ZrB_2)	----	450	2–3	----	14–23	----	5.9 × 10^{-6} °C^{-1}
	500	380	3.5 - 4	----	22	267	----
Alumina (Al_2O_3)	379	375	4	2600	1440	----	8.4 x 10−6 $^oC^{-1}$
Alumina-toughened zirconia (ATZ)	----	250	8-12	2600	N/A	----	10 x $10^{-6}$$^oC^{-1}$
Aluminium nitride (AlN)	----	330	2.6	2100	1100	----	4.2-5.8 x 10−6 $^oC^{-1}$
Aluminiu mtitanate (Al_2TiO_5)	----	10–20	----	----	----	----	1× 10^{-6} K^{-1}

Silicon aluminium oxynitride(SIALON)	760	288	6-7.5	----	1430-1850	----	3 x 10−6 $^{o}C^{-1}$
Silicon carbide (SiC)	----	410	4.6	3900	2800	----	4.5 × 10−6 K^{-1}
Silicon nitride(Si_3N_4)	689-830	310	5.7-6.1	----	1450-1580	----	3.3 x 10−6 $^{o}C^{-1}$
Titanium dioxide (TiO_2)	----	----	3.2	680	----	----	9 x 10^{-6} $^{o}C^{-1}$
Titanium carbide (TiC)	----	450	----	----	3200	----	----
Titanium silico-carbide (Ti_3SiC_2)	----	322	----	----	4	----	9.1 x 10^{-6} K^{-1}
Titanium di-boride (TiB_2)	----	----	----	----	33.7	----	----
Tungsten acid scandium ($Sc_2W_3O_{12}$)	----	----	----	----	----	----	−11 × 10^{-6} °C^{-1}
Boron carbide (B_4C)	900	460	2.2	----	37	----	----

5. Future aspects

At all times of ceramic industry from past to present and in the future, ceramic productions play a vital role in the dental and orthopedics practices. One of the interesting aspect lies in its precision and accuracy when it is fabricated and manufactured from both conventional and new techniques. Ceramic manufacturing methods such as Tape Casting, Gel casting (direct foaming), Slip Casting, Sol-gel Casting, Freeze Casting, Hot pressing, Extrusion technique, Phase inversion method. These techniques are being employed to minimize the cost of components and to improve the production rate for engineering applications.

- Most of these approaches only supports the possibility in enhancing the microstructural stability, but researchers can also work on particle incorporation during the fabricating time in the mold. Compositional particle integration can be find out for the better results.

- Employing various techniques for ceramic production are transforming into three dimensional processing due to its flexibility, durability, easy to produce more components in less time.
- Fabrication of green bodies may affect the sintered material or component which has demonstrated enhanced particle stability, crystalline microstructure, particle size distribution and densifies the composition of mixture.
- From our literature reviews, one main difficulty in every processing techniques is to enhance particle distribution and reduce porous space in the processed component. With the ceramic material properties like thermal conductance, fracture toughness, durability, coloration (in dental implants), flexural strength and hardness, which have proved some enhancements after heat treatment of the ceramic materials.
- In this regard, the main problem is to improve the durability, porous space in the compositional structure and also the crystalline phase. The main aim in ceramic research findings is to develop and implement easily processing products in less time and with low labor cost (for ceramic components producers).
- Ceramics advancements has been established or developed in the dental practices due to its availability and durable nature for implanting in to human body. Most common used ceramic materials in market include alumina, zirconia and silicates among others due to their integrative/ incorporative behavior in to human body easily and rapidly.
- New ceramic compositions can also be found by reinforcing various raw ceramic materials for reducing the cost and to make it available to common people.
- In the recent era, new techniques for fabricating the ceramics has been introduced which are called 3D printing, Additive manufacturing and CAD manufacturing.
- All these techniques are being employed because of its interesting manufacturing capacity with more accuracy also the precision.
- 3D printing will continue to play an important role in the production of porous ceramic components in developing a production perspective.
- Economic development of production includes functional development of prototypes and the feasibility testing as well as rapid tooling.
- Many other processes of 3D printing still concern the production considerations, like Massive production with quicker and cheaper manufacturing, makes the components easier to manufacture. In addition, the size and shape of the component and designs can be used as being easy to produce.
- Porous ceramic fabrication techniques are used in many fields of application, particularly in dental practices. It is widely used for research and development in tissue engineering, medical implant filtration technology, and engineering and replacement parts manufacturing.
- It is used for the production of porous ceramic materials due to the challenging rheological transfer and specific features of the ceramics. At the moment, AM approaches are in the early developmental stages.
- New technological innovation is required to focus on increasing the optimization of its application performance by new methods.

6. Conclusions

In recent years, ceramic materials have attracted increasing attention due to its physicochemical integration, biocompatibility, and its ability to incorporate into the human body. The manufacturing process plays an important role to produce various required shaped ceramics, and to produce the ceramics in our own requirements (customized) such as porosity and durability. This is so that it can be used in dentistry as well as in various engineering and industrial applications. This article addressed about various types of ceramics which are manufactured using different materials such as alumina, zirconia and 3YZTP in order to achieve a significant property such as thermal conductivity, biocompatibility, corrosion resistance, strength and incorporating into body. Due to technological advancements ,there will be new approaches in producing the components especially ceramic components in a new direction, as we have a lot of conventional fabrication techniques which includes, tape casting, gel casting, hot pressing, freeze casting and phase inversion method. In addition, three dimensional customized products especially in dental practices are now becoming a great advancement in this generation. With huge demand in market for ceramic materials, a novel solution is found to produce more in an effective way and cost effectively. All fabrication techniques such as 3D printing and additive manufacturing approaches in various engineering applications as well as an outline for better understanding insight about ceramics and some methods and approaches for synthesizing and fabrications which are ease to use for industrial production. In this comprehensive review, we specifically summarize all previous works of experimental findings and present various beneficiary aspects of future ceramics implementation process with more beneficial attributes.

References

[1] F. T. Filser, "Direct Ceramic Machining of Ceramic Dental Restorations," *Ph.D. thesis. Zurich*, 2001.

[2] C. Ritzberger, E. Apel, W. Höland, A. Peschke, and V. M. Rheinberger, "Properties and clinical application of three types of dental glass-ceramics and ceramics for CAD-CAM technologies," *Materials (Basel).*, 2010, doi: 10.3390/ma3063700.

[3] M. Montazerian and E. D. Zanotto, "Bioactive and inert dental glass-ceramics," *Journal of Biomedical Materials Research - Part A*. 2017, doi: 10.1002/jbm.a.35923.

[4] T. Kokubo, *Bioceramics and their Clinical Applications*. 2008.

[5] D. F. Williams, "Discussion session one: general biomaterials," in *Progress in Biomedical Engineering, 4. Definitions in Biomaterials*, 1987.

[6] G. Kaur, O. P. Pandey, K. Singh, D. Homa, B. Scott, and G. Pickrell, "A review of bioactive glasses: Their structure, properties, fabrication and apatite formation," *Journal of Biomedical Materials Research - Part A*. 2014, doi: 10.1002/jbm.a.34690.

[7] D. S. Brauer, "Bioactive glasses - Structure and properties," *Angewandte Chemie - International Edition*. 2015, doi: 10.1002/anie.201405310.

[8] M. Javaid, A. Haleem, and L. Kumar, "Current status and applications of 3D scanning

in dentistry," *Clin. Epidemiol. Glob. Heal.*, 2019, doi: 10.1016/j.cegh.2018.07.005.

[9] J. Tinschert, D. Zwez, R. Marx, and K. J. Anusavice, "Structural reliability of alumina-, feldspar-, leucite-, mica- and zirconia-based ceramics," *J. Dent.*, 2000, doi: 10.1016/S0300-5712(00)00030-0.

[10] R. R. Seghi, T. Daher, and A. Caputo, "Relative flexural strength of dental restorative ceramics," *Dent. Mater.*, 1990, doi: 10.1016/0109-5641(90)90026-B.

[11] J. R. Mackert, M. B. Butts, and C. W. Fairhurst, "The effect of the leucite transformation on dental porcelain expansion," *Dent. Mater.*, 1986, doi: 10.1016/S0109-5641(86)80067-7.

[12] S. J. Saint-Jean, "Dental Glasses and Glass-ceramics," in *Advanced Ceramics for Dentistry*, 2014.

[13] Mohamed N. Rahaman and Aihua Yao, B. Sonny Bal, Jonathan P. Garino, Michael D. Ries "First clinical study of a novel complete metal-free ceramic total knee replacement system.," *J. Orthop. Surg. Res.*, 2016, doi: 10.1111/j.1551-2916.2007.01725.x.

[14] M. N. Rahaman, A. Yao, B. S. Bal, J. P. Garino, and M. D. Ries, "Ceramics for prosthetic hip and knee joint replacement," *J. Am. Ceram. Soc.*, 2007, doi: 10.1111/j.1551-2916.2007.01725.x.

[15] F. C. Serbena, I. Mathias, C. E. Foerster, and E. D. Zanotto, "Crystallization toughening of a model glass-ceramic," *Acta Mater.*, 2015, doi: 10.1016/j.actamat.2014.12.007.

[16] O. Peitl, E. D. Zanotto, F. C. Serbena, and L. L. Hench, "Compositional and microstructural design of highly bioactive P 2O 5-Na 2O-CaO-SiO 2 glass-ceramics," *Acta Biomater.*, 2012, doi: 10.1016/j.actbio.2011.10.014.

[17] E. a Mclaren and P. T. Cao, "Ceramics in Dentistry—Part I: Classes of Materials," *Insid. Dent.*, 2009.

[18] I. Denry and J. R. Kelly, "Emerging ceramic-based materials for dentistry," *Journal of Dental Research*. 2014, doi: 10.1177/0022034514553627.

[19] I. Dion, L. Bordenave, F. Lefebvre, R. Bareille, Ch. Baquey, J.-R. Monties and P. Havlik, "Physico-chemistry and cytotoxicity of ceramics - Part II Cytotoxicity of ceramics," *J. Mater. Sci. Mater. Med.*, 1994, doi: 10.1007/BF00121148.

[20] I. Denry and J. R. Kelly, "State of the art of zirconia for dental applications," *Dent. Mater.*, 2008, doi: 10.1016/j.dental.2007.05.007.

[21] R. Sakaguchi and J. Powers, *Craig's Restorative Dental Materials*. 2012.

[22] F. MANNOCCI, B. BHUVA, and S. STERN, "Restoring teeth following root canal re-treatment," *Endod. Top.*, 2008, doi: 10.1111/j.1601-1546.2011.00263.x.

[23] C. Piconi, M. Labanti, G. Magnani, M. Caporale, G. MacCauro, and G. Magliocchetti, "Analysis of a failed alumina THR ball head," *Biomaterials*, 1999, doi: 10.1016/S0142-9612(99)00028-9.

[24] Hideki Warashina, Shinji Sakano, Shinji Kitamura, Ken-Ichi Yamauchi, Jin Yamaguchi, Naoki Ishiguro, Yukiharu Hasegawa "Biological reaction to alumina,

zirconia, titanium and polyethylene particles implanted onto murine calvaria," *Biomaterials*, 2003, doi: 10.1016/S0142-9612(03)00120-0.

[25] F. Butz, G. Heydecke, M. Okutan, and J. R. Strub, "Survival rate, fracture strength and failure mode of ceramic implant abutments after chewing simulation," *J. Oral Rehabil.*, 2005, doi: 10.1111/j.1365-2842.2005.01515.x.

[26] K. H.-K. and K. S.-H., "Optical properties of pre-colored dental monolithic zirconia ceramics," *J. Dent.*, 2016, doi: 10.1016/j.jdent.2016.10.001 LK

[27] M. Sedda, A. Vichi, M. Carrabba, A. Capperucci, C. Louca, and M. Ferrari, "Influence of coloring procedure on flexural resistance of zirconia blocks," *J. Prosthet. Dent.*, 2015, doi: 10.1016/j.prosdent.2015.02.001.

[28] H. K. Kim and S. H. Kim, "Effect of the number of coloring liquid applications on the optical properties of monolithic zirconia," *Dent. Mater.*, 2014, doi: 10.1016/j.dental.2014.04.008.

[29] T. Kosmač, C. Oblak, P. Jevnikar, N. Funduk, and L. Marion, "The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic," *Dent. Mater.*, 1999, doi: 10.1016/S0109-5641(99)00070-6.

[30] Y. S. Jung, J. W. Lee, Y. J. Choi, J. S. Ahn, S. W. Shin, and J. B. Huh, "A study on the in-vitro wear of the natural tooth structure by opposing zirconia or dental porcelain," *J. Adv. Prosthodont.*, 2010, doi: 10.4047/jap.2010.2.3.111.

[31] N. C. Lawson, S. Janyavula, S. Syklawer, E. A. McLaren, and J. O. Burgess, "Wear of enamel opposing zirconia and lithium disilicate after adjustment, polishing and glazing," *J. Dent.*, 2014, doi: 10.1016/j.jdent.2014.09.008.

[32] J. H. Park, S. Park, K. Lee, K. D. Yun, and H. P. Lim, "Antagonist wear of three CAD/CAM anatomic contour zirconia ceramics," *J. Prosthet. Dent.*, 2014, doi: 10.1016/j.prosdent.2013.06.002.

[33] H. Shin, S. Jo, and A. G. Mikos, "Biomimetic materials for tissue engineering," *Biomaterials*. 2003, doi: 10.1016/S0142-9612(03)00339-9.

[34] R. Shah, A. C. M. Sinanan, J. C. Knowles, N. P. Hunt, and M. P. Lewis, "Craniofacial muscle engineering using a 3-dimensional phosphate glass fibre construct," *Biomaterials*, 2005, doi: 10.1016/j.biomaterials.2004.04.049.

[35] P. Ducheyne and Q. Qiu, "Bioactive ceramics: The effect of surface reactivity on bone formation and bone cell function," *Biomaterials*, 1999, doi: 10.1016/S0142-9612(99)00181-7.

[36] Silvia Minardi, Bruna Corradetti, Francesca Taraballi, Monica Sandri, Jeffrey Van Eps, Fernando Cabrera, Bradley K. Weiner, Anna Tampieri, Ennio Tasciotti "Evaluation of the osteoinductive potential of a bio-inspired scaffold mimicking the osteogenic niche for bone augmentation," *Biomaterials*, 2015, doi: 10.1016/j.biomaterials.2015.05.011.

[37] Richard M. Daya, Aldo R. Boccaccini, Sandra Shurey, Judith A. Roether, Alastair Forbes, Larry L. Hench, Simon M. Gabe "Assessment of polyglycolic acid mesh and bioactive glass for soft-tissue engineering scaffolds," *Biomaterials*, 2004, doi: 10.1016/j.biomaterials.2004.01.043.

[38] H. H. Lu, S. F. El-Amin, K. D. Scott, and C. T. Laurencin, "Three-dimensional, bioactive, biodegradable, polymer-bioactive glass composite scaffolds with improved mechanical properties support collagen synthesis and mineralization of human osteoblast-like cells in vitro," *J. Biomed. Mater. Res. - Part A*, 2003, doi: 10.1002/jbm.a.10399.

[39] S. S. Kim, K. M. Ahn, M. S. Park, J. H. Lee, C. Y. Choi, and B. S. Kim, "A poly(lactide-co-glycolide)/hydroxyapatite composite scaffold with enhanced osteoconductivity," *J. Biomed. Mater. Res. - Part A*, 2007, doi: 10.1002/jbm.a.30836.

[40] L. L. Hench, R. J. Splinter, W. C. Allen, and T. K. Greenlee, "Bonding mechanisms at the interface of ceramic prosthetic materials," *J. Biomed. Mater. Res.*, 1971, doi: 10.1002/jbm.820050611.

[41] D. Arcos and M. Vallet-Regí, "Sol-gel silica-based biomaterials and bone tissue regeneration," *Acta Biomaterialia*. 2010, doi: 10.1016/j.actbio.2010.02.012.

[42] T. Albrektsson and C. Johansson, "Osteoinduction, osteoconduction and osseointegration," *Eur. Spine J.*, 2001, doi: 10.1007/s005860100282.

[43] T. Albrektsson and C. Johansson, "Osteoinduction, osteoconduction and osseointegration," in *The Use of Bone Substitutes in Spine Surgery*, 2002.

[44] G. Kaur, G. Pickrell, N. Sriranganathan, V. Kumar, and D. Homa, "Review and the state of the art: Sol–gel and melt quenched bioactive glasses for tissue engineering," *Journal of Biomedical Materials Research - Part B Applied Biomaterials*. 2016, doi: 10.1002/jbm.b.33443.

[45] R. D. Rawlings, "Bioactive glasses and glass-ceramics," *Clinical Materials*. 1993, doi: 10.1016/0267-6605(93)90038-9.

[46] L. L. Hench, "Role of inorganic and theoretical chemistry in ceramics: past, present, and future," *Br. Ceram. Trans.*, 1999, doi: 10.1179/096797899680525.

[47] D. Shi, D. Shi, and G. Jiang, "Introduction to Bioceramics," in *Introduction to Biomaterials*, 2005.

[48] L. L. Hench, "The story of Bioglass®," 2006, doi: 10.1007/s10856-006-0432-z.

[49] L. L. Hench and J. M. Polak, "Third-generation biomedical materials," *Science*. 2002, doi: 10.1126/science.1067404.

[50] E. Apel, J. Deubener, A. Bernard, M. Höland, R. Müller, H. Kappert, V. Rheinberger, W. Höland "Phenomena and mechanisms of crack propagation in glass-ceramics," *J. Mech. Behav. Biomed. Mater.*, 2008, doi: 10.1016/j.jmbbm.2007.11.005.

[51] K. Rezwan, Q. Z. Chen, J. J. Blaker, and A. R. Boccaccini, "Biodegradable and bioactive porous polymer/inorganic composite scaffolds for bone tissue engineering," *Biomaterials*. 2006, doi: 10.1016/j.biomaterials.2006.01.039.

[52] T. Kokubo, H. M. Kim, and M. Kawashita, "Novel bioactive materials with different mechanical properties," *Biomaterials*, 2003, doi: 10.1016/S0142-9612(03)00044-9.

[53] Q. Z. Chen, K. Rezwan, D. Armitage, S. N. Nazhat, and A. R. Boccaccini, "The surface functionalization of 45S5 Bioglass®-based glass-ceramic scaffolds and its impact on bioactivity," 2006, doi: 10.1007/s10856-006-0433-y.

[54] L. G. Griffith, "Emerging design principles in biomaterials and scaffolds for tissue engineering," 2002, doi: 10.1111/j.1749-6632.2002.tb03056.x.

[55] T. Kokubo, S. Ito, M. Shigematsu, S. Sanka, and T. Yamamuro, "Fatigue and life-time of bioactive glass-ceramic A-W containing apatite and wollastonite," *J. Mater. Sci.*, 1987, doi: 10.1007/BF01133359.

[56] M. Bohner, "Resorbable biomaterials as bone graft substitutes," *Materials Today*. 2010, doi: 10.1016/S1369-7021(10)70014-6.

[57] J. R. Jones, "Review of bioactive glass: From Hench to hybrids," *Acta Biomaterialia*. 2013, doi: 10.1016/j.actbio.2012.08.023.

[58] J. R. Jones, "Reprint of: Review of bioactive glass: From Hench to hybrids," *Acta Biomaterialia*. 2015, doi: 10.1016/j.actbio.2015.07.019.

[59] S. R. Kandavalli, Q. Wang, M. Ebrahimi, and C. Gode, "A Brief Review on the Evolution of Metallic Dental Implants : History , Design , and Application," vol. 8, no. May, 2021, doi: 10.3389/fmats.2021.646383.

[60] F. Duret, J. L. Blouin, and B. Duret, "CAD-CAM in dentistry.," *J. Am. Dent. Assoc.*, 1988, doi: 10.14219/jada.archive.1988.0096.

[61] G. Davidowitz and P. G. Kotick, "The Use of CAD/CAM in Dentistry," *Dental Clinics of North America*. 2011, doi: 10.1016/j.cden.2011.02.011.

[62] R. W. K. Li, T. W. Chow, and J. P. Matinlinna, "Ceramic dental biomaterials and CAD/CAM technology: State of the art," *Journal of Prosthodontic Research*. 2014, doi: 10.1016/j.jpor.2014.07.003.

[63] E. D. Rekow, N. R. F. A. Silva, P. G. Coelho, Y. Zhang, P. Guess, and V. P. Thompson, "Performance of dental ceramics: Challenges for improvements," *Journal of Dental Research*. 2011, doi: 10.1177/0022034510391795.

[64] A. Gahler, J. G. Heinrich, and J. Günster, "Direct laser sintering of Al2O3-SiO2 dental ceramic components by layer-wise slurry deposition," *J. Am. Ceram. Soc.*, 2006, doi: 10.1111/j.1551-2916.2006.01217.x.

[65] R. Galante, C. G. Figueiredo-Pina, and A. P. Serro, "Additive manufacturing of ceramics for dental applications: A review," *Dent. Mater.*, vol. 35, no. 6, pp. 825–846, 2019, doi: 10.1016/j.dental.2019.02.026.

[66] H. Li, L. Song, J. Sun, J. Ma, and Z. Shen, "Dental ceramic prostheses by stereolithography-based additive manufacturing: potentials and challenges," *Adv. Appl. Ceram.*, 2019, doi: 10.1080/17436753.2018.1447834.

[67] E. özkol, W. Zhang, J. Ebert, and R. Telle, "Potentials of the ' Direct inkjet printing' method for manufacturing 3Y-TZP based dental restorations," *J. Eur. Ceram. Soc.*, 2012, doi: 10.1016/j.jeurceramsoc.2012.03.006.

[68] J. Ebert, E. Özkol, A. Zeichner, K. Uibel, Ö. Weiss, U. Koops, R. Telle, and H. Fischer "Direct inkjet printing of dental prostheses made of zirconia," *J. Dent. Res.*, 2009, doi: 10.1177/0022034509339988.

[69] M. Javaid and A. Haleem, "Current status and applications of additive manufacturing in dentistry: A literature-based review," *Journal of Oral Biology and Craniofacial*

Research. 2019, doi: 10.1016/j.jobcr.2019.04.004.

[70] A. Sola, D. Bellucci, V. Cannillo, and A. Cattini, "Bioactive glass coatings: A review," *Surface Engineering*. 2011, doi: 10.1179/1743294410Y.0000000008.

[71] S. Lopez-Esteban, E. Saiz, S. Fujino, T. Oku, K. Suganuma, and A. P. Tomsia, "Bioactive glass coatings for orthopedic metallic implants," *J. Eur. Ceram. Soc.*, 2003, doi: 10.1016/S0955-2219(03)00303-0.

[72] E. Saiz, S. Lopez-Esteban, S. Fujino, T. Oku, K. Suganuma, and A. P. Tomsia, "Characterization of Metal/Glass Interfaces in Bioactive Glass Coatings on Ti-6Al-4V and Co-Cr Alloys," in *Nano and Microstructural Design of Advanced Materials: A Commemorative Volume on Professor G. Thomas' Seventieth Birthday*, 2003.

[73] Lutz-Christian Gerhardt, Kate L. Widdows, Melek M. Erol, Charles W. Burch, José A. Sanz-Herrera, Ignacio Ochoa, Rolf Stämpfli, Iman S. Roqan, Simon Gabe, Tahera Ansari, Aldo R. Boccaccini "The pro-angiogenic properties of multi-functional bioactive glass composite scaffolds," *Biomaterials*, 2011, doi: 10.1016/j.biomaterials.2011.02.032.

[74] Francesco Baino, Elisa Fiume, Marta Miola, Federica Leone, Barbara Onida, Francesco Laviano, Roberto Gerbaldo and Enrica Verné "Fe-doped sol-gel glasses and glass-ceramics for magnetic hyperthermia," *Materials (Basel).*, 2018, doi: 10.3390/ma11010173.

[75] H. Zreiqat, C. R. Howlett, A. Zannettino, P. Evans, G. Schulze-Tanzil, C. Knabe, M. Shakibaei "Mechanisms of magnesium-stimulated adhesion of osteoblastic cells to commonly used orthopaedic implants," *J. Biomed. Mater. Res.*, 2002, doi: 10.1002/jbm.10270.

[76] E. Verne`, S. Di Nunzio, M. Bosetti, P. Appendino, C. Vitale Brovarone, G. Maina, M. Cannas "Surface characterization of silver-doped bioactive glass," *Biomaterials*, 2005, doi: 10.1016/j.biomaterials.2005.01.038.

[77] Sara Pourshahrestani, Ehsan Zeimaran, Nahrizul Adib Kadri, Nicola Gargiulo, Shani Samuel, Sangeetha Vasudevaraj Naveen, Tunku Kamarul and Mark R. Towler "Gallium-containing mesoporous bioactive glass with potent hemostatic activity and antibacterial efficacy," *J. Mater. Chem. B*, 2016, doi: 10.1039/c5tb02062j.

[78] M. Vincent, P. Hartemann, and M. Engels-Deutsch, "Antimicrobial applications of copper," *Int. J. Hyg. Environ. Health*, 2016, doi: 10.1016/j.ijheh.2016.06.003.

[79] J. Ye, J. He, C. Wang, K. Yao, and Z. Gou, "Copper-containing mesoporous bioactive glass coatings on orbital implants for improving drug delivery capacity and antibacterial activity," *Biotechnol. Lett.*, 2014, doi: 10.1007/s10529-014-1465-x.

[80] F. Minandri, C. Bonchi, E. Frangipani, F. Imperi, and P. Visca, "Promises and failures of gallium as an antibacterial agent," *Future Microbiology*. 2014, doi: 10.2217/fmb.14.3.

[81] L. L. Hench, "Genetic design of bioactive glass," *J. Eur. Ceram. Soc.*, 2009, doi: 10.1016/j.jeurceramsoc.2008.08.002.

[82] I. D. Xynos, M. V. J. Hukkanen, J. J. Batten, L. D. Buttery, L. L. Hench, and J. M. Polak, "Bioglass ®45S5 stimulates osteoblast turnover and enhances bone formation in vitro: Implications and applications for bone tissue engineering," *Calcif. Tissue Int.*,

2000, doi: 10.1007/s002230001134.

[83] L. L. Hench, I. D. Xynos, and J. M. Polak, “Bioactive glasses for in situ tissue regeneration,” *Journal of Biomaterials Science, Polymer Edition*. 2004, doi: 10.1163/156856204323005352.

[84] I. D. Xynos, A. J. Edgar, L. D. K. Buttery, L. L. Hench, and J. M. Polak, “Gene-expression profiling of human osteoblasts following treatment with the ionic products of Bioglass® 45S5 dissolution,” *J. Biomed. Mater. Res.*, 2001, doi: 10.1002/1097-4636(200105)55:2<151::AID-JBM1001>3.0.CO;2-D.

[85] D. Boyd, O. M. Clarkin, A. W. Wren, and M. R. Towler, “Zinc-based glass polyalkenoate cements with improved setting times and mechanical properties,” *Acta Biomater.*, 2008, doi: 10.1016/j.actbio.2007.07.010.

[86] Ensanya A. Abou Neel, Wojciech Chrzanowski, David M. Pickup, Luke A. O’Dell, Nicola J. Mordan, Robert J. Newport, Mark E. Smith and Jonathan C. Knowles “Structure and properties of strontium-doped phosphate-based glasses,” *J. R. Soc. Interface*, 2009, doi: 10.1098/rsif.2008.0348.

[87] J. Y. Reginster, E. Seeman, M. C. De Vernejoul, S. Adami, J. Compston, C. Phenekos, J. P. Devogelaer, M. Diaz Curiel, A. Sawicki, S. Goemaere, O. H. Sorensen, D. Felsenberg, and P. J. Meunier “Strontium ranelate reduces the risk of nonvertebral fractures in postmenopausal women with osteoporosis: Treatment of Peripheral Osteoporosis (TROPOS) study,” *J. Clin. Endocrinol. Metab.*, 2005, doi: 10.1210/jc.2004-1774.

[88] L. Cianferotti, F. D'Asta, M. L. Brandi, “A review on strontium ranelate long-term antifracture efficacy in the treatment of postmenopausal osteoporosis,” *Ther. Adv. Musculoskelet. Dis.*, 2013.

[89] E. Bonnelye, A. Chabadel, F. Saltel, and P. Jurdic, “Dual effect of strontium ranelate: Stimulation of osteoblast differentiation and inhibition of osteoclast formation and resorption in vitro,” *Bone*, 2008, doi: 10.1016/j.bone.2007.08.043.

[90] A. Patel and J. C. Knowles, “Investigation of silica-iron-phosphate glasses for tissue engineering,” *J. Mater. Sci. Mater. Med.*, 2006, doi: 10.1007/s10856-006-0183-x.

[91] Saeid Kargozar, Nasrin Lotfibakhshaiesh, Jafar Ai , Masoud Mozafari, Peiman Brouki Milan, Sepideh Hamzehlou, Mahmood Barati, Francesco Baino, Robert G. Hill, Mohammad Taghi Joghataei “Strontium- and cobalt-substituted bioactive glasses seeded with human umbilical cord perivascular cells to promote bone regeneration via enhanced osteogenic and angiogenic activities,” *Acta Biomater.*, 2017, doi: 10.1016/j.actbio.2017.06.021.

[92] V. Miguez-Pacheco, D. de Ligny, J. Schmidt, R. Detsch, and A. R. Boccaccini, “Development and characterization of niobium-releasing silicate bioactive glasses for tissue engineering applications,” *J. Eur. Ceram. Soc.*, 2018, doi: 10.1016/j.jeurceramsoc.2017.07.028.

[93] O. Bretcanu, E. Verné, M. Cöisson, P. Tiberto, and P. Allia, “Magnetic properties of the ferrimagnetic glass-ceramics for hyperthermia,” *J. Magn. Magn. Mater.*, 2006, doi: 10.1016/j.jmmm.2006.02.264.

[94] N. Shankhwar and A. Srinivasan, “Evaluation of sol-gel based magnetic 45S5 bioglass

and bioglass-ceramics containing iron oxide," *Mater. Sci. Eng. C*, 2016, doi: 10.1016/j.msec.2016.01.054.

[95] Lianxiang Bi, Mohamed N. Rahaman, Delbert E. Day, Zackary Brown, Christopher Samujh, Xin Liu, Ali Mohammadkhah, Vladimir Dusevich, J. David Eick, Lynda F. Bonewald "Effect of bioactive borate glass microstructure on bone regeneration, angiogenesis, and hydroxyapatite conversion in a rat calvarial defect model," *Acta Biomater.*, 2013, doi: 10.1016/j.actbio.2013.04.043.

[96] Tetsuhiro Tanaka, Ichiro Kojima, Takamoto Ohse, Julie R Ingelfinger, Stephen Adler, Toshiro Fujita and Masaomi Nangaku "Cobalt promotes angiogenesis via hypoxia-inducible factor and protects tubulointerstitium in the remnant kidney model," *Lab. Investig.*, 2005, doi: 10.1038/labinvest.3700328.

[97] G. F. Hu, "Copper stimulates proliferation of human endothelial cells under culture," *J. Cell. Biochem.*, 1998, doi: 10.1002/(SICI)1097-4644(19980601)69:3<326::AID-JCB10>3.0.CO;2-A.

[98] A. M. El-Kady, A. F. Ali, R. A. Rizk, and M. M. Ahmed, "Synthesis, characterization and microbiological response of silver doped bioactive glass nanoparticles," *Ceram. Int.*, 2012, doi: 10.1016/j.ceramint.2011.05.158.

[99] A. A. Ahmed, A. A. Ali, D. A. R. Mahmoud, and A. M. El-Fiqi, "Preparation and characterization of antibacterial P2O 5-CaO-Na2O-Ag2O glasses," *J. Biomed. Mater. Res. - Part A*, 2011, doi: 10.1002/jbm.a.33101.

[100] K. Magyari, R. Stefan, D. C. Vodnar, A. Vulpoi, and L. Baia, "The silver influence on the structure and antibacterial properties of the bioactive 10B2O3- 30Na2O-60P2O 2 glass," *J. Non. Cryst. Solids*, 2014, doi: 10.1016/j.jnoncrysol.2014.05.033.

[101] N. Baheiraei, F. Moztarzadeh, and M. Hedayati, "Preparation and antibacterial activity of Ag/SiO 2 thin film on glazed ceramic tiles by sol-gel method," *Ceram. Int.*, 2012, doi: 10.1016/j.ceramint.2011.11.068.

[102] R. Ciceo Lucacel, T. Radu, A. S. Tătar, I. Lupan, O. Ponta, and V. Simon, "The influence of local structure and surface morphology on the antibacterial activity of silver-containing calcium borosilicate glasses," *J. Non. Cryst. Solids*, 2014, doi: 10.1016/j.jnoncrysol.2014.08.004.

[103] Xanthippi Chatzistavrou, J. Christopher Fenno, Denver Faulk, Stephen Badylak, Toshihiro Kasuga, Aldo R. Boccaccini, Petros Papagerakis "Fabrication and characterization of bioactive and antibacterial composites for dental applications," *Acta Biomater.*, 2014, doi: 10.1016/j.actbio.2014.04.030 LK

[104] S. Ni, X. Li, P. Yang, S. Ni, F. Hong, and T. J. Webster, "Enhanced apatite-forming ability and antibacterial activity of porous anodic alumina embedded with CaO-SiO2-Ag2O bioactive materials," *Mater. Sci. Eng. C*, 2016, doi: 10.1016/j.msec.2015.09.011.

[105] Sabeel P. Valappil, Marc Coombes, Lucy Wright, Gareth J. Owens, Richard J.M. Lynch, Christopher K. Hope, Susan M. Higham "Role of gallium and silver from phosphate-based glasses on in vitro dual species oral biofilm models of Porphyromonas gingivalis and Streptococcus gordonii," *Acta Biomater.*, 2012, doi: 10.1016/j.actbio.2012.01.017.

[106] Shaoxin Yang, Yihe Zhang, Jiemei Yu, Zhichao Zhen, Taizhong Huang, Qi Tang, Paul K. Chu, Lei Qi, Hongbo Lv "Antibacterial and mechanical properties of honeycomb ceramic materials incorporated with silver and zinc," *Mater. Des.*, 2014, doi: 10.1016/j.matdes.2014.03.025.

[107] Y. F. Goh, A. Z. Alshemary, M. Akram, M. R. Abdul Kadir, and R. Hussain, "In-vitro characterization of antibacterial bioactive glass containing ceria," *Ceram. Int.*, 2014, doi: 10.1016/j.ceramint.2013.06.062.

[108] A. M. Mulligan, M. Wilson, and J. C. Knowles, "The effect of increasing copper content in phosphate-based glasses on biofilms of Streptococcus sanguis," *Biomaterials*, 2003, doi: 10.1016/S0142-9612(02)00577-X.

[109] M. Zehnder, T. Waltimo, B. Sener, and E. Söderling, "Dentin enhances the effectiveness of bioactive glass S53P4 against a strain of Enterococcus faecalis," *Oral Surgery, Oral Med. Oral Pathol. Oral Radiol. Endodontology*, 2006, doi: 10.1016/j.tripleo.2005.03.014.

[110] T. Waltimo, T. J. Brunner, M. Vollenweider, W. J. Stark, and M. Zehnder, "Antimicrobial effect of nanometric bioactive glass 45S5," *J. Dent. Res.*, 2007, doi: 10.1177/154405910708600813.

[111] D. Batalu, A. M. Stanciuc, L. Moldovan, G. Aldica, and P. Badica, "Evaluation of pristine and Eu2O3-added MgB 2 ceramics for medical applications: Hardness, corrosion resistance, cytotoxicity and antibacterial activity," *Mater. Sci. Eng. C*, 2014, doi: 10.1016/j.msec.2014.05.046.

[112] Hyung-Jin Choi, Jin-Seok Choi, Byeong-Ju Park, Ji-Ho Eom, So-Young Heo, Min-Wook Jung, Ki-Seok An & Soon-Gil Yoon "Enhanced transparency, mechanical durability, and antibacterial activity of zinc nanoparticles on glass substrate," *Sci. Rep.*, 2014, doi: 10.1038/srep06271.

[113] Delia S. Brauer, Natalia Karpukhina, Gopal Kedia, Aditya Bhat, Robert V. Law, Izabela Radecka and Robert G. Hill "Bactericidal strontium-releasing injectable bone cements based on bioactive glasses," *J. R. Soc. Interface*, 2013, doi: 10.1098/rsif.2012.0647.

[114] J. S. Fernandes, M. Martins, N. M. Neves, M. H. V. Fernandes, R. L. Reis, and R. A. Pires, "Intrinsic Antibacterial Borosilicate Glasses for Bone Tissue Engineering Applications," *ACS Biomater. Sci. Eng.*, 2016, doi: 10.1021/acsbiomaterials.6b00162.

[115] Di Zhang, Outi Lepparanta, Eveliina Munukka, Heimo Ylanen, Matti K. Viljanen, Erkki Eerola, Mikko Hupa, Leena Hupa "Antibacterial effects and dissolution behavior of six bioactive glasses," *J. Biomed. Mater. Res. - Part A*, 2010, doi: 10.1002/jbm.a.32564.

[116] Minna Vaahtio, Eveliina Munukka, Outi Leppäranta, Di Zhang, Erkki Eerola, Heimo Ylänen and Timo Peltola "Effect of Ion Release on Antibacterial Activity of Melt-Derived and Sol-Gel-Derived Reactive Ceramics," *Key Eng. Mater.*, 2006, doi: 10.4028/www.scientific.net/kem.309-311.349.

[117] J. Liu, S. C. F. Rawlinson, R. G. Hill, and F. Fortune, "Strontium-substituted bioactive glasses in vitro osteogenic and antibacterial effects," *Dent. Mater.*, 2016, doi: 10.1016/j.dental.2015.12.013.

[118] Bele´n Cabal, Luı´s Alou, Fabio Cafini, Ramiro Couceiro, David Sevillano, Leticia Esteban-Tejeda, Francisco Guitia´n, Ramo´n Torrecillas & Jose´ S. Moya "A new biocompatible and antibacterial phosphate free glass-ceramic for medical applications," *Sci. Rep.*, 2014, doi: 10.1038/srep05440.

[119] M. M. Echezarreta-López, T. De Miguel, F. Quintero, J. Pou, and M. Landin, "Antibacterial properties of laser spinning glass nanofibers," *Int. J. Pharm.*, 2014, doi: 10.1016/j.ijpharm.2014.09.050.

[120] J. S. Moya, L. Esteban-Tejeda, C. Pecharromán, S. R. H. Mello-Castanho, A. C. Da Silva, and F. Malpartida, "Glass powders with a high content of calcium oxide: A step towards a 'green' universal biocide," *Adv. Eng. Mater.*, 2011, doi: 10.1002/adem.201080133.

[121] J.S. Moya, B. Cabal, J. Sanz, A.C. da Silva, S. Mello-Castanho, R. Torrecillas , F. Rojo "Mechanism of calcium lixiviation in soda-lime glasses with a strong biocide activity," *Mater. Lett.*, 2012, doi: 10.1016/j.matlet.2011.11.104.

[122] J. Chevalier and L. Gremillard, "Ceramics for medical applications: A picture for the next 20 years," *J. Eur. Ceram. Soc.*, 2009, doi: 10.1016/j.jeurceramsoc.2008.08.025.

[123] Gianmario Schierano, Federico Mussano, Maria Giulia Faga, Giulio Menicucci, Carlo Manzella, Cristian Sabione, Tullio Genova, Mitzy Mauthe von Degerfeld, Bruno Peirone, Adele Cassenti, Paola Cassoni, and Stefano Carossa "An alumina toughened zirconia composite for dental implant application: In vivo animal results," *Biomed Res. Int.*, 2015, doi: 10.1155/2015/157360.

[124] R. B. Osman and M. V. Swain, "A critical review of dental implant materials with an emphasis on titanium versus zirconia," *Materials*. 2015, doi: 10.3390/ma8030932.

[125] P. Papaspyridakos, C. J. Chen, M. Singh, H. P. Weber, and G. O. Gallucci, "Success criteria in implant dentistry: A systematic review," *Journal of Dental Research*. 2012, doi: 10.1177/0022034511431252.

[126] W. S. Lin, C. Ercoli, C. Feng, and D. Morton, "The Effect of Core Material, Veneering Porcelain, and Fabrication Technique on the Biaxial Flexural Strength and Weibull Analysis of Selected Dental Ceramics," *J. Prosthodont.*, 2012, doi: 10.1111/j.1532-849X.2012.00845.x.

[127] A. Balamurugan, G. Balossier, D. Laurent-Maquin, S. Pina, A.H.S. Rebelo, J. Faure, J.M.F. Ferreira "An in vitro biological and anti-bacterial study on a sol-gel derived silver-incorporated bioglass system," *Dent. Mater.*, 2008, doi: 10.1016/j.dental.2008.02.015.

[128] A. Goel, S. Kapoor, R. R. Rajagopal, M. J. Pascual, H. W. Kim, and J. M. F. Ferreira, "Alkali-free bioactive glasses for bone tissue engineering: A preliminary investigation," *Acta Biomater.*, 2012, doi: 10.1016/j.actbio.2011.08.026.

[129] S. Zhang, H. Miyanaji, L. Yang, A. A. Zandinejad, J. J. S. Dilip, and B. Stucker, "An experimental study of ceramic dental porcelain materials using a 3D print (3DP) process," 2014.

[130] A. Withell, O. Diegel, I. Grupp, S. Reay, D. De Beer, and J. Potgieter, "Porous ceramic filters through 3D printing," 2012, doi: 10.1201/b11341-50.

[131] Y. Yang and Y. Wu, "Tape-casted transparent alumina ceramic wafers," *J. Mater.*

Res., 2014, doi: 10.1557/jmr.2014.225.

[132] G. N. Howatt, R. G. Breckenridge, and J. M. Brownlow, "FABRICATION OF THIN CERAMIC SHEETS FOR CAPACITORS," *J. Am. Ceram. Soc.*, 1947, doi: 10.1111/j.1151-2916.1947.tb18889.x.

[133] P. Monash, G. Pugazhenthi, and P. Saravanan, "Various fabrication methods of porous ceramic supports for membrane applications," *Rev. Chem. Eng.*, 2013, doi: 10.1515/revce-2013-0006.

[134] A. R. Studart, U. T. Gonzenbach, E. Tervoort, and L. J. Gauckler, "Processing routes to macroporous ceramics: A review," 2006, doi: 10.1111/j.1551-2916.2006.01044.x.

[135] J. H. Eom, Y. W. Kim, and S. Raju, "Processing and properties of macroporous silicon carbide ceramics: A review," *Journal of Asian Ceramic Societies*. 2013, doi: 10.1016/j.jascer.2013.07.003.

[136] Elisabeta Horvath-Bordon, Ralf Riedel, Andreas Zerr, Paul F. McMillan, Gudrun Auffermann, Yurii Prots, Welf Bronger, Rudiger Kniep and Peter Kroll "High-pressure chemistry of nitride-based materials," *Chem. Soc. Rev.*, 2006, doi: 10.1039/b517778m.

[137] A. Zerr, R. Riedel, T. Sekine, J. E. Lowther, W. Y. Ching, and I. Tanaka, "Recent advances in new hard high-pressure nitrides," *Advanced Materials*. 2006, doi: 10.1002/adma.200501872.

[138] J. Wilkes, Y. C. Hagedorn, W. Meiners, and K. Wissenbach, "Additive manufacturing of ZrO2-Al2O3 ceramic components by selective laser melting," *Rapid Prototyp. J.*, 2013, doi: 10.1108/13552541311292736.

[139] I. Shishkovsky, I. Yadroitsev, P. Bertrand, and I. Smurov, "Alumina-zirconium ceramics synthesis by selective laser sintering/melting," *Appl. Surf. Sci.*, 2007, doi: 10.1016/j.apsusc.2007.09.001.

[140] W. Y. Yeong, C. Y. Yap, M. Mapar, and C. K. Chua, "State-of-the-art review on selective laser melting of ceramics," 2014, doi: 10.1201/b15961-14.

[141] Zhangwei Chen , Ziyong Li, Junjie Li, Chengbo Liu, Changshi Lao, Yuelong Fu, Changyong Liu, Yang Li, Pei Wang, Yi He "3D printing of ceramics: A review," *J. Eur. Ceram. Soc.*, vol. 39, no. 4, pp. 661–687, 2019, doi: 10.1016/j.jeurceramsoc.2018.11.013.

[142] A. Nold, J. Zeiner, T. Assion, and R. Clasen, "Electrophoretic deposition as rapid prototyping method," *J. Eur. Ceram. Soc.*, 2010, doi: 10.1016/j.jeurceramsoc.2009.03.021.

[143] F. Doreau, C. Chaput, and T. Chartier, "Stereolithography for Manufacturing Ceramic Parts," *Adv. Eng. Mater.*, 2000, doi: 10.1002/1527-2648(200008)2:8<493::aid-adem493>3.3.co;2-3.

[144] Passakorn Tesavibul, Ruth Felzmann, Simon Gruber, Robert Liska, Ian Thompson, Aldo R. Boccaccini, Jürgen Stampfl "Processing of 45S5 Bioglass® by lithography-based additive manufacturing," *Mater. Lett.*, 2012, doi: 10.1016/j.matlet.2012.01.019.

[145] J. C. Wang, "A novel fabrication method of high strength alumina ceramic parts based on solvent-based slurry stereolithography and sintering," *Int. J. Precis. Eng. Manuf.*,

2013, doi: 10.1007/s12541-013-0065-3.

[146] M. Dehurtevent, L. Robberecht, J. C. Hornez, A. Thuault, E. Deveaux, and P. Béhin, "Stereolithography: A new method for processing dental ceramics by additive computer-aided manufacturing," *Dent. Mater.*, 2017, doi: 10.1016/j.dental.2017.01.018.

[147] Marion Dehurtevent, Lieven Robberecht, Anthony Thuault, Etienne Deveaux, Anne Leriche, Fabrice Petit, Corentin Denis, Jean-Christophe Hornez, and Pascal Béhin "Effect of build orientation on the manufacturing process and the properties of stereolithographic dental ceramics for crown frameworks," *J. Prosthet. Dent.*, 2020, doi: 10.1016/j.prosdent.2020.01.024.

[148] Y. de Hazan, M. Thänert, M. Trunec, and J. Misak, "Robotic deposition of 3d nanocomposite and ceramic fiber architectures via UV curable colloidal inks," *J. Eur. Ceram. Soc.*, 2012, doi: 10.1016/j.jeurceramsoc.2011.12.007.

[149] Jia Ping Li, Pamela Habibovic, Mirella van den Doel, Clayton E. Wilson, Joost R. de Wijn, Clemens A. van Blitterswijk, Klaas de Groot "Bone ingrowth in porous titanium implants produced by 3D fiber deposition," *Biomaterials*, 2007, doi: 10.1016/j.biomaterials.2007.02.020.

[150] Z. Han, P. Feng, C. Gao, Y. Shen, C. Shuai, and S. Peng, "Microstructure, mechanical properties and in vitro bioactivity of akermanite scaffolds fabricated by laser sintering," 2014, doi: 10.3233/BME-141017.

[151] S. Kroll, C. Soltmann, D. Koch, P. Kegler, A. Kunzmann, and K. Rezwan, "Colored ceramic foams with tailored pore size and surface functionalization used as spawning plates for fish breeding," *Ceram. Int.*, 2014, doi: 10.1016/j.ceramint.2014.07.100.

[152] R. Shang, A. Goulas, C. Y. Tang, X. de Frias Serra, L. C. Rietveld, and S. G. J. Heijman, "Atmospheric pressure atomic layer deposition for tight ceramic nanofiltration membranes: Synthesis and application in water purification," *J. Memb. Sci.*, 2017, doi: 10.1016/j.memsci.2017.01.023.

[153] I. Miccoli, R. Spampinato, F. Marzo, P. Prete, and N. Lovergine, "DC-magnetron sputtering of ZnO:Al films on (00.1)Al 2 O 3 substrates from slip-casting sintered ceramic targets," *Appl. Surf. Sci.*, 2014, doi: 10.1016/j.apsusc.2014.05.225.

[154] S. Zhang, Y. Du, H. Jiang, Y. Liu, and R. Chen, "Controlled synthesis of TiO2 nanorod arrays immobilized on ceramic membranes with enhanced photocatalytic performance," *Ceram. Int.*, 2017, doi: 10.1016/j.ceramint.2017.03.019.

[155] V. D. Phadtare, V. G. Parale, G. K. Kulkarni, H. H. Park, and V. R. Puri, "Microwave dielectric properties of barium substituted screen printed CaBi2Nb2O9 ceramic thick films," *Ceram. Int.*, 2018, doi: 10.1016/j.ceramint.2018.01.150.

[156] C. Y. Huang, C. C. Ko, L. H. Chen, C. T. Huang, K. L. Tung, and Y. C. Liao, "A simple coating method to prepare superhydrophobic layers on ceramic alumina for vacuum membrane distillation," *Sep. Purif. Technol.*, 2018, doi: 10.1016/j.seppur.2016.12.037.

[157] S. A. Leonardi, M. A. Zanuttini, E. E. Miró, and V. G. Milt, "Catalytic paper made from ceramic fibres and natural ulexite. Application to diesel particulate removal," *Chem. Eng. J.*, 2017, doi: 10.1016/j.cej.2017.02.013.

[158] R. Kumar and P. Bhargava, "In situ-growth of silica nanowires in ceramic carbon composites," *J. Asian Ceram. Soc.*, 2017, doi: 10.1016/j.jascer.2017.06.003.

[159] Marieke M. Hoog Antinka, Lisa Röpke, Julia Bartelsa, Christian Soltmann, Andreas Kunzmann, Kurosch Rezwan, Stephen Kroll "Porous ceramics with tailored pore size and morphology as substrates for coral larval settlement," *Ceram. Int.*, 2018, doi: 10.1016/j.ceramint.2018.06.078.

[160] L. Wang, W. tao Kang, P. zhao Gao, X. pan Liu, and E. V. Rebrov, "Influence of ceramic substrate porosity and glass phase content on the microstructure and mechanical properties of metallized ceramics via an activated Mo-Mn method," *Ceram. Int.*, 2020, doi: 10.1016/j.ceramint.2019.12.052.

[161] S. Barg, E. G. de Moraes, D. Koch, and G. Grathwohl, "New cellular ceramics from high alkane phase emulsified suspensions (HAPES)," *J. Eur. Ceram. Soc.*, 2009, doi: 10.1016/j.jeurceramsoc.2009.02.003.

[162] S. Barg, C. Soltmann, M. Andrade, D. Koch, and G. Grathwohl, "Cellular ceramics by direct foaming of emulsified ceramic powder suspensions," *J. Am. Ceram. Soc.*, 2008, doi: 10.1111/j.1551-2916.2008.02553.x.

[163] Wiebke Wesseling, Sabine Wittka, Stephen Kroll, Christian Soltmann, Pia Kegler, Andreas Kunzmann, Hans Wolfgang Riss, Michael Lohmeyer "Functionalised ceramic spawning tiles with probiotic Pseudoalteromonas biofilms designed for clownfish aquaculture," *Aquaculture*, 2015, doi: 10.1016/j.aquaculture.2015.04.017.

[164] N. Gao and Z. K. Xu, "Ceramic membranes with mussel-inspired and nanostructured coatings for water-in-oil emulsions separation," *Sep. Purif. Technol.*, 2019, doi: 10.1016/j.seppur.2018.11.084.

[165] Philipp Ninz, Frank Kern, Eugen Ermantraut, Hagen Müller, Wolfgang Eberhardt, André Zimmermann and Rainer Gadow "Doping of Alumina Substrates for Laser Induced Selective Metallization," 2018, doi: 10.1016/j.procir.2017.12.037.

[166] Xi-Wang Liu, Yue Cao, Yu-Xuan Li, Zhen-Liang Xu, Ze Li, Ming Wang, Xiao-Hua Ma "High-performance polyamide/ceramic hollow fiber TFC membranes with TiO2 interlayer for pervaporation dehydration of isopropanol solution," *J. Memb. Sci.*, 2019, doi: 10.1016/j.memsci.2019.01.023.

[167] L. F. Han, Z. L. Xu, Y. Cao, Y. M. Wei, and H. T. Xu, "Preparation, characterization and permeation property of Al2O3, Al2O3-SiO2 and Al2O3-kaolin hollow fiber membranes," *J. Memb. Sci.*, 2011, doi: 10.1016/j.memsci.2011.01.065.

[168] Chia-Chieh Ko, Aamer Ali, Enrico Drioli, Kuo-Lun Tung, Chien-Hua Chen, Yi-Rui Chen, Francesca Macedonio "Performance of ceramic membrane in vacuum membrane distillation and in vacuum membrane crystallization," *Desalination*, 2018, doi: 10.1016/j.desal.2018.03.011.

[169] N. M. Terra, L. P. Bessa, V. L. Cardoso, and M. H. M. Reis, "Graphite coating on alumina substrate for the fabrication of hydrogen selective membranes," *Int. J. Hydrogen Energy*, 2018, doi: 10.1016/j.ijhydene.2017.10.179.

[170] Xianfu Chen, Ting Chen, Jian Li, Minghui Qiu, Kaiyun Fu, Zhaoliang Cui, Yiqun Fan, Enrico Drioli "Ceramic nanofiltration and membrane distillation hybrid membrane processes for the purification and recycling of boric acid from simulative radioactive

waste water," *J. Memb. Sci.*, 2019, doi: 10.1016/j.memsci.2019.02.044.

[171] Z. Wang, Y. M. Wei, Z. L. Xu, Y. Cao, Z. Q. Dong, and X. L. Shi, "Preparation, characterization and solvent resistance of γ-Al2O3/α-Al2O3 inorganic hollow fiber nanofiltration membrane," *J. Memb. Sci.*, 2016, doi: 10.1016/j.memsci.2015.12.039.

[172] S. Wang, J. Tian, Q. Wang, Z. Zhao, F. Cui, and G. Li, "Low-temperature sintered high-strength CuO doped ceramic hollow fiber membrane: Preparation, characterization and catalytic activity," *J. Memb. Sci.*, 2019, doi: 10.1016/j.memsci.2018.10.078.

[173] E. David and J. Kopac, "Devlopment of palladium/ceramic membranes for hydrogen separation," *International Journal of Hydrogen Energy*. 2011, doi: 10.1016/j.ijhydene.2010.12.032.

[174] S. Danwittayakul and J. Dutta, "Controlled growth of zinc oxide microrods by hydrothermal process on porous ceramic supports for catalytic application," *J. Alloys Compd.*, 2014, doi: 10.1016/j.jallcom.2013.10.019.

[175] S. Blindow, M. Pulkin, D. Koch, G. Grathwohl, and K. Rezvwan, "Hydroxyapatite/SiO2 composites via freeze casting for bone tissue engineering," *Adv. Eng. Mater.*, 2009, doi: 10.1002/adem.200900208.

[176] J. Verma, M. Vijayakumar, and R. Mitra, "Processing and microstructure of freeze-cast silica foams," *Mater. Lett.*, 2015, doi: 10.1016/j.matlet.2015.04.019.

[177] Q. Dong, T. Zhu, Z. Xie, Y. Han, and D. An, "Optimization of the tape casting slurries for high-quality zirconia substrates," *Ceram. Int.*, 2017, doi: 10.1016/j.ceramint.2017.09.099.

[178] N. Wang, D. P. Wang, Z. W. Yang, Y. Wang, and X. G. Liu, "Zirconia ceramic and Nb joints brazed with Mo-particle-reinforced Ag-Cu-Ti composite fillers: Interfacial microstructure and formation mechanism," *Ceram. Int.*, 2017, doi: 10.1016/j.ceramint.2017.04.133.

[179] H. Guo, S. Zhao, X. Wu, and H. Qi, "Fabrication and characterization of TiO2/ZrO2 ceramic membranes for nanofiltration," *Microporous Mesoporous Mater.*, 2018, doi: 10.1016/j.micromeso.2016.03.011.

[180] Y. Yuan, Z. Li, L. Cao, B. Tang, and S. Zhang, "Modification of Si3N4 ceramic powders and fabrication of Si3N4/PTFE composite substrate with high thermal conductivity," *Ceram. Int.*, 2019, doi: 10.1016/j.ceramint.2019.05.194.

[181] C. F. Xiao and B. Han, "Preparation of porous silicon nitride ceramics by freeze drying," *J. Mater. Res. Technol.*, 2019, doi: 10.1016/j.jmrt.2019.10.014.

[182] J. Seuba, J. Leloup, S. Richaud, S. Deville, C. Guizard, and A. J. Stevenson, "Fabrication of ice-templated tubes by rotational freezing: Microstructure, strength, and permeability," *J. Eur. Ceram. Soc.*, 2017, doi: 10.1016/j.jeurceramsoc.2017.01.014.

[183] J. Z. Yang, R. Sultana, X. Z. Hu, and Z. H. Huang, "Porous hydroxyapatite coating on strong ceramic substrate fabricated by low density slip coating-deposition and coating-substrate co-sintering," *J. Eur. Ceram. Soc.*, 2011, doi: 10.1016/j.jeurceramsoc.2011.05.025.

[184] L. Huang, S. Ding, X. Yan, T. Song, and Y. Zhang, "Structure and microwave dielectric properties of BaAl2Si2O8 ceramic with Li2O–B2O3 sintering additive," *J. Alloys Compd.*, 2020, doi: 10.1016/j.jallcom.2019.153100.

[185] X. Hu, L. Yang, L. Li, D. Xie, and H. Du, "Freeze casting of composite system with stable fiber network and movable particles," *J. Eur. Ceram. Soc.*, 2016, doi: 10.1016/j.jeurceramsoc.2016.05.049.

[186] Alves Manuel F.R.P., Santos Claudinei dos, Cossu Caio M.F.A., Suzuki Paulo A., Ramos Alfeu S., Ramos Erika C.T., Simba Bruno G., Strecker Kurt "Development of dense Al2O3–TiO2 ceramic composites by the glass-infiltration of porous substrates prepared from mechanical alloyed powders," *Ceram. Int.*, 2020, doi: 10.1016/j.ceramint.2019.09.225.

[187] G. LI, H. QI, Y. FAN, and N. XU, "Toughening macroporous alumina membrane supports with YSZ powders," *Ceram. Int.*, 2009, doi: 10.1016/j.ceramint.2008.09.008.

[188] W. Chen, Z. Wang, X. Liu, J. Jia, and Y. Hua, "Effect of load on the friction and wear characteristics of Si3N4-hBN ceramic composites sliding against PEEK in artificial seawater," *Tribol. Int.*, 2020, doi: 10.1016/j.triboint.2019.105902.

[189] M. G. Chourashiya, S. R. Bharadwaj, and L. D. Jadhav, "Synthesis and characterization of electrolyte-grade 10%Gd-doped ceria thin film/ceramic substrate structures for solid oxide fuel cells," *Thin Solid Films*, 2010, doi: 10.1016/j.tsf.2010.08.110.

[190] J. Bartels, A. G. Batista, S. Kroll, M. Maas, and K. Rezwan, "Hydrophobic ceramic capillary membranes for versatile virus filtration," *J. Memb. Sci.*, 2019, doi: 10.1016/j.memsci.2018.10.022.

[191] L. Wu, F. Xiang, W. Liu, R. Ma, and H. Wang, "Hot-pressing sintered BN-SiO2 composite ceramics with excellent thermal conductivity and dielectric properties for high frequency substrate," *Ceram. Int.*, 2018, doi: 10.1016/j.ceramint.2018.06.084.

[192] Yixuan Zhao, Xiaoguo Song, Shengpeng Hu, Jingyi Zhang, Jian Cao, Wei Fu, Jicai Feng "Interfacial microstructure and mechanical properties of porous-Si3N4 ceramic and TiAl alloy joints vacuum brazed with AgCu filler," *Ceram. Int.*, 2017, doi: 10.1016/j.ceramint.2017.04.149.

[193] R. E. Mistler and E. R. Twiname, "Tape Casting: Theory and Practice," *Am. Ceram. Soc. Westerville, Ohio*, 2000.

[194] M. Jabbari, N. ; Pryds, and J. H. Hattel, "Modelling of Tape Casting for Ceramic Applications," *Citation*, 2014.

[195] R. E. Mistler, "The principles of tape casting and tape casting applications," in *Ceramic Processing*, 1995.

[196] Z. Feng, J. Qi, and T. Lu, "Highly-transparent AlON ceramic fabricated by tape-casting and pressureless sintering method," *J. Eur. Ceram. Soc.*, 2020, doi: 10.1016/j.jeurceramsoc.2019.11.065.

[197] D. J. Kim, M. H. Lee, and C. E. Kim, "Mechanical properties of tape-cast alumina-glass dental composites," *J. Am. Ceram. Soc.*, 1999, doi: 10.1111/j.1151-2916.1999.tb02219.x.

[198] C. Pagnoux, T. Chartier, M. D. F. Granja, F. Doreau, J. M. Ferreira, and J. F. Baumard, "Aqueous suspensions for tape-casting based on acrylic binders," *J. Eur. Ceram. Soc.*, 1998, doi: 10.1016/s0955-2219(97)00115-5.

[199] Xuewei Ba, Jiang Li, Yubai Pan, Yanping Zeng, Huamin Kou, Wenbin Liu, Jing Liu, Lexiang Wu, Jingkun Guo "Comparison of aqueous- and non-aqueous-based tape casting for preparing YAG transparent ceramics," *Journal of Alloys and Compounds*. 2013, doi: 10.1016/j.jallcom.2013.04.209.

[200] J. R. Kelly, I. Nishimura, and S. D. Campbell, "Ceramics in dentistry: Historical roots and current perspectives," *J. Prosthet. Dent.*, 1996, doi: 10.1016/S0022-3913(96)90413-8.

[201] Y. Zhang and J. R. Kelly, "Dental Ceramics for Restoration and Metal Veneering," *Dent. Clin. North Am.*, vol. 61, no. 4, pp. 797–819, 2017, doi: 10.1016/j.cden.2017.06.005.

[202] L. H. da Silva, E. de Lima, R. B. de P. Miranda, S. S. Favero, U. Lohbauer, and P. F. Cesar, "Dental ceramics: A review of new materials and processing methods," *Brazilian Oral Research*. 2017, doi: 10.1590/1807-3107BOR-2017.vol31.0058.

[203] D.-J. Kim, M.-H. Lee, and C.-E. Kim, "Fabrication of in-ceram core by sheet forming process," in *Bioceramics*, 1997.

[204] Chaoyang Ma, Fei Tang, Jiangfeng Zhu, Miaomiao Du, Xuanyi Yuan, Yang Yu, Ke Wang, Zicheng Wen, Jiantao Zhang, Jiaqi Long, Wang Guo, and Yongge Cao "Spectral and Laser Properties of Yb:LuAG Transparent Ceramics Fabricated by Tape Casting Method," *J. Am. Ceram. Soc.*, 2016, doi: 10.1111/jace.14322.

[205] D. Hotza and P. Greil, "Review: aqueous tape casting of ceramic powders," *Mater. Sci. Eng. A*, 1995, doi: 10.1016/0921-5093(95)09785-6.

[206] K. P. Plucknett, C. H. Cáceres, and D. S. Willinson, "Tape Casting of Fine Alumina/Zirconia Powders for Composite Fabrication," *J. Am. Ceram. Soc.*, 1994, doi: 10.1111/j.1151-2916.1994.tb07109.x.

[207] B. Bitterlich, C. Lutz, and A. Roosen, "Rheological characterization of water-based slurries for the tape casting process," *Ceram. Int.*, 2002, doi: 10.1016/S0272-8842(02)00027-5.

[208] J. C. WILLIAMS, "Doctor-Blade Process," 1976.

[209] G. W. Scherer, "Theory of Drying," *J. Am. Ceram. Soc.*, 1990, doi: 10.1111/j.1151-2916.1990.tb05082.x.

[210] A. Kristoffersson and E. Carlström, "Tape Casting of Alumina in Water with an Acrylic Latex Binder," *J. Eur. Ceram. Soc.*, 1997, doi: 10.1016/s0955-2219(96)00143-4.

[211] J. Kiennemann, T. Chartier, C. Pagnoux, J. F. Baumard, M. Huger, and J. M. Lamérant, "Drying mechanisms and stress development in aqueous alumina tape casting," *J. Eur. Ceram. Soc.*, 2005, doi: 10.1016/j.jeurceramsoc.2004.05.028.

[212] Z. Fu, A. Dellert, M. Lenhart, and A. Roosen, "Effect of pore orientation on anisotropic shrinkage in tape-cast products," *J. Eur. Ceram. Soc.*, 2014, doi: 10.1016/j.jeurceramsoc.2014.03.002.

[213] J. Yang, J. Yu, and Y. Huang, "Recent developments in gelcasting of ceramics," *J. Eur. Ceram. Soc.*, 2011, doi: 10.1016/j.jeurceramsoc.2010.12.035.

[214] O. O. Omatete, M. A. Janney, and R. A. Strehlow, "Gelcasting – A New Ceramic Forming Process," *Am. Ceram. Soc. Bull.*, 1991.

[215] O. O. Omatete, M. A. Janney, and S. D. Nunn, "Gelcasting: From Laboratory Development Toward Industrial Production," *J. Eur. Ceram. Soc.*, 1997, doi: 10.1016/s0955-2219(96)00147-1.

[216] A. C. Young, O. O. Omatete, M. A. Janney, and P. A. Menchhofer, "Gelcasting of Alumina," *J. Am. Ceram. Soc.*, 1991, doi: 10.1111/j.1151-2916.1991.tb04068.x.

[217] X. Mao, S. Shimai, and S. Wang, "Gelcasting of alumina foams consolidated by epoxy resin," *J. Eur. Ceram. Soc.*, 2008, doi: 10.1016/j.jeurceramsoc.2007.06.006.

[218] L. Han, F. Li, X. Deng, J. Wang, H. Zhang, and S. Zhang, "Foam-gelcasting preparation, microstructure and thermal insulation performance of porous diatomite ceramics with hierarchical pore structures," *J. Eur. Ceram. Soc.*, 2017, doi: 10.1016/j.jeurceramsoc.2017.02.032.

[219] J. Zhang, D. Jiang, Q. Lin, Z. Chen, and Z. Huang, "Gelcasting and pressureless sintering of silicon carbide ceramics using Al2O3-Y2O3 as the sintering additives," *J. Eur. Ceram. Soc.*, 2013, doi: 10.1016/j.jeurceramsoc.2013.02.009.

[220] M. Dong, X. Mao, Z. Zhang, and Q. Liu, "Gelcasting of SiC using epoxy resin as gel former," *Ceram. Int.*, 2009, doi: 10.1016/j.ceramint.2008.07.008.

[221] K. Prabhakaran and C. Pavithran, "Gelcasting of alumina using urea-formaldehyde. II. Gelation and ceramic forming," *Ceram. Int.*, 2000, doi: 10.1016/S0272-8842(99)00020-6.

[222] Y. S. Jung, U. Paik, C. Pagnoux, and Y. G. Jung, "Consolidation of aqueous concentrated silicon nitride suspension by direct coagulation casting," *Mater. Sci. Eng. A*, 2003, doi: 10.1016/S0921-5093(02)00256-3.

[223] A. Kochanowski, R. Dziembaj, M. Molenda, A. Izak, and E. Bortel, "Dehydration of polymeric hydrogels designed for gelcasting method in ceramics," *J. Therm. Anal. Calorim.*, 2007, doi: 10.1007/s10973-006-8138-5.

[224] F. F. Lange, "Powder Processing Science and Technology for Increased Reliability," *J. Am. Ceram. Soc.*, 1989, doi: 10.1111/j.1151-2916.1989.tb05945.x.

[225] K. Prabhakaran, A. Melkeri, N. M. Gokhale, T. K. Chongdar, and S. C. Sharma, "Direct coagulation casting of YSZ powder suspensions using MgO as coagulating agent," *Ceram. Int.*, 2009, doi: 10.1016/j.ceramint.2008.08.003.

[226] J. G. P. Binner, A. M. McDermott, Y. Yin, R. M. Sambrook, and B. Vaidhyanathan, "In situ coagulation moulding: A new route for high quality, net-shape ceramics," *Ceram. Int.*, 2006, doi: 10.1016/j.ceramint.2004.12.006.

[227] Z. P. Xie, Y. Huang, Y. L. Chen, and Y. Jia, "A new gel casting of ceramics by reaction of sodium alginate and calcium iodate at increased temperatures," *J. Mater. Sci. Lett.*, 2001, doi: 10.1023/A:1010943427450.

[228] L. J. Gauckler, T. Graule, and F. Baader, "Ceramic forming using enzyme catalyzed

reactions," *Mater. Chem. Phys.*, 1999, doi: 10.1016/S0254-0584(99)00117-0.

[229] Y. Huang, L. Zhang, J. Yang, Z. Xie, C. Wang, and R. Chen, "Research progress of new colloidal forming processes for advanced ceramics," *Kuei Suan Jen Hsueh Pao/ Journal of the Chinese Ceramic Society*. 2007.

[230] A. R. Studart, V. C. Pandolfelli, E. Tervoort, and L. J. Gauckler, "Gelling of alumina suspensions using alginic acid salt and hydroxyaluminum diacetate," *J. Am. Ceram. Soc.*, 2002, doi: 10.1111/j.1151-2916.2002.tb00518.x.

[231] Xinming Ren, Beiyue Ma, Chang Su, Fan Qian, Wengang Yang, Lei Yuan, Jingkun Yu, Guoqi Liu, Hongxia Li "In-situ synthesis of FexSiy phases and their effects on the properties of SiC porous ceramics," *J. Alloys Compd.*, 2019, doi: 10.1016/j.jallcom.2019.01.031.

[232] K. K. Kandi and C. S. P. Rao, "Modeling of Process Parameters of Gelcast Fused Silica Ceramics using Response Surface Methodology," 2017, doi: 10.1016/j.matpr.2017.02.011.

[233] K. K. Kandi, G. Punugupati, S. K. Pal, and S. P. Rao Chilakalapalli, "Effect of Monomers Content and their Ratio on Gelcasting of Fused Silica Ceramics," *Trans. Indian Ceram. Soc.*, 2016, doi: 10.1080/0371750X.2016.1190671.

[234] V. L. Wiesner, L. M. Rueschhoff, A. I. Diaz-Cano, R. W. Trice, and J. P. Youngblood, "Producing dense zirconium diboride components by room-temperature injection molding of aqueous ceramic suspensions," *Ceram. Int.*, 2016, doi: 10.1016/j.ceramint.2015.11.005.

[235] G. Xu, Z. Chen, X. Zhang, H. Cui, Z. Zhang, and X. Zhan, "Preparation of porous Al2TiO5-Mullite ceramic by starch consolidation casting and its corrosion resistance characterization," *Ceram. Int.*, 2016, doi: 10.1016/j.ceramint.2016.06.024.

[236] B. J. J. Zelinski and D. R. Uhlmann, "Gel technology in ceramics," *J. Phys. Chem. Solids*, 1984, doi: 10.1016/0022-3697(84)90049-0.

[237] H. Akhondi, E. Taheri-Nassaj, H. Sarpoolaky, and A. Taavoni-Gilan, "Gelcasting of alumina nanopowders based on gelation of sodium alginate," *Ceram. Int.*, 2009, doi: 10.1016/j.ceramint.2008.04.023.

[238] J. M. F. Ferreira, "Role of the clogging effect in the slip casting process," *J. Eur. Ceram. Soc.*, 1998, doi: 10.1016/s0955-2219(98)00038-7.

[239] K. -S Chou and L. -J Lee, "Effect of Dispersants on the Rheological Properties and Slip Casting of Concentrated Alumina Slurry," *J. Am. Ceram. Soc.*, 1989, doi: 10.1111/j.1151-2916.1989.tb06293.x.

[240] L. M. Schifferli, "Slip casting," *JOM*, 1958, doi: 10.1007/bf03398239.

[241] S. O. Hondrum, "A review of the strength properties of dental ceramics," *J. Prosthet. Dent.*, 1992, doi: 10.1016/0022-3913(92)90602-7.

[242] Y. Zhang and J. Binner, "Enhanced casting rate by dynamic heating during slip casting," *J. Eur. Ceram. Soc.*, 2002, doi: 10.1016/S0955-2219(01)00243-6.

[243] J. Mouzon, E. Glowacki, and M. Odén, "Comparison between slip-casting and uniaxial pressing for the fabrication of translucent yttria ceramics," *J. Mater. Sci.*, 2008, doi:

10.1007/s10853-007-2261-y.

[244] A. G. King, "Slip Preparation Procedures," in *Ceramic Technology and Processing*, 2002.

[245] Y. Takao, T. Hotta, M. Naito, N. Shinohara, M. Okumiya, and K. Uematsu, "Microstructure of alumina compact body made by slip casting," *J. Eur. Ceram. Soc.*, 2002, doi: 10.1016/S0955-2219(01)00307-7.

[246] M. A. Camerucci, A. L. Cavalieri, and R. Moreno, "Slip casting of cordierite and cordierite- mullite materials," *J. Eur. Ceram. Soc.*, 1998, doi: 10.1016/S0955-2219(98)00108-3.

[247] K. Lin, J. Chang, J. Lu, W. Wu, and Y. Zeng, "Properties of β-Ca3(PO4)2 bioceramics prepared using nano-size powders," *Ceram. Int.*, 2007, doi: 10.1016/j.ceramint.2006.02.011.

[248] H. R. R. Ramay and M. Zhang, "Biphasic calcium phosphate nanocomposite porous scaffolds for load-bearing bone tissue engineering," *Biomaterials*, 2004, doi: 10.1016/j.biomaterials.2003.12.023.

[249] R. M. Williams and A. Ezis, "SLIP CASTING OF SILICON SHAPES AND THEIR NITRIDING.," *Am. Ceram. Soc. Bull.*, 1983.

[250] S. J. Powell and J. R. G. Evans, "The structure of ceramic foams prepared from polyurethane-ceramic suspensions," *Mater. Manuf. Process.*, 1995, doi: 10.1080/10426919508935063.

[251] F. F. LANGE and K. T. MILLER, "Open-Cell, Low-Density Ceramics Fabricated from Reticulated Polymer Substrates," *Adv. Ceram. Mater.*, 1987, doi: 10.1111/j.1551-2916.1987.tb00156.x.

[252] R. W. Rice, *Ceramic Fabrication Technology*. 2002.

[253] O. Lyckfeldt, E. Lidén, M. Persson, R. Carlsson, and P. Apell, "Progress in the fabrication of Si3N4 turbine rotors by pressure slip casting," *J. Eur. Ceram. Soc.*, 1994, doi: 10.1016/0955-2219(94)90076-0.

[254] Q. Xu, B. Gabbitas, S. Matthews, and D. Zhang, "The development of porous titanium products using slip casting," *J. Mater. Process. Technol.*, 2013, doi: 10.1016/j.jmatprotec.2013.03.011.

[255] D. S. ADCOCK and I. C. McDOWALL, "The Mechanism of Filter Pressing and Slip Casting," *J. Am. Ceram. Soc.*, 1957, doi: 10.1111/j.1151-2916.1957.tb12552.x.

[256] R. Greenwood and K. Kendall, "Acoustophoretic studies of aqueous suspensions of alumina and 8 mol% yttria stabilised zirconia powders," *J. Eur. Ceram. Soc.*, 2000, doi: 10.1016/s0955-2219(99)00091-6.

[257] J. A. Lewis, "Colloidal processing of ceramics," *J. Am. Ceram. Soc.*, 2000, doi: 10.1111/j.1151-2916.2000.tb01560.x.

[258] R. Moreno, "Colloidal processing of ceramics and composites," *Adv. Appl. Ceram.*, 2012, doi: 10.1179/1743676111Y.0000000075.

[259] W. E. Lee, S. Zhang, and M. Karakus, "Refractories: Controlled microstructure composites for extreme environments," *Journal of Materials Science*. 2004, doi:

10.1023/B:JMSC.0000045599.84988.9e.

[260] A. Mattern, R. Oberacker, and M. J. Hoffmann, "Multi-phase ceramics by computer-controlled pressure filtration," *J. Eur. Ceram. Soc.*, 2004, doi: 10.1016/j.jeurceramsoc.2003.10.037.

[261] J. F. A. K. Kotte, J. A. M. Denissen, and R. Metselaar, "Pressure casting of silicon nitride," *J. Eur. Ceram. Soc.*, 1991, doi: 10.1016/0955-2219(91)90108-C.

[262] Y. Zhang, D. Kong, and X. Feng, "Fabrication and properties of porous β-tricalcium phosphate ceramics prepared using a double slip-casting method using slips with different viscosities," *Ceram. Int.*, 2012, doi: 10.1016/j.ceramint.2011.11.078.

[263] A. Jillavenkatesa and R. A. Condrate, "Sol-gel processing of hydroxyapatite," *J. Mater. Sci.*, 1998, doi: 10.1023/A:1004436732282.

[264] I. Bogdanoviciene, A. Beganskiene, K. Tõnsuaadu, J. Glaser, H. J. Meyer, and A. Kareiva, "Calcium hydroxyapatite, Ca10(PO4)6(OH)2 ceramics prepared by aqueous sol-gel processing," *Mater. Res. Bull.*, 2006, doi: 10.1016/j.materresbull.2006.02.016.

[265] C. B. Mo, S. I. Cha, K. T. Kim, K. H. Lee, and S. H. Hong, "Fabrication of carbon nanotube reinforced alumina matrix nanocomposite by sol-gel process," *Mater. Sci. Eng. A*, 2005, doi: 10.1016/j.msea.2004.12.031.

[266] S. R. Inbaraj, R. M. Francis, N. V. Jaya, and A. Kumar, "Processing and properties of sol gel derived alumina-carbon nano tube composites," *Ceram. Int.*, 2012, doi: 10.1016/j.ceramint.2012.01.064.

[267] L. Esquivias, P. Rivero-Antúnez, C. Zamora-Ledezma, A. Domínguez-Rodríguez, and V. Morales-Flórez, "Intragranular carbon nanotubes in alumina-based composites for reinforced ceramics," *J. Sol-Gel Sci. Technol.*, 2019, doi: 10.1007/s10971-018-4834-4.

[268] M. Vallet-Regí, "Revisiting ceramics for medical applications," *Dalt. Trans.*, 2006, doi: 10.1039/b610219k.

[269] M. Vallet-Regí, F. Balas, and D. Arcos, "Mesoporous materials for drug delivery," *Angewandte Chemie - International Edition*. 2007, doi: 10.1002/anie.200604488.

[270] G. Bezzi, G. Celotti, E. Landi, T. M. G. La Torretta, I. Sopyan, and A. Tampieri, "A novel sol-gel technique for hydroxyapatite preparation," *Mater. Chem. Phys.*, 2003, doi: 10.1016/S0254-0584(02)00392-9.

[271] J. Ferreira, L. F. Santos, and R. M. Almeida, "Sol–gel-derived Yb:YAG polycrystalline ceramics for laser applications," *J. Sol-Gel Sci. Technol.*, 2017, doi: 10.1007/s10971-017-4420-1.

[272] A. Boukerika, L. Guerbous, and N. Brihi, "Ce-doped YAG phosphors prepared via sol-gel method: Effect of some modular parameters," *J. Alloys Compd.*, 2014, doi: 10.1016/j.jallcom.2014.06.133.

[273] S. Yu, W. Jing, M. Tang, T. Xu, W. Yin, and B. Kang, "Fabrication of Nd:YAG transparent ceramics using powders synthesized by citrate sol-gel method," *J. Alloys Compd.*, 2019, doi: 10.1016/j.jallcom.2018.09.184.

[274] H. Schmidt, H. Scholze, and A. Kaiser, "Principles of hydrolysis and condensation reaction of alkoxysilanes," *J. Non. Cryst. Solids*, 1984, doi: 10.1016/0022-

3093(84)90381-8.

[275] A. Nieto, S. Areva, T. Wilson, R. Viitala, and M. Vallet-Regi, "Cell viability in a wet silica gel," *Acta Biomater.*, 2009, doi: 10.1016/j.actbio.2009.05.033.

[276] A. Coiffier, T. Coradin, C. Roux, O. M. M. Bouvet, and J. Livage, "Sol-gel encapsulation of bacteria: A comparison between alkoxide and aqueous routes," *J. Mater. Chem.*, 2001, doi: 10.1039/b101308o.

[277] E. J. A. Pope, K. Braun, and C. M. Peterson, "Bioartificial Organs I: Silica Gel Encapsulated Pancreatic Islets for the Treatment of Diabetes Mellitus," *J. Sol-Gel Sci. Technol.*, 1997, doi: 10.1007/BF02436914.

[278] J. Fenech, C. Viazzi, J. P. Bonino, F. Ansart, and A. Barnabé, "Morphology and structure of YSZ powders: Comparison between xerogel and aerogel," *Ceram. Int.*, 2009, doi: 10.1016/j.ceramint.2009.06.014.

[279] J. Simitzis and D. E. Baciu, "Synthesis, characterization and bioactivity of a glass/acrylic bone cement composite," *J. Optoelectron. Adv. Mater.*, 2012.

[280] L. Hu, C. A. Wang, Y. Huang, C. Sun, S. Lu, and Z. Hu, "Control of pore channel size during freeze casting of porous YSZ ceramics with unidirectionally aligned channels using different freezing temperatures," *J. Eur. Ceram. Soc.*, 2010, doi: 10.1016/j.jeurceramsoc.2010.07.032.

[281] A. M. El-Kady, E. A. Saad, B. M. A. El-Hady, and M. M. Farag, "Synthesis of silicate glass/poly(l-lactide) composite scaffolds by freeze-extraction technique: Characterization and in vitro bioactivity evaluation," *Ceram. Int.*, 2010, doi: 10.1016/j.ceramint.2009.11.012.

[282] T. Y. Yang, H. B. Ji, S. Y. Yoon, B. K. Kim, and H. C. Park, "Porous mullite composite with controlled pore structure processed using a freeze casting of TBA-based coal fly ash slurries," *Resour. Conserv. Recycl.*, 2010, doi: 10.1016/j.resconrec.2009.12.012.

[283] M. C. Gutiérrez, M. Jobbágy, N. Rapún, M. L. Ferrer, and F. Del Monte, "A biocompatible bottom-up route for the preparation of hierarchical biohybrid materials," *Adv. Mater.*, 2006, doi: 10.1002/adma.200502550.

[284] C. M. Patist, M. B. Mulder, S. E. Gautier, V. Maquet, R. Jérôme, and M. Oudega, "Freeze-dried poly(D,L-lactic acid) macroporous guidance scaffolds impregnated with brain-derived neurotrophic factor in the transected adult rat thoracic spinal cord," *Biomaterials*, 2004, doi: 10.1016/S0142-9612(03)00503-9.

[285] Q. Hou, D. W. Grijpma, and J. Feijen, "Preparation of Interconnected Highly Porous Polymeric Structures by a Replication and Freeze-Drying Process," *J. Biomed. Mater. Res. - Part B Appl. Biomater.*, 2003, doi: 10.1002/jbm.b.10066.

[286] S. Stokols and M. H. Tuszynski, "Freeze-dried agarose scaffolds with uniaxial channels stimulate and guide linear axonal growth following spinal cord injury," *Biomaterials*, 2006, doi: 10.1016/j.biomaterials.2005.06.039.

[287] N. Wang, Y. Liu, Y. Zhang, Y. Du, and J. Zhang, "Control of pore structure during freeze casting of porous SiC ceramics by different freezing modes," *Ceram. Int.*, 2019, doi: 10.1016/j.ceramint.2019.03.025.

[288] Aaron Lichtner, Denis Roussel, Daniel R¨ohrens, David Jauffres, Julie Villanova, Christophe L. Martin, Rajendra K. Bordia "Anisotropic sintering behavior of freeze-cast ceramics by optical dilatometry and discrete-element simulations," *Acta Mater.*, 2018, doi: 10.1016/j.actamat.2018.06.001.

[289] S. Deville, E. Saiz, R. K. Nalla, and A. P. Tomsia, "Freezing as a path to build complex composites," *Science (80-.).*, 2006, doi: 10.1126/science.1120937.

[290] F. Liu, N. A. Hashim, Y. Liu, M. R. M. Abed, and K. Li, "Progress in the production and modification of PVDF membranes," *Journal of Membrane Science*. 2011, doi: 10.1016/j.memsci.2011.03.014.

[291] K. K. Mallick and J. Winnett, "Preparation and characterization of porous bioglass ® and PLLA scaffolds for tissue engineering applications," 2012, doi: 10.1111/j.1551-2916.2012.05071.x.

[292] T. Krause, A. Molotnikov, M. Carlesso, J. Rente, K. Rezwan, Y. Estrin and D. Koch "Mechanical properties of topologically interlocked structures with elements produced by freeze gelation of ceramic slurries," *Adv. Eng. Mater.*, 2012, doi: 10.1002/adem.201100244.

[293] H. Zhao, Z. Yang, and L. Guo, "Nacre-inspired composites with different macroscopic dimensions: Strategies for improved mechanical performance and applications," *NPG Asia Materials*. 2018, doi: 10.1038/s41427-018-0009-6.

[294] R. Liu, T. Xu, and C. an Wang, "A review of fabrication strategies and applications of porous ceramics prepared by freeze-casting method," *Ceramics International*. 2016, doi: 10.1016/j.ceramint.2015.10.148.

[295] J. R. Rodrigues, N. M. Alves, and J. F. Mano, "Nacre-inspired nanocomposites produced using layer-by-layer assembly: Design strategies and biomedical applications," *Materials Science and Engineering C*. 2017, doi: 10.1016/j.msec.2017.02.043.

[296] M. J. Ribeiro, S. Blackburn, J. M. Ferreira, and J. A. Labrincha, "Extrusion of alumina and cordierite-based tubes containing Al-rich anodising sludge," *J. Eur. Ceram. Soc.*, 2006, doi: 10.1016/j.jeurceramsoc.2005.07.040.

[297] N. Akhtar, S. P. Decent, and K. Kendall, "Cell temperature measurements in micro-tubular, single-chamber, solid oxide fuel cells (MT-SC-SOFCs)," 2010, doi: 10.1016/j.jpowsour.2009.04.078.

[298] M. Faes, H. Valkenaers, F. Vogeler, J. Vleugels, and E. Ferraris, "Extrusion-based 3D printing of ceramic components," 2015, doi: 10.1016/j.procir.2015.04.028.

[299] H. Takashima, K. Miyagai, T. Hashida, and V. C. Li, "A design approach for the mechanical properties of polypropylene discontinuous fiber reinforced cementitious composites by extrusion molding," *Eng. Fract. Mech.*, 2003, doi: 10.1016/S0013-7944(02)00154-6.

[300] S. Blackburn and H. Böhm, "Silicon carbide fiber-reinforced alumina extrusion," *J. Mater. Res.*, 1995, doi: 10.1557/JMR.1995.2481.

[301] Y. Goto and A. Tsuge, "Mechanical Properties of Unidirectionally Oriented SiC-Whisker-Reinforced Si3N4 Fabricated by Extrusion and Hot-Pressing," *J. Am. Ceram. Soc.*, 1993, doi: 10.1111/j.1151-2916.1993.tb03920.x.

[302] W. Chang-An, H. Yong, and Z. Hongxiang, "The effect of whisker orientation in SiC whisker-reinforced Si3N4 ceramic matrix composites," *J. Eur. Ceram. Soc.*, 1999, doi: 10.1016/S0955-2219(98)00289-1.

[303] L. Zou, D. S. Park, B. U. Cho, Y. Huang, and H. D. Kim, "Characterization of grain alignment in Si3N 4(w)/Si3N4 composites," *Mater. Lett.*, 2004, doi: 10.1016/j.matlet.2003.10.031.

[304] G.-J. Bang, J.-F. Yang, and T. Ohji, "Porous Ceramics with Fine Uni-Directionally-Aligned Continuous Pores," 2008.

[305] T. Isobe, T. Tomita, Y. Kameshima, A. Nakajima, and K. Okada, "Preparation and properties of porous alumina ceramics with oriented cylindrical pores produced by an extrusion method," *J. Eur. Ceram. Soc.*, 2006, doi: 10.1016/j.jeurceramsoc.2004.11.015.

[306] G. J. Zhang, J. F. Yang, and T. Ohji, "Fabrication of Porous Ceramics with Unidirectionally Aligned Continuous Pores," *J. Am. Ceram. Soc.*, 2001, doi: 10.1111/j.1151-2916.2001.tb00849.x.

[307] F. Händle, *Extrusion in Ceramics*. 2007.

[308] N. Abdullah, M. A. Rahman, M. H. D. Othman, A. F. Ismail, J. Jaafar, and A. A. Aziz, "Preparation and characterization of self-cleaning alumina hollow fiber membrane using the phase inversion and sintering technique," *Ceram. Int.*, 2016, doi: 10.1016/j.ceramint.2016.05.003.

[309] C. C. Wei, O. Y. Chen, Y. Liu, and K. Li, "Ceramic asymmetric hollow fibre membranes-One step fabrication process," *J. Memb. Sci.*, 2008, doi: 10.1016/j.memsci.2008.04.003.

[310] S. LOEB and S. SOURIRAJAN, "Sea Water Demineralization by Means of an Osmotic Membrane," 1963.

[311] C. A. Smolders, A. J. Reuvers, R. M. Boom, and I. M. Wienk, "Microstructures in phase-inversion membranes. Part 1. Formation of macrovoids," *J. Memb. Sci.*, 1992, doi: 10.1016/0376-7388(92)80134-6.

[312] Z. Zhu, J. Xiao, W. He, T. Wang, Z. Wei, and Y. Dong, "A phase-inversion casting process for preparation of tubular porous alumina ceramic membranes," *J. Eur. Ceram. Soc.*, 2015, doi: 10.1016/j.jeurceramsoc.2015.04.026.

[313] S. H. Paiman, M. A. Rahman, M. H. D. Othman, A. F. Ismail, J. Jaafar, and A. A. Aziz, "Morphological study of yttria-stabilized zirconia hollow fibre membrane prepared using phase inversion/sintering technique," *Ceram. Int.*, 2015, doi: 10.1016/j.ceramint.2015.06.066.

[314] J. Luyten , A. Buekenhoudt, W. Adriansens, J. Cooymans, H. Weyten, F. Servaes, R. Leysen "Preparation of LaSrCoFeO3-x membranes," *Solid State Ionics*, 2000, doi: 10.1016/S0167-2738(00)00425-2.

[315] B. Henriques, D. Soares, and F. S. Silva, "Microstructure, hardness, corrosion resistance and porcelain shear bond strength comparison between cast and hot pressed CoCrMo alloy for metal-ceramic dental restorations," *J. Mech. Behav. Biomed. Mater.*, 2012, doi: 10.1016/j.jmbbm.2012.03.015.

[316] Yaohui Lv, Hong Liu, Zhen Wang, Shujiang Liu, Lujiang Hao, Yuanhua Sang, Duo Liu, Jiyang Wang, R.I. Boughton "Silver nanoparticle-decorated porous ceramic composite for water treatment," *J. Memb. Sci.*, 2009, doi: 10.1016/j.memsci.2009.01.007.

[317] Y. Liu, H. Ma, B. S. Hsiao, B. Chu, and A. H. Tsou, "Improvement of meltdown temperature of lithium-ion battery separator using electrospun polyethersulfone membranes," *Polymer (Guildf).*, 2016, doi: 10.1016/j.polymer.2016.11.020.

[318] J. Oliva, X. Oliva, and J. D. Oliva, "Erste klinische Einjahresergebnisse von 100 Zirkonoxidimplantaten - One-year follow-up of first consecutive 100 zirconia dental implants in humans: a comparison of 2 different rough surfaces," *Int.J.Oral Maxillofac.Implants.*, 2007.

[319] D. Hashim, N. Cionca, D. S. Courvoisier, and A. Mombelli, "A systematic review of the clinical survival of zirconia implants," *Clinical Oral Investigations*. 2016, doi: 10.1007/s00784-016-1853-9.

[320] Andrea Enrico Borgonovo, Rachele Censi, Virna Vavassori, Marcello Dolci, Josè Luis Calvo-Guirado, Rafael Arcesio Delgado Ruiz, and Carlo Maiorana "Evaluation of the success criteria for zirconia dental implants: A four-year clinical and radiological study," *Int. J. Dent.*, 2013, doi: 10.1155/2013/463073.

[321] M. Saini, "Implant biomaterials: A comprehensive review," *World J. Clin. Cases*, 2015, doi: 10.12998/wjcc.v3.i1.52.

[322] I. K. Karoussis, G. E. Salvi, L. J. A. Heitz-Mayfield, U. Brägger, C. H. F. Hämmerle, and N. P. Lang, "Long-term implant prognosis in patients with and without a history of chronic periodontitis: A 10-year prospective cohort study of the ITI® Dental Implant System," *Clin. Oral Implants Res.*, 2003, doi: 10.1034/j.1600-0501.000.00934.x.

[323] F. C. Setzer and S. Kim, "Comparison of long-term survival of implants and endodontically treated teeth," *J. Dent. Res.*, 2014, doi: 10.1177/0022034513504782.

[324] Cho, Young-Dan, Ji-Cheol Shin, Hye-Lee Kim, Myagmar Gerelmaa, Hyung-In Yoon, Hyun-Mo Ryoo, Dae-Joon Kim, and Jung-Suk Han "Comparison of the osteogenic potential of titanium- and modified zirconia-based bioceramics," *Int. J. Mol. Sci.*, 2014, doi: 10.3390/ijms15034442 LK

[325] R. Velázquez-Cayón, C. Vaquero-Aguilar, D. Torres-Lagares, M. Jiménez-Melendo, and J. L. Gutiérrez-Pérez, "Mechanical resistance of zirconium implant abutments: A review of the literature," *Medicina Oral, Patologia Oral y Cirugia Bucal*. 2012, doi: 10.4317/medoral.17462.

[326] Carl E. Misch, Morton L. Perel, Hom-Lay Wang, Gilberto Sammartino, Pablo Galindo-Moreno, Paolo Trisi, Marius Steigmann, Alberto Rebaudi, Ady Palti, Michael A. Pikos, Schwartz-Arad, Joseph Choukroun, Jose-Luis Gutierrez-Perez, Gaetano Marenzi, and Dimosthenis K. Valavanis, "Implant success, survival, and failure: The International Congress of Oral Implantologists (ICOI) pisa consensus conference," *Implant Dentistry*. 2008.

[327] K. Karthik, Sivakumar, Sivaraj, and V. Thangaswamy, "Evaluation of implant success: A review of past and present concepts," *Journal of Pharmacy and Bioallied Sciences*. 2013, doi: 10.4103/0975-7406.113310.

[328] S. M. Abusrewil, W. McLean, and J. A. Scott, “The use of Bioceramics as root-end filling materials in periradicular surgery: A literature review,” *Saudi Dental Journal*. 2018, doi: 10.1016/j.sdentj.2018.07.004.

[329] Xiannian Sun, Haokai Wu, Gongzhi Zhu, Yingchun Shan, Jiujun Xu, Jiangtao Li, Eugene A. Olevsky “Direct coarse powder aqueous slip casting and pressureless sintering of highly transparent AlON ceramics,” *Ceram. Int.*, 2020, doi: 10.1016/j.ceramint.2019.10.219.

[330] W. Chen, Y. Hotta, T. Tamura, K. Miwa, and K. Watari, “Effect of suction force and starting powders on microstructure of Bi4Ti3O12 ceramics prepared by magnetic alignment via slip casting,” *Scr. Mater.*, 2006, doi: 10.1016/j.scriptamat.2006.03.010.

[331] Songfeng Xu, Kaili Lin, Zhen Wang, Jiang Chang, Lin Wang, Jianxi Lu, Congqin Ning “Reconstruction of calvarial defect of rabbits using porous calcium silicate bioactive ceramics,” *Biomaterials*, 2008, doi: 10.1016/j.biomaterials.2008.03.013.

[332] X. Jin, J. Chang, W. Zhai, and K. Lin, “Preparation and characterization of clinoenstatite bioceramics,” *J. Am. Ceram. Soc.*, 2011, doi: 10.1111/j.1551-2916.2010.04032.x.

[333] F. Tavangarian and R. Emadi, “Nanostructure effects on the bioactivity of forsterite bioceramic,” *Mater. Lett.*, 2011, doi: 10.1016/j.matlet.2010.11.014.

[334] F. Tavangarian, R. Emadi, and M. H. Enayati, “Synthesis and Characterization of Nanostructure Forsterite Bioceramic for Tissue Engineering Applications,” in *Supplemental Proceedings: Materials Fabrication, Properties, Characterization, and Modeling*, 2011.

[335] C. Wu and J. Chang, “Synthesis and in vitro bioactivity of bredigite powders,” *J. Biomater. Appl.*, 2007, doi: 10.1177/0885328206062360.

[336] Yogambha Ramaswamy, Chengtie Wu, Colin R. Dunstan, Benjamin Hewson, Tanja Eindorf, Gail I. Anderson, Hala Zreiqat “Sphene ceramics for orthopedic coating applications: An in vitro and in vivo study,” *Acta Biomater.*, 2009, doi: 10.1016/j.actbio.2009.04.028.

[337] W. Lu, W. Duan, Y. Guo, C. Ning, “Mechanical properties and in vitro bioactivity of Ca5(PO4)2SiO4 bioceramic.,” *J. Biomater. Appl.*, 2012, doi: 10.1177/0885328210383599 LK

[338] Hala Zreiqat, Yogambha Ramaswamy, Chengtie Wu, Angelo Paschalidis, ZuFu Lu, Barbara James, Oliver Birke, Michelle McDonald, David Little, Colin R. Dunstan “The incorporation of strontium and zinc into a calcium-silicon ceramic for bone tissue engineering,” *Biomaterials*, 2010, doi: 10.1016/j.biomaterials.2010.01.024.

[339] C. Wu and J. Chang, “A novel akermanite bioceramic: Preparation and characteristics,” *J. Biomater. Appl.*, 2006, doi: 10.1177/0885328206057953.

[340] K. Lin, W. Zhai, S. Ni, J. Chang, Y. Zeng, and W. Qian, “Study of the mechanical property and in vitro biocompatibility of CaSiO3 ceramics,” *Ceram. Int.*, 2005, doi: 10.1016/j.ceramint.2004.05.023.

[341] E. El-Meliegy, R. van Noort, E. El-Meliegy, and R. van Noort, “Machinable Mica Dental Glass-Ceramics,” in *Glasses and Glass Ceramics for Medical Applications*, 2012.

[342] T. Zhao, Y. Qin, B. Wang, and J. F. Yang, "Improved densification and properties of pressureless-sintered lithium disilicate glass-ceramics," *Mater. Sci. Eng. A*, 2015, doi: 10.1016/j.msea.2014.10.037.

[343] P. Zhang, X. Li, J. Yang, and S. Xu, "Effect of heat treatment on the microstructure and properties of lithium disilicate glass-ceramics," *J. Non. Cryst. Solids*, 2014, doi: 10.1016/j.jnoncrysol.2014.05.023.

[344] S. Gali, "Mica glass ceramics for dental restorations," *Mater. Technol.*, 2019, doi: 10.1080/10667857.2018.1494240.

[345] I. L. Denry and J. A. Holloway, "Effect of heat pressing on the mechanical properties of a mica-based glass-ceramic," *J. Biomed. Mater. Res. - Part B Appl. Biomater.*, 2004, doi: 10.1002/jbm.b.30010.

[346] X. Chen, T. C. Chadwick, R. M. Wilson, R. G. Hill, and M. J. Cattell, "Crystallization and flexural strength optimization of fine-grained leucite glass-ceramics for dentistry," *Dent. Mater.*, 2011, doi: 10.1016/j.dental.2011.08.009.

[347] A. Theocharopoulos, X. Chen, R. M. Wilson, R. Hill, and M. J. Cattell, "Crystallization of high-strength nano-scale leucite glass-ceramics," *Dent. Mater.*, 2013, doi: 10.1016/j.dental.2013.08.209.

[348] P. Zhang, X. Li, J. Yang, and S. Xu, "The crystallization and microstructure evolution of lithium disilicate-based glass-ceramic," *J. Non. Cryst. Solids*, 2014, doi: 10.1016/j.jnoncrysol.2014.03.020.

[349] S. E. Elsaka and A. M. Elnaghy, "Mechanical properties of zirconia reinforced lithium silicate glass-ceramic," *Dent. Mater.*, 2016, doi: 10.1016/j.dental.2016.03.013.

[350] C. Gautam, J. Joyner, A. Gautam, J. Rao, and R. Vajtai, "Zirconia based dental ceramics: structure, mechanical properties, biocompatibility and applications," *Dalt. Trans.*, vol. 45, no. 48, pp. 19194–19215, 2016, doi: 10.1039/c6dt03484e.

[351] Y. Zhang, P. Rao, M. Lü, and J. Wu, "Mechanical properties of dental porcelain with different leucite particle sizes," *J. Am. Ceram. Soc.*, 2008, doi: 10.1111/j.1551-2916.2007.02179.x.

[352] C. C. Gonzaga, P. F. Cesar, C. Y. Okada, C. Fredericci, F. B. Neto, and H. N. Yoshimura, "Mechanical properties and porosity of dental glass-ceramics hot-pressed at different temperatures," *Mater. Res.*, 2008, doi: 10.1590/S1516-14392008000300012.

[353] N. Monmaturapoj, P. Lawita, and W. Thepsuwan, "Characterisation and properties of lithium disilicate glass ceramics in the SiO2-Li2O-K2O-Al2O3 system for dental applications," *Adv. Mater. Sci. Eng.*, 2013, doi: 10.1155/2013/763838.

[354] D. S. Baik, K. S. No, J. S. Chun, and Y. J. Yoon, "Mechanical Properties of Mica Glass-Ceramics," *J. Am. Ceram. Soc.*, 1995, doi: 10.1111/j.1151-2916.1995.tb08472.x.

[355] S. Habelitz, G. Carl, C. Russel, S. Thiel, U. Gerth, J.-D. Schnapp, A. Jordanov, H. Knake "Mechanical properties of oriented mica glass ceramic," *J. Non. Cryst. Solids*, 1997, doi: 10.1016/S0022-3093(97)00299-8.

[356] G. Wen, X. Zheng, and L. Song, "Effects of P2O5 and sintering temperature on microstructure and mechanical properties of lithium disilicate glass-ceramics," *Acta*

Mater., 2007, doi: 10.1016/j.actamat.2007.02.009.

[357] W. Höland, V. Rheinberger, E. Apel, and C. van't Hoen, "Principles and phenomena of bioengineering with glass-ceramics for dental restoration," *J. Eur. Ceram. Soc.*, 2007, doi: 10.1016/j.jeurceramsoc.2006.04.101.

[358] T. Ayode Otitoju, P. Ugochukwu Okoye, G. Chen, Y. Li, M. Onyeka Okoye, and S. Li, "Advanced ceramic components: Materials, fabrication, and applications," *J. Ind. Eng. Chem.*, vol. 85, pp. 34–65, 2020, doi: 10.1016/j.jiec.2020.02.002.

[359] J. B. Quinn, V. Sundar, and I. K. Lloyd, "Influence of microstructure and chemistry on the fracture toughness of dental ceramics," *Dent. Mater.*, 2003, doi: 10.1016/S0109-5641(03)00002-2.

[360] M. Guazzato, M. Albakry, S. P. Ringer, and M. V. Swain, "Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part I. Pressable and alumina glass-infiltrated ceramics," *Dent. Mater.*, vol. 20, no. 5, pp. 441–448, 2004, doi: 10.1016/j.dental.2003.05.003.

[361] C. Wu and J. Chang, "A review of bioactive silicate ceramics," *Biomedical Materials (Bristol)*. 2013, doi: 10.1088/1748-6041/8/3/032001.

[362] Wanyin Zhai, Hongxu Lu, Lei Chen, Xiaoting Lin, Yan Huang, Kerong Dai, Kawazoe Naoki, Guoping Chen, Jiang Chang "Silicate bioceramics induce angiogenesis during bone regeneration," *Acta Biomater.*, 2012, doi: 10.1016/j.actbio.2011.09.008.

[363] P. N. De Aza, Z. B. Luklinska, M. R. Anseau, F. Guitian, and S. De Aza, "Transmission electron microscopy of the interface between bone and pseudowollastonite implant," *J. Microsc.*, 2001, doi: 10.1046/j.1365-2818.2001.00779.x.