Materials Properties, Manufacturing Methods, and Applications of Bioglass-Ceramics: A Review

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Abstract: - Glass-ceramics, in addition to having extremely low coefficients of thermal expansion, may also have properties that promote particular applications. Examples include their high thermal shock resistance. Unlike glasses, glass-ceramic materials have a high degree of crystalline structure, with virtually zero vitreous material. In general, the crystals measure under one meter long, measure consistently, and are compact. In consequence, bioglass ceramics have been defined as a new class of glass ceramics that can be used for biomedical applications. As compared with glass, the mechanical properties of ceramics are superior. In this review, bioglass-ceramics properties, processing, and applications were discussed.

Key Words: — ***Glass- ceramics, Nucleation, Crystallization, Microstructure, Nanotechnology, Ceramics technology.***

I. INTRODUCTION

When we think about glass materials, we usually think of windows in buildings, residences, and vehicles. While this is true, there are many distinct types of glasses with various compositions. Glass is typically straightforward and highly fragile (when not heat-treated). Glass is an amorphous and non-crystalline solid, while ceramics, however, are inorganic materials that can be crystalline or semi-crystalline, but are never non-crystalline, Ceramics are never transparent and are always opaque, glass is cheaper than ceramics. The lack of grain boundaries and pores in the glass structure causes transparency. Brittleness is also caused by a lack of grain boundaries since cracks can propagate freely[1]. Glass-ceramic materials have the same chemical makeup as glasses but are 95-98 percent crystalline by volume, with only a tiny fraction vitreous. The crystals themselves are often relatively small, less than 1m in size, and highly consistent. Furthermore, they are no longer transparent due to their crystallinity and network of grain boundaries[2]. Corning glass works pioneered the development of glass-ceramic materials, which combine the characteristics of parent glass and polycrystalline materials.

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In this article, we'll examine how they vary from glass materials, how they're made, some standard compositions, and how they're used[3, 4]. Glass-ceramics have been around for over 65 years and are known for their unique combination of characteristics, which has resulted in a plethora of high-tech goods for both consumer and specialist sectors. Pyroceram (glass code 9606) was marketed by corning glass works in 1957, and S.D. Stookey developed the term glass-ceramic for it. Stookey used “a process-based description to identify this new class of materials, which he created by first melting and then chilling to create particular glasses using nucleating chemicals and then producing controlled crystallization of glass particles”[5, 6]. Controlled crystallization of inorganic, nonmetallic glasses produce them[7]. Non-crystalline metastable materials that serve as the foundation for glass ceramics are known as glasses. When glass melts, it forms glass-ceramics, which are fine-grained polycrystalline solids. Due to controlled crystallization, glasses containing the necessary components are heated to a lower-energy, crystalline form[8]. A few aspects should be highlighted in this glass-ceramics remark. To begin with, only certain glass compositions are acceptable as glass-ceramic precursors; certain glasses, such as common window glass, are too stable and difficult to crystallize, while others crystallize too fast and uncontrolled, resulting in undesired microstructures. Second, heat treatment is important to produce a satisfactory and repeatable result. “A variety of typical heat treatment techniques exist, each of which must be carefully designed and customized for a given glass composition"[9, 10]. Glasses may be made from a number of species, including as silicate, phosphate, and oxynitride glasses, all of which have been shown to be suitable for glass-ceramic production depending on the presence of additional additives. "The glass-ceramic microstructure is normally between 50 and 95 percent crystalline, with the remaining 20 to 30 percent residual glass"[11]. A crystalline phase or phases may form during heat treatment, and because their composition differs from that of the precursor glass (parent glass), the remaining glass is also different[12, 13]. Glass-ceramics exceed parent glass in terms of mechanical properties. In contrast, glass-ceramics are thought to have additional advantages, such as their exceptionally low coefficient of thermal expansion, which makes them suitable for thermal shock applications such as ovenware, cooker tops, and heat resistant windows[14, 15].

Glass crystallization, or devitrification, is a heterogeneous process used to make glass-ceramics. A heterogeneous transformation: i. produces significant atomic rearrangements on a tiny scale; ii. establishes a well-defined interface between the parent phase (in this case, glass) and the daughter phase(s); and iii. has two stages: nucleation and growth. The nucleation stage occurs when small, stable volumes of the product crystalline phase are formed, typically at desired locations inside the parent glass [16]. Sites inside the parent glass or on the free surface are optimal. Fig.1.shows the glass ceramics polycrystalline structure.

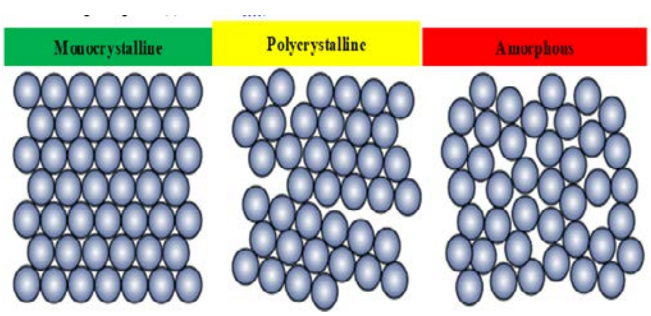

Fig.1. A diagram depicting the combined structure of monocrystalline silicon, polycrystalline silicon, and amorphous glass-ceramics

The latter is in most cases undesirable because the "resultant glass-ceramic microstructure contains large orientated crystals that degrade mechanical characteristics"[17, 18]. However, in a few cases, such as glass-ceramics for piezoelectric and pyroelectric devices, an orientated structure is advantageous. The possibilities for glass-ceramic pairings are endless, and all that is required is the capacity to produce a glass and regulate its crystallization through internal nucleation. The thermodynamically stable mix of crystals regulated by phase equilibria rules, on the other hand, is limited to metastable crystals that may form from Glass[19]. The crystal development stage begins once a stable nucleus has been established. Through the glass-crystal interface, atoms/molecules move from the glass into the crystal [20]. In this process, there is a loss of chemical free energy, 'G-v, as the glass phase is displaced by the crystalline phase. The thermally induced transport of atoms/molecules across the interface has a corresponding activation energy G-a. The form of the resultant curve has been generated using models for the temperature dependence of the growth rate, which include the parameters G_v and G_a is as in Fig.2. a[21, 22].

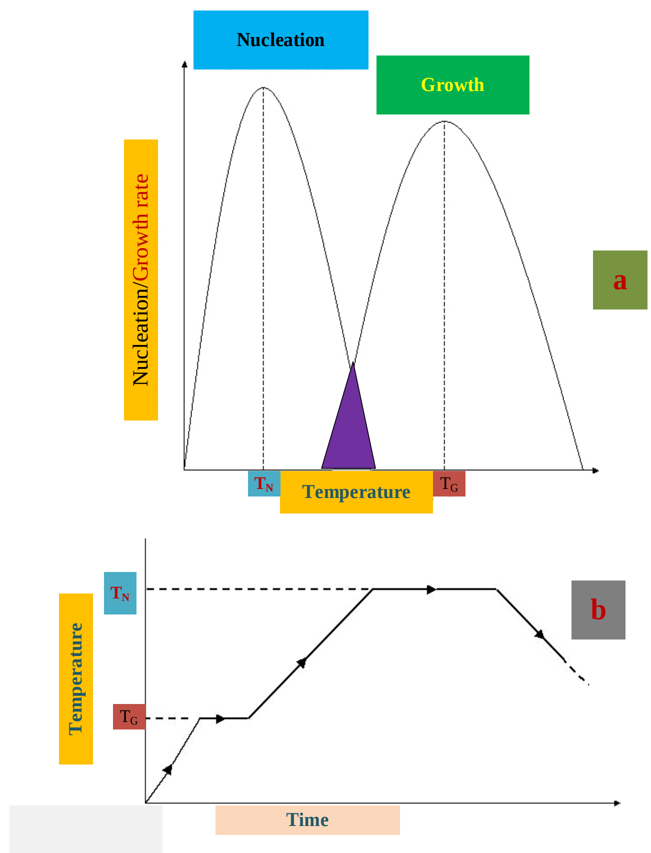

Fig.2. To make a glass-ceramic, glass crystallization used. (a) Temperature affects nucleation and growth rates, with minimal overlap. (b) a two-stage heat treatment

Prior to creating Pyroceram, Stookey worked on a radiation-sensitive glass called "Photosensitive Opal Glass"[23].

Glass-ceramics are recognized for their unique, exotic mix of characteristics, which has resulted in a plethora of high-tech goods for both consumer and specialized sectors. In 1959, Stookey developed a uniform way for referring to both types of materials as glass-ceramic, independent of the nucleating chemical employed (Cu, Ag, Au, or TiO2). Specifically, this study examines the properties and applications of glass ceramics in modern technology.

II. PROPERTIES

At the corning glass works, glass ceramic materials were developed, and they share properties both with polycrystalline materials and with parent glass materials. A crystalline phase may develop during heat treatment, and that phase's composition is different from the precursor (parent) glass, so that the remaining glass is also different [24].

All glass-ceramic characteristics are good; zero porosity, high strength, toughness, transparency or opacity, pigmentation, opalescence, machinability, ferromagnetism, restorability or chemical durability [25].

Tuning these properties requires changing the composition of the base glass and regulating the heat treatment/crystallization of the base glass. Compared with pure glass, glass ceramics have improved mechanical properties[26]. Besides their “thermal shock resistance, glass-ceramics may have other unique features that make them ideal for certain applications, such as their extremely low thermal expansion coefficient when compared to other ceramic materials, such as Li2O-Al2O3-SiO2”[27].

Numerous comprehensive reviews and devoted books on their manufacturing, properties, and uses have been published, and there are a wide variety of glass-ceramics with customized properties. Both composition and microstructure influence glass-ceramic properties [28].

Even though they can have the same composition, the Fig.3. show some of the structural distinctions between a glass and a ceramic on an atomic basis. For example, the composition of silica glass is identical to that of quartz (crystallized silica). The building blocks (SiO4 tetrahedral) of glass, on the other hand, are placed randomly, whereas silica crystals have a fairly structured structure[29, 30].

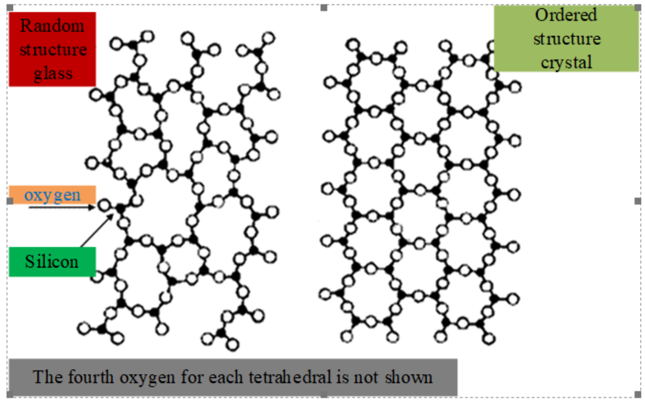

Fig.3.Tetrahedral structure of glass-ceramics

Heating glass can turn it into a ceramic. This allows a random structure to become an ordered structure that is more stable than a disordered structure. In the manufacture of glass-ceramic materials, the materials are molded first as glasses (using glass moulding techniques), and then they are converted to ceramic materials to improve their properties. Glass-ceramics are well-known for their ability to have a thermal expansion coefficient that approaches zero, such as the 'ceramic' stove cooktop. In this way, the hob can be heated and cooled quickly without causing tension[31].

In addition to its chemical composition, a glass's capacity to form and degree of workability is determined by its bulk chemical composition [32, 33]. Nucleating chemicals are melted inside the glass to achieve internal nucleation. As well as the bulk composition, the type of crystalline phase assemblage also influences its general physical and chemical properties, such as toughness, density, and acid resistance [34, 35]. The relevance of microstructure is second but equally significant. Most mechanical and optical characteristics are determined by microstructure, which can enhance or reduce the function of critical crystals in glass ceramics. As a result, glass-ceramics must be characterized in terms of composition as well as microstructure [35-37]. Throughout the eastern part of Europe, including in Hungary and Russia, glass ceramics have been made from blast furnace slags for more than two decades. This residual glass matrix contains fine (1-5, urn) alkaline-earth silicate crystals which provide abrasion resistance as well as excellent chemical endurance[38, 39].Generally glass ceramics have the following properties mechanical strength is rather strong, low thermal expansion coefficients, light temperature resistance. Dielectric characteristics that are satisfactory, biocompatibility is excellent and by using the correct high-temperature heat treatment, non-crystalline materials can be converted to crystalline materials. Materials containing the major phases spinel and enstatite may be useful as magnetic disk substrates for computer hard drives because they are nanocrystalline, of high strength and toughness, and of higher wear resistance[40, 41].

III. MANUFACTURING PROCESS

A glass is first manufactured using a glass production technique, and then a glass-ceramic is created in two phases. Before being warmed a second time, the glass is cooled. In glass ceramics, devitrification may occur spontaneously during cooling or during service, but it is most commonly incorporated after the cooling process[42]. During the process, the formed glass product is heated to a temperature high enough to stimulate crystal nucleation throughout the whole product. The temperature is then raised, causing the nuclei to grow, thereby causing the glass to crystallize. For a nucleus to form, it takes a critical number of atoms to converge. Eventually, the nucleus will nucleate. It is difficult for the required atoms to form in many glass compositions due to the fact that it is silica-based and highly viscous, making it difficult for nucleation to occur. It is also possible for crystal compositions to be complex, making nucleation challenging. Consequently, there can be no crystallization of the glass. For most glass-basic ceramics, nucleation agents are used during this heat treatment[43]. There is an amorphous phase and a crystalline phase in glass-ceramics, and the process makes use of controlled crystallization, instead of spontaneous crystallization, which is typically unsuitable for the glass industry[44]. To ensure that a maximum number and shape of nuclei are formed during the devitrification process, the heat treatment must be carefully controlled. It is common to add a nucleating agent to the glass composition in order to achieve a high concentration of nuclei throughout the structure. Several nucleating agents, such as TiO_2 and ZrO_2, have also been used, including P_2O_5, platinum group metals, and some fluorides[45].

Ceramic, glass-ceramic combines the properties of glass with those of ceramics to produce a product that is easy to manufacture and can withstand brazing temperatures of up to 700°C, but does not always require brazing when used to seal components. There are many traditional methods of processing ceramics, including pressing, plastic shaping, slip casting, and tape casting, followed by sintering or burning[46]. Research by Penn state researchers is producing a new type of ceramic for applications in lasers, optical communications, implants, spark plugs, and microelectronics. Glass ceramics may be processed in the following way as Fig.4. For glass-ceramic to be produced, a specific element is added to the raw materials: a nucleating agent. sand, lithium, and aluminum oxides constitute the basic elements, but the glass-ceramic is strengthened by a secondary ingredient. The glassy compound is melted, cooled, and eventually cooled down to roughly 1,100 degrees Fahrenheit when the basic ingredients are combined [47].

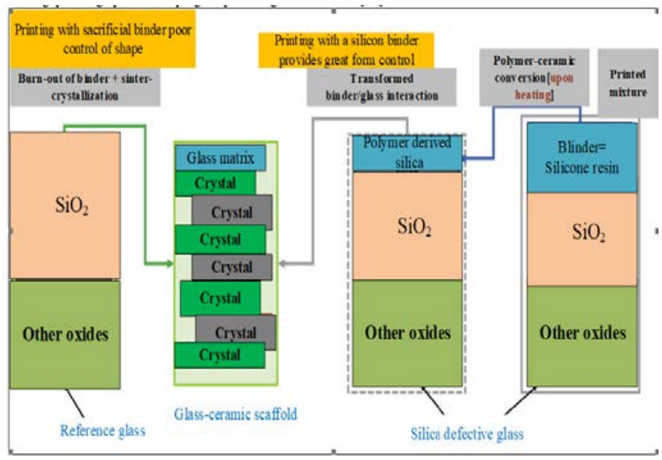

Fig.4.Glass-ceramic processing schemes: traditional devitrification (left) vs heat treatment of silicone/silica-defective glass mixes (right) [48]

IV. NANO-GLASS CERAMIC IN BIOMEDICAL APPLICATION

Bioactive glass-ceramics are required as a biomaterial for artificial bone and dental implants because of their superior mechanical properties, good bioactivity, biocompatibility, and non-toxicity. The development of biomedical materials or biomaterials has contributed significantly to the expansion of the contemporary healthcare sector during the past four to five decades[49]. As an alternative to the conventional metallic implants, bioactive glasses and glass-ceramics have been developed for small defect reconstruction, ear surgery, and dentistry, as well as load-bearing coatings of inert materials. Due to their physico-chemical properties, ceramics can be applied as biomaterials in a variety of contexts[38].

In addition to being inert in the body, their hardness and resistance to abrasion make them useful for replacing bones and teeth. This type of material includes natural or synthetic materials suitable for injection into living tissue, most commonly as part of a medical device[50]. On the other hand, bioactive glasses and glass ceramics have gained great interest for therapeutic applications, notably following the pioneering work of Hench et al. (1971) and the production of the first bioactive glasses[51, 52].

In the biomedical ceramics industry, material development is becoming increasingly diverse. As shown in Fig.5, below, a primary goal of clinically utilized biomedical glass ceramics is to repair and replace tissues that have lost function due to damage, aging, illness, or accidents.

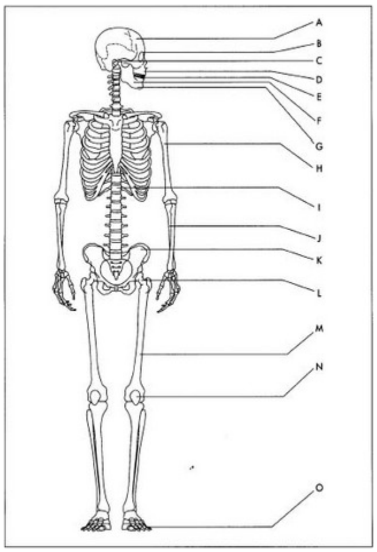

Fig.5. Bio-ceramics in clinical settings

Several bioactive materials, including glass-ceramics, calcium phosphate ceramics, composites and coatings, are linked to living tissue[53]. This is due to the interaction of implant-tissue interfaces and bonding mechanisms between the different bioactive materials. Metal ions can be retarded by the ceramic from diffusing into the human body through an effective barrier. Calcium phosphate ceramics such as hydroxyapatite, tricalcium phosphate, and tetra calcium phosphate, zirconia, bioactive glasses or silica, as well as pyrolytic carbons have been used to substitute bone[54]. The applications of calcium phosphate ceramics are currently focused primarily on bone defect filling in orthopedics and dental procedures[55]. As a result of their biological activity, these materials vary from inert to bioactive, which implies that they can remain unchanged, disintegrate, or participate actively in physiological processes to support bone growth[56]. It is not possible to achieve mechanical strengths greater than cortical bone, even with thick glass-ceramic. Since 1983, glass-ceramic has been used for spine and hip surgeries for patients with severe lesions and bone abnormalities, and the results have been excellent Fig.6.

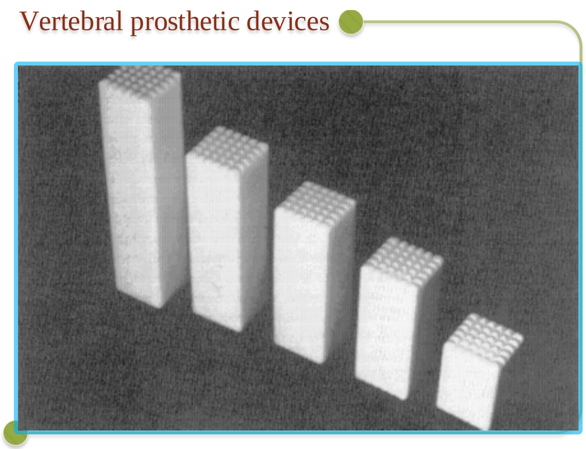

Fig.6.Choosing a spinal prosthetic device made of glass ceramics

developed for the repair and replacement of bones and joints over the past five decades[57]. The first step in the process was to synthesize a "bio inert" substance with the sole purpose of reducing the formation of scar tissue on the surface of the host tissue Fig.7. Illustrates. An MgO-CaO-SiO_2-P_2O_5 based glass-ceramic with apatite and wollastonite phases has demonstrated excellent mechanical properties as well as chemical durability and the ability to bond strongly with living bone [58]. Increasingly, glass ceramics based on apatite-wollastonite are being used for both biomaterials, such as bone fillers or bulk materials for prosthetics, because of their desirable properties [59].

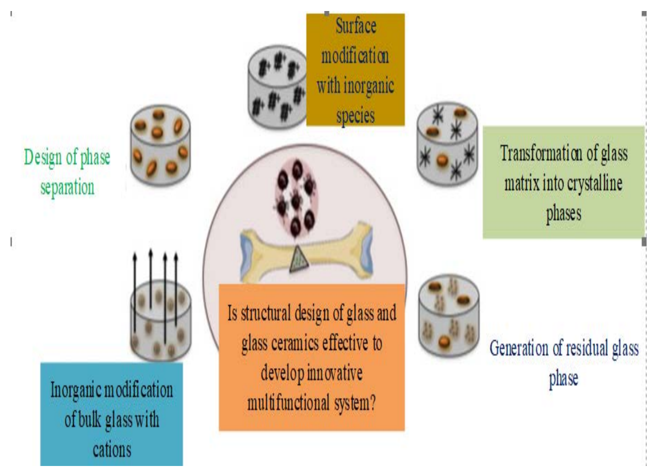

Fig.7. Bone tissue regeneration using bioglass and glass ceramics

Nevertheless, depending on the scenario, i.e. the size, form, and location of the bone defect, as well as the intended use, each material's mechanical properties and bioactivity are essential [60]. The combination of high bioactivity and mechanical strength is necessary when both are unavailable simultaneously, such as when a vertebral body is being replaced[61, 62]. To serve as a covering material over a joint prosthesis, however, they need to exhibit great bioactivity rather than tremendous mechanical strength Fig.8.[63]. As scaffolds for regenerating bone tissue, bioactive ceramics, such as tricalcium phosphates, hydroxyapatite, and bioglass, have gained a lot of traction in recent years. As a result, bone regeneration is improved when these scaffolds either induce bone production from surrounding tissue or serve as carriers or guides for cell migration, proliferation, and differentiation.

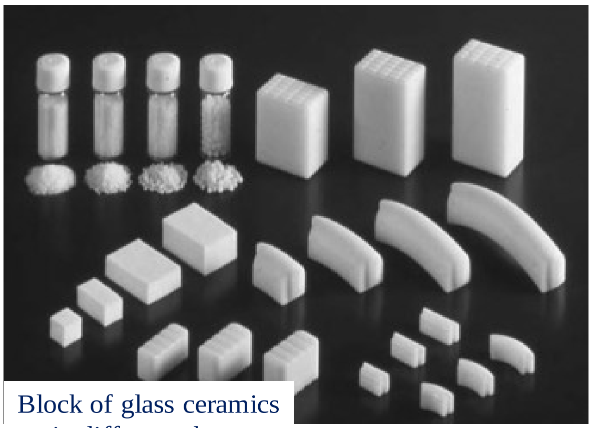

Fig.8. Block glass ceramics for medical applications, as produced in the laboratory

V. Conclusion And Future Prospects

A comprehensive study of glass ceramics is presented in this paper, including its composition and preparation methods, therapeutic uses, manufacturing, and bone-bonding properties. Despite the superior Osseo integration properties of glass-ceramic materials and their therapeutically desirable mechanical properties, including fracture toughness and flexural strength[64, 65], bulk nucleating is difficult and bioresorbable materials are scarce, creating considerable difficulties for researchers[66]. Its biodegradability (resorption) combined with its low mechanical strength are fundamental challenges of bio ceramics' application in bone tissue engineering. As a tool for producing porous bio ceramics that are highly mechanically strong, bioactive, and resorbable, nanotechnology can play a key role. Although newly generated GCs demonstrate the requisite resorbing capacity and Osseo integration, more study is needed to determine in vivo activity and mechanism of action. The author wishes to conclude that knowledge obtained from biomaterials research, particularly glass-ceramics, continues to astonish and convey new ideas in the structural solid-state with undeniably significant future promise.

Disclosure and Conflict Of Interest:

There are no conflicts of interest, according to the author.

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