Influence of Reinforcement Oxides on Structural and Mechanical Properties of Glass-Ceramics: A Review Article

Amr Ali, Sabreen Abdallah Abdelwahab, Khaled Abdelwahed, Ibrahim Ahmed, Ahmed I. Ali

Abstract: This review studied the mechanical behaviors of Glass ceramics (GC) based on the Al_2O_3/SiO_2 system. Glass ceramics are great interest due to their wide variety of applications, which have the ability to fulfil the recent demands of advanced mechanical, optical and biomedical applications. Glass-ceramics are typically heat-stable and have greater mechanical features than glasses. In addition, mechanical properties can be customized to provide variable volume fractions of crystalline phases by regulating nucleation and growth of the crystalline phases. The distribution of these crystalline phases in the glass matrix increases the consistency of the material and, in comparison, effectively limits the growth of cracks. The crystallization process resulted in substantial improvements in micro-hardness and density values such as sodium calcium phosphate ($Na_4Ca(PO_3)_6$ and calcium pyrophosphate (β-$Ca_2P_2O_7$) had sufficient properties for bone grafts and dental applications. This article outlines recent developments in the field of doping Oxides as reinforced with SiO_2-Al_2O_3-based Glass-ceramics, to enhance the mechanical properties of Glass-ceramics combination. The research focused on the mechanical and the tribological behaviour of Biomedical, Electronics applications and selection of fabrication methods.

Keywords: Glass-ceramics - Synthesis - Reinforcements - Structure - Mechanical behavior

I. INTRODUCTION

Now a day, promoting clean energy initiatives and urge for ecofriendly innovative materials for their usage at the present time world have brought the researchers from where over the world on the common ground to develop ecofriendly innovative materials which are simple to fabricate with sufficient mechanical and Chemical features and economically viable, these are the materials now the need of the hour considered the Glass-ceramics are one of them [1][2]. Actually, because of their theoretically superior mechanical properties, a great deal of interest is paid to ceramic matrix composites Oxide ceramics, non-oxide ceramics, Glass and Glass-ceramics are all called matrix materials, the ideal matrix, based on factors such as cost and the necessary mechanical properties [3].

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Glass-ceramics can be identified by the controlled crystallization of glasses as composite materials formed in their bulk [4]. Light concentrations of nucleating agents such as TiO_2 and ZrO_2 must be applied to the glass formulation to induce their bulk homogeneous crystallization [5]. Nucleation or crystallisation of glasses may be promoted by such agents using the following techniques: (1) the nucleating agent dissolved in the melt will serve as a site for the creation of additional crystalline phases [6][7], (2) The nucleating agent may facilitate the immiscibility of glass or the differentiation of phases, leading to crystallization [8], and (3) the composition can be transferred to a phase region that is more readily crystallized by the agent applied in appropriate amounts. Alumina-ceramics are now widely used as bone and joint repair materials because of their useful biocompatibility and high mechanical strength [9]. In the other hand, the bones do not form a close chemical bond, and their fixation inside the body involves a mechanical interlocking of the bone. This interlocking is prone to become loose over a long period [10]. Despite the great downside of high aluminum content Glasses have very high melting temperatures of up to 1650°C and high viscosity, which make them difficult to melt, homogenize and refine. Given this fact, it has been proposed that the use of TiO_2 as a nucleating agent rather than ZrO_2 decreases the system's melting temperature. When TiO_2 is used, nucleation is based on the notion of an ultra-fine size, highly uniform liquid phase separation into SiO_2 and TiO_2/Al_2O_3-rich zones. The octahedral position of the spinal structure can be occupied by charge balanced replacement Ti^{+4} [11].

The most common methodologies for the preparation of Ceramic Matrix Nano composites are the powder metallurgy method; Polymer precursor method; Spray pyrolysis; Vapor systems and Chemical methods, which involve the Sol-Gel process, colloidal and precipitation approaches and the template installation [12]. Ceramics are usually brittle and easy to fracture as a consequence of crack propagation. Ceramics are made suitable for engineering applications by integrating into the matrix a ductile metal phase or another ceramic. This leads to improved mechanical characteristics such as hardness and fracture strength, which occur due to the relationship between the various phases, matrix and reinforcements at phase boundary [13]. Glass-Powder compact sintering is a public processing tool for extracting favorite properties of Glass-ceramic (GC) materials [14]. The glass powders with high specific surface area substantially progress uniformly distributed nucleus sites in the entire volume of the glass[15][16].

Crystalline phases precipitated from the glass reservoir decide the characteristics of GCs, while an overly high degree of crystal growth should be avoided in order not to boost coarse microstructure, restricting the achievement of high mechanical power[17][18]. Furthermore, sintering should preferably occur previously crystallization thus both events being independent processes.

II. CERAMIC, GLASS-CERAMICS AND THEIR APPLICATIONS

A mixture of covalent, ionic, and sometimes metallic ceramics is typically associated with varying bonding. They consist of interlinked atom matrices; there are no isolated molecules. We still classify Diamond and Graphite as ceramics, though. In the most fundamental sense of the word, these sources of carbon are inorganic: they were not prepared from the living body. Ceramics typically have unique characteristics associated with them, most ceramics are weak at room temperature, but not always at elevated temperatures, weak electrical and thermal conduction, greater compression than tension stress, a large amount of ceramics are stable in both cruel chemical and thermal conditions, and many ceramics are transparent because they have a high E_g. The uses for these materials are diverse, from bricks and tiles to electrical and magnetic components. These applications use the broad variety of properties that ceramics display. Any of these properties, along with examples of particular ceramics and applications, are given in Table.1. Each of these fields would later be discussed in greater detail. Ceramic products' occupations depend on their chemical composition and microstructure, which define their properties. A central feature in materials science and engineering is the interrelationship of structure and properties.

Table.1 Ceramics Applications and Properties.

Property	Example	Application
Electrical	Doped ZrO_2, TiO_2	Electrolyte in fuel cells with solid-oxide [19]
	SiC	Elements for the furnace for resistive heating [20]
	SnO_2	Electrodes for molten furnaces of electric glass [21]
Dielectric	α-Al_2O_3	Insulator with spark plug [22]
	SiO_2	Bricks for furnace [23]
Mechanical	Al_2O_3	Implants of the Thigh [24]
	TiN	Coatings that are wear-resistant [25]
	SiC	Abrasives designed for polishing [26]
	Diamond	Tools to Cut [27]
Thermal	SiO_2	Tiles of space shuttle padding [28]
	Al_2O_3 and AlN	Packages for built-in circuits [29]

In addition to separating ceramics according to their properties and uses, you may find that it is prevalent to label those as conventional ceramics, typically based on clay and silica. And specialized so-called special ceramics, scientific or engineering ceramics. They demonstrate superior mechanical characteristics, resistance to corrosion or electrical, optical and magnetic characteristics.

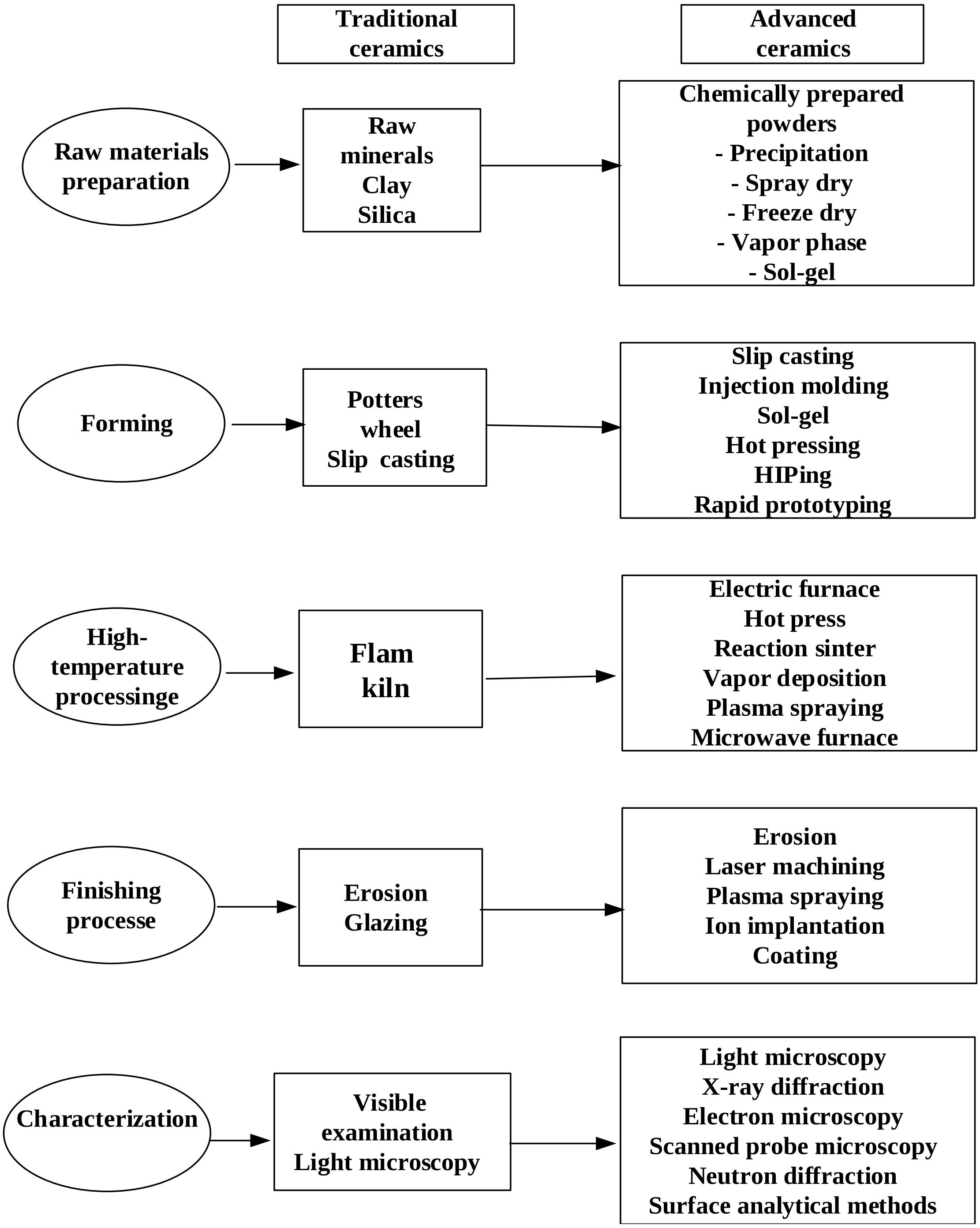

Fig.1 Conventional and modern ceramics are contrasted in terms of the type of raw materials used in the formation and shaping processes and the techniques used for characterization. reproduced[14].

The Glass-ceramics applications in several fields are shown in **Fig. 2**. In a wide variety of fields in our everyday life, Glass-ceramics have been commonly used. Many Glass-ceramics exhibit high translucency in the optical field or can even be translucent since zero porosity can be achieved reasonably easily[30][31][32]. For optical applications, these make Glass-ceramics excellent stuff. For example, Transparent and low thermal expansion system-based Lithium Alumino-silicate (LAS) Glass-ceramics have been used as telescope mirror blanks and laser gyroscopes. [30]. Glass-ceramics are now used in high-performance aircraft and missile nose cones in the defense industry. The components used in these applications must have a complicated combination of properties to survive the critical conditions of high-speed atmospheric flight: Low thermal expansion coefficient; high mechanical strength; high resistance to abrasion; clarity of high radar waves for navigation; [33]. Glass-ceramics combine Glass and crystalline ceramics properties in the medical field, attracting significant attention because of their strong mechanical properties and biological activity in dental reconstruction and bone filler products[34][35][36][37]. Currently there are three types of Glass-ceramic systems that have been mostly developed for dental reconstruction, including mica-based, leucite-based and lithium disilicate Glass-ceramic systems. Based on the SiO_2-Li_2O material system, lithium disilicate Glass-ceramic has been recognized as a suitable dental restorative material due to its outstanding mechanical properties and excellent translucency [32][38][39][40].

In the electronic sector, secondary all-solid-state batteries with inorganic solid batteries Electrolytes are anticipated to be high-output batteries for the next decade. Various types of inorganic solid electrolytes produced by Glass-ceramics have been developed, and there is evidence that Graphene plays a key role in a variety of applications such as energy storage batteries [41]. In various solvents such as water, organic solvents, and several different matrices, Graphene have been distributed, which is very significant in enhancing electrical and mechanical characteristics [42]. **Yalcin and Yakuphanogluu**[43] In Graphene-TiO_2 dependent systems, the voltage and frequency dependence of negative capacitance output has been studied. Besides, **Fan et al.** [44] The electrical and dielectric properties of graphene/PPScomposites were analyzed and the negative permittivity in the radio frequency area was investigated. Furthermore, **Ashery et al.** [41] The dielectric and electrical characteristics of devices based on GO have been tested. A higher emphasis on GO-based systems will yield fascinating results that is more critical for the long-term longevity of prepared devices and the widespread use of different microelectronic implementations.

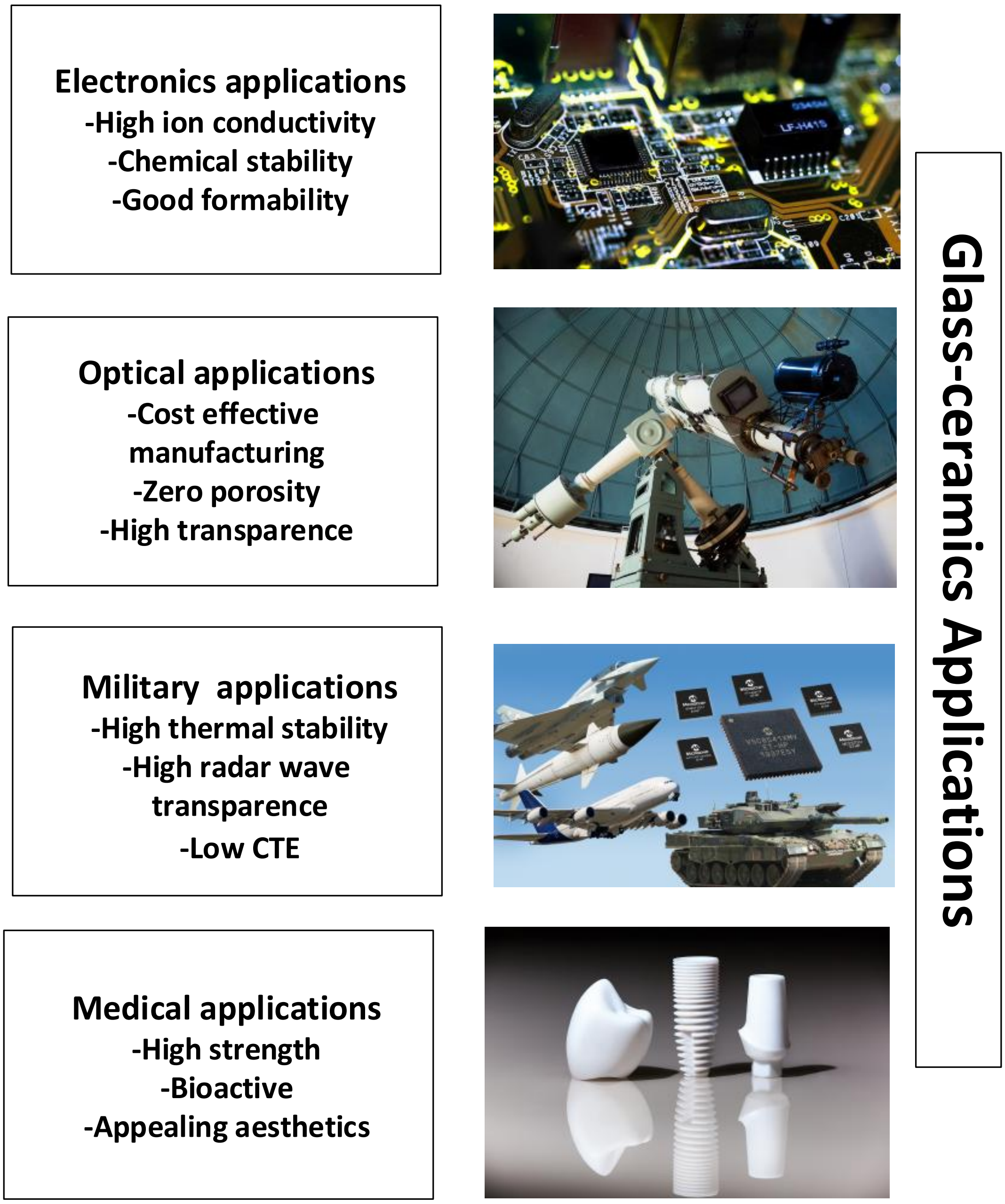

Fig. 2. Glass-ceramic uses in a large variety of areas, reproduced[32].

Glass-ceramics are prepared by (a) the conventional method of melting-casting-annealing; (b) simultaneous sinter-crystallization. Three general phases are involved in processing Glass-ceramic using the classic melting-casting-annealing technique. Firstly, the preparation of parts and nucleating agents for glass products. Homogeneous batch mixtures that are obtained by ball milling. Secondly, at melting point, the batch of materials is heated into crucibles, then cast into a mould to the desired shape and then cooled to room temperature to create a precursor Glass. Finally, the precursor glass is recycled to cause crystallisation, much like the Glass-ceramic formation process[45][46].

III. INFLUENCE OF THE PRESENCE OF TITANIUM DIOXIDE (TIO2) ON THE CRYSTALLIZATION OF GLASS-CERAMIC STRUCTURES

The structure of engineering materials is the most important aspect, so researching a material's microstructure offers knowledge related to its composition, manufacturing, and performance. Several scholars have researched and documented the microstructural properties of TiO_2 hardened or doped Glass-ceramics. Now in recent written papers, the findings are presented.

Weiwei et al. [47] Studied Kinetics of crystallization, microstructure, and phase evolution for Y_2O_3-Al_2O_3-SiO_2. Glass-ceramics with eutectic composition have been applied to TiO_2 and CaF_2 as nucleating agents. The results show that by reducing the activation energy from 310 kJ/mol to 280.4 kJ/mol, TiO_2 is effective in promoting the crystallization of YAS Glass. However, the addition CaF_2 into YAS Glass leads to an increase in from 310 kJ/mol to 385.2 kJ/mol activation energy. Due to, the formation of [AlO_4] tetrahedrold by means of Ca^{2+} ions and facilities Glass forming.

Rebekah and Elizabeth.[48] Studied effect adds Titanium Dioxide in a system Calcium-Magnesium Alumina Silicate Glass in addendum of 5-20 wt%. Over a series of temperature profiles, the crystallization activity of the blends was characterized and compared to that of CMAS alone. The results appear that, the crystallinity of model cooled at a rate of 10°C/min from 1300/1500°C decrease at additions TiO_2 between 5 and 10 wt%. The behavior of crystallization appears improving to be at~12.5 wt% TiO_2. With increased TiO_2 additions (15, 20 wt% TiO_2), $CaTiO_3$ is formed. Holding CMAS + TiO_2 compositions with a TiO_2 content of ≥10 wt% at 900°C. After cooling, the melting assisted in the crystallization of additional phases, including melilite, paqueite, and a Ticontaining diopside TiO_2, in sufficient quantity, may be useful as a coating constituent, from a thermochemical standpoint, in the crystallization of model-Glass [49].

Aygun et al [50] Studied combined TiO_2 into an yttria stabilized Zirconia to determine its ability to promote crystallization of (CaO–MgO–Al_2O_3–SiO_2) and prevent coating penetration. The authors reported increased barrier resistance (compared to yttria stabilized Zirconia alone) for samples containing 20 mol% Al_2O_3 and 5 mol% TiO_2. They concluded that Al solutes within the coating shifted the Glass to a phase more easily crystallized while Ti acted as nucleation sites for the new phase.

Chavoutier et al. [51] Glass–ceramics produced by controlling Li_2O–Al_2O_3–SiO_2 parent crystallization Glasses are well-known for their low thermal expansion and transparency. In order to facilitate bulk crystallization, it is essential to add nucleating agents such as TiO_2 and ZrO_2 to the Glass composition which leads to $ZrTiO_4$ nuclei during heating, continued by the crystallization of a β-quartz phase that converts into β-spodumene at high temperature.

IV. EFFECT DOPING ON MECHANICAL CHARACTERISTICS OF GLASS-CERAMICS

Composite material is needed to be homogeneous for effective load-bearing capability for effective use as a candidate material in engineering applications, such as vehicles and aircraft. Several of the results are discussed below in recently published papers.

Bhaskar Raju et al. [52] Studied mechanical properties of Zinc-Aluminum-27 reinforced with silicone carbide have been investigated. The ZA-27 alloy was strengthened with SiC of 0,3,6, and 9 percent by weight. Reports revealed that with an improvement in packing material over the unreinforced alloy, the hardness, impact strength, tensile strength and compressive strength of the ZA-27/SiC composites increased substantially. This enhancement was therefore attributed to the presence of the hard ceramic spots in the matrix alloy [53].

Dalmis et al. [54] studied the physical and mechanical properties of ZA-27 composites, Graphite (Gr) Nano-Particles studied addition. Reports suggested that hardness and ultimate tensile strength decreased as the content of Gr increased as shown in Table .2 This phenomenon was attributed to weekly bonding with the matrix alloy between the Gr particles, aggregation, indeed that Gr applications of metal matrix composites are known to decrease tensile and compression strength due to the growing brittle existence of Gr particles, which quickly tends to plastically deform the composites.

Table. 2 Hardness and Effective Elastic Modulus.

GO contents wt. %	Effective Elastic Modulus	Vickers Hardness (GPa)
0	118	9.25
1	119	9.5
2	124	9.3
3	121	9.1

Sharma et al. [55] Studied the effect of short Glass-fibers on the mechanical properties of cast ZA-27 alloy composites has been investigated. In the cast ZA-27 alloy, the inclusion of short Glass-fibers varied from 0 to 5 percent by weight. Reports revealed that with an improvement in reinforcement, but at the expense of ductility and impact strength, the ultimate tensile strength, stiffness, and Young's modulus improved dramatically as shown in Table. 3.

Table. 3 Hardness and Ultimate tensile strength of Zinc-Aluminum-27 at variation doping material.

Chemical Composition	Doping Contents	Hardness (HRA)	Ultimate Tensile Strength(MPa)
Zinc-aluminum (ZA-27)	SiC	70	220
Zinc-aluminum (ZA-27)	Graphite	135	183
Zinc-aluminum (ZA-27)	Glass fibers	137	381

Alaneme et al. [56] Studied the mechanical and wear behavior of ZA-27 composites reinforced by steel chips. The composites based on ZA-27 contain 5, 7.5 and 10 weights of percent of steel machining chips, while unreinforced ZA-27 alloy and a 5 weight of percent Alumina formulation were also prepared as control samples[57]. Reports showed that the composites' hardness and wear levels improved between 5 and 10 weights of percent with an improvement in weight of percent of the steel chips. Higher hardness was due to the comparatively higher hardness of the steel chips compared to Zn-Al based alloys, although lower strength was due to the less consistent dispersion of steel chips and agglomeration above 5 weights of percent. However, increased fracture resistance of the ZA-27 reinforced steel chips over non-reinforced alloy and 5 weights of percent reinforced Aluminum composite was attributed to the comparative durability of the steel chips over the ZA-27 matrix.

Manuela et al. [58] Studied the analysis of mechanical properties the crystallization and microstructure of cordierite is one of the most important phases within the MgO-Al_2O_3-SiO_2 model. The cordierite was prepared for four samples, which were thermal treatment at a temperature of 1200 °C with a permanent time of 2 h. Depending on the critical working temperature, specific applications like Glass-ceramic material coatings were chosen for the temperature of the thermal treatment. The average crystal size of the crystalline phases in the study was greater without an introduction of NiO, and the crystals sizes, especially α-cordierite with higher NiO concentrations, and the crystals within the domains decrease, which results in better a mechanical properties and microstructure (hardness=8–11 GPa and effective elastic modulus=11–14 GPa), than those reported in the literature (hardness=7–8 GPa and effective elastic modulus=10–13 GPa). The Glass-ceramics showed the highest effective elastic modulus and a marginal decrease in hardness with the higher %wt of α-cordierite phases. Noticeable, the increase of %wt NiO encouraged crystallization of α-cordierite, encouraging a uniform and dense distribution of cordierite-structures embedded in a vitreous matrix, enabling an increase in compactness of the composite homogenize its mechanical efficiency, which can then be used as an effective composite for large machinable applications, attributed to this well controlled property. **Li Chen et al. [11]** Studied the density, hardness, physical and crystallization properties of MgO–Al_2O_3–SiO_2 Glasses with different La_2O_3 additions (0–10 wt.%). The results showed significant improvements in Hardness values, The densities of of MgO–Al_2O_3–SiO_2-La_2O_3 Glasses increased from 2.69 to 2.88 g/cm^3 as the La_2O_3 content increased from 0 to 10 wt.%. The hardness and coefficient of thermal expansion of the glasses increase as increasing La_2O_3 content as well. There was an increase of 12% for an addition of 10% La_2O_3 to MgO–Al_2O_3–SiO_2 alloy.

Mukherjee and et al. [59] Studied the effect of MgF_2 on the different properties of the SiO_2–Al_2O_3–MgO–K_2O–B_2O_3 Glass system, such as crystalline behavior, microstructure phases, and hardness. The growth of crystal in three-dimensions is observed. Mica crystals are known as fluorophlogopite, the predominant crystal phase for all three heat treated glass specimens at a temperature of 1050 °C. In incremental addition of the MgF_2 content, the hardness value for Glass-ceramic specimen decreases, high fluorine Glass-ceramic specimen containing mica with strongly interlocking microstructure has lower Hv (5.03 GPa) as well as highest machinability parameter (0.029) and lowest cutting energy (37.89 J mm^{-3}) than specimens without MgF_2. Therefore, 5 wt.% MgF_2 containing mica Glass has better machinable characteristics.

Mollazadeh and et al. [60] Studied the impact of TiO_2, ZrO_2, BaO and extra silica on an apatite-mullite-based Glass-ceramic model's crystallization behavior, mechanical properties and microstructure. The accelerated crystalline phases were fluorapatite [$Ca_{10}(PO_4)6F_2$] and mullite [$Al_6Si_2O_{13}$], which in addition to the extra bearing SiO_2 specimen, were rod-like in the other specimens. Limited lengths of the rod-like crystalline phases were, i.e. <20 μm, The intensity of crystalline phases increased to around 50 μm in the TiO_2 and BaO containing Glass-ceramics, but a limited edition of ZrO_2. Flexural strength and fracture strength of prepared glasses and Glass-ceramics have also been tested. The results showed that both parameters were influenced differently by the additive oxides. The highest fracture strength and fracture strength values were TiO_2 and BaO containing Glass-ceramics with a lower crystal size. The mechanical properties of the prepared Glass–ceramic samples were not substantially different and/or were even decreased by addition of ZrO_2 and extra SiO_2 [60].

Wei and et al. [61] Studied the development of alpha-cordierite Glass-ceramics without and with the inclusion of B_2O_3 in the MgO-Al_2O_3-SiO_2 system. The findings show that B_2O_3 mainly plays the role of two elements as an additive used in MgO-Al_2O_3-SiO_2 Glass-ceramics. Glass-ceramics' properties are influenced by the transition in the conduct of crystallization.

The coefficient of thermal expansion rises from 1.70×10^{-6} °C^{-1} to 3.72×10^{-6} °C^{-1} and Glass-ceramics' Vickers hardness decreases from 9.4 GPa to 6.9 GPa with the increase of B_2O_3 content from 0 mol% to 12 mol%. The proper quantity of B_2O_3 will greatly shorten the crystallisation pathway, decreasing the temperature of forming and facilitating the direct precipitation of alpha-cordierite in the Glass-ceramics system [61].

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Muroya and et al. [62] Studied densification of ceramic coatings based on SiO_2–Al_2O_3–TiO_2 in a wet process-based system was investigated by optimizing the quantity of alkali silicates. From the present analysis, the following conclusions are drawn.

1) The number of through-holes of the coating decreased drastically with increasing concentrations of alkali silicates. It is assumed that the Glass phase arising from the alkali silicates effectively fills large pores within ceramic grains, contributing to densification.

2) With the concentrations of alkali silicates, the reliability of thermal shocks that cool down from high temperatures to room temperatures has been enhanced.

3) The corrosion resistance of the coating in 1 mol/l HCl solution was observed to improve with an increase in the quantity of alkali silicates and calcination temperature.

4) The adhesive strength of coatings containing larger concentrations of alkali silicates has been increased by a factor of three, with a median adhesion of 700 °C[62].

JianYANG and et al. [63] Studied the effect of TiO_2 addition on the crystallization behavior and mechanical properties of the stainless steel slag Glass-ceramics. It was found that the addition of TiO_2 to the parent Glass changed the phase composition; refined grain sand and the addition of TiO_2 increased both the quantity and the uniformity of the crystal nuclei.[64] As shown **Table .**4 improved the Vickers hardness and the bending strength. Besides, the addition of TiO_2 was effective in suppressing the akermanite phase formation by capturing Ca^{2+} and forming the perovskite phase. On the other hand, the micro structure with fine and uniform grains corresponds to excellent mechanical [65]. The optimal amount of TiO_2 was 7 mass% as shown **Fig**.5 the main crystal phase of the Glass-ceramics were diopside. The bending strength and Vickers hardness were determined as 147 MPa and 6.68 GPa, respectively, for the sample with 7 mass% TiO_2.

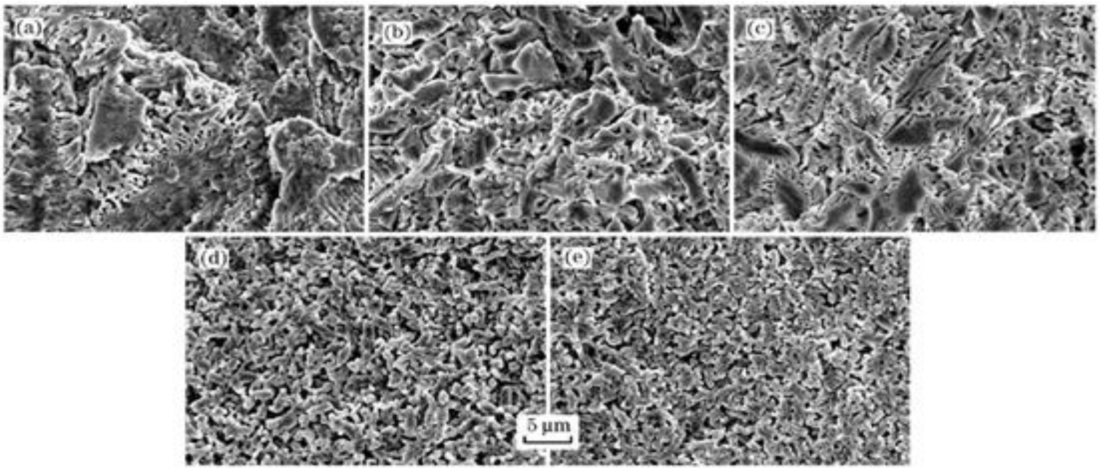

Fig.4 SEM images of samples with different TiO_2contents: (a) 0 mass%; (b) 3 mass%; (c) 5 mass%; (d) 7 mass%; (e) 9 mass%, reproduced[63].

Table . 4 Bending strength and Vickers hardness dependence on TiO_2 content.

TiO_2 content wt.%	*Bending Strenght (MPa)*	*Vickers Hardness (GPa)*
0	50	5
3	60	5.25
5	120	6.2
7	142	6.6
9	140	6.75

M. Feng et al.[66] Studied the effects of addition of Cr_2O_3 on wear behavior of the SiO_2-Al_2O_3-ZrO_2-Ba(Sr,Ca)O based Glass-ceramics with are investigated. The system contains varied inclusion of 0 and 6wt.% Cr_2O_3 were added to Glass frit when smelted and ball-milling process. Adding Cr_2O_3 reduces resistance to wear. But with the add method Cr_2O_3 is applied, this retardation effect varies. When Cr_2O_3 is implemented by ball milling, $BaSi_2O_5$ precipitation is only partially retarded, and the wear rate is reduced moderately. However, the precipitation of $BaSi_2O_5$ is almost totally prohibited when adding Cr_2O_3 during the smelting process, and $BaCrO_4$ and/or $BaCr_2O_4$ substituting $BaSi_2O_5$ precipitate out. The Nano barium chromate scale facilitates the development of a lubricating glaze coating on worn surfaces, greatly decreasing the wear and friction rate[67].

D. Herman et al. [68] Studied evaluate the wear resistance of CaO-MgO-ZnO-Al_2O_3-B_2O_3-SiO_2 systems with different heat treatment temperature. The values of the wear rate fluctuate within 10^{-4} mm^3/Nm. Compared to the wear resistance of Glass-ceramics, this is still a high wear resistance with the addition of mica being comparatively tinny[67].

In fact, precipitation from Glass-ceramic only of the ghanite phase induces a relative increase in its fracture strength and wear resistance compared to the two phase materials.

Wang et al. [69] Studied the mechanical characterization of SiO_2-Al_2O_3-K_2O-CaO-P_2O_5 fluoropatite Glass-ceramic has been investigated. A sintering process with varying CaO contents and heat treatment regimens has been used to manufacture Glass-ceramics. The findings demonstrate that the crystallinity of the main fluorapatite crystal can be modified by the different CaO content and heat treatment temperatures. Larger crystallinity enhances the mechanical properties, significantly affecting the behavior of friction and wear. By can heat treatment temperatures, the pore size of the Glass-ceramic may also decrease and make it denser. Adjusting the content of CaO and increasing the heat treatment temperature is both valid ways of optimizing mechanical properties[70]. The 6.0-wt specimens. The highest detailed efficiency is percent CaO and sintered at 1100 °C, showing outstanding mechanical characteristics and wear tolerance.

Houg et al. [71] Studied investigating the effects of K_2O in the Li_2O-K_2O-Al_2O_3-SiO_2 system on sintering and crystallization of Glass powder compacts. On the basis of general formula 23.7 (71.78-x) SiO_2-2.63 Al_2O_3-(2.63 + x) K_2O-23.7 Li_2O, where x modified from 0 to10, a total of 8 formulations were prepared [72]. High mechanical strength (173-224 MPa) Glass-ceramics have led to the prevalent crystallization of lithium disilicate in low-K_2O formulations, chemical resistance (25-50 g/cm^2) and low overall conductivity (2-10^{-18} S/cm) making materials suitable for a range of practical applications. In recently published papers, some of the results are introduced below.

Tsuru at al [73] **and Yabuta et al.** [74] Using PDMS, TEOS and $Ca(NO_3)_2$ via a Sol-Gel process, bioactive organic-inorganic hybrids were manufactured. Via incorporation of highly reactive Ti alkoxides (TiPT) **Chen at al** [75] Hybrids with greater mechanical efficiency obtained [76]. A comparable technique was proposed by **Aburatani et al**. [77] Who changed the method of synthesis suggested by **Tsuru** [73]To improve the mechanical properties by the addition of colloidal silica. The higher compressive strength of these hybrids resulted in increased colloidal silica content [77].

Yongxin et al. [78] Studied Titanium dioxide (TiO_2) decorated Graphene Oxide (GO) was processed as a Nano filler and incorporated into the chemically bonded ceramic coatings. GO–TiO_2 composites are prepared and introduced as a Nano filter in chemically bonded ceramic coatings to enhance corrosion resistance performance. On the surface of GO, the TiO_2 nanoparticles are decorated with chemical bonds, as shown by TGA, XRD, SEM and TEM. The surfaces of the fracture SEM explores ceramic coatings without and with GO–TiO_2. The findings show that GO–TiO_2 is well embodied in a ceramic matrix with less pores and cracks. In addition, potentiodynamic polarization tests show that corrosion resistance of ceramic coatings increases with an increase in GO–TiO_2 content. It can be assumed that the GO–TiO_2 can take advantage of this. Both GO and TiO_2 are designed to enhance corrosion resistance of chemically bonded ceramic coatings.

We authors studied, Glass-ceramics, were successfully synthesized using GO doping SiO_2-Al_2O_3-TiO_2 system. The effect of the TiO_2/GO weight ratio was extensively studied on the structure, mechanical and electrical properties of Glass-ceramics, under publishing.

1) The Glass-ceramic density decreased, but the micro-hardness of the samples improved to 14 GPa. In addition, the Glass-ceramics' primary crystalline phase TiO2-Anatase was refined. The second phase (Graphite), onset appeared at the addition of GO. The Graphite phase intensity increased with the increase of GO contents.
2) The coefficient of friction decreased during rising GO contents, wear rate variation in the order of 10^{-5} mm^3/Nm, and a systematic decrease in wear rate was recorded in both cases of the testing medium. The specimen which contained the highest GO content, showed excellent low friction and wear in both dry and lubrication conditions.

V. BIOMEDICAL APPLICATIONS

Research has been performed on (GC) products for biomedical and dental applications. Nevertheless, in recent years, some scholars have studied and documented mechanical properties for materials used in biomedical.

Jainxia et al. [37] Studied the objective of the research was to assess the mechanical and bioactive efficiency of Glass-ceramic lithium disilicate mixtures provided by the Sol-Gel and melting routes of the SiO_2-Li_2O-ZrO_2-K_2O-P_2O_5-Al_2O_3 system. The SBG was prepared using the Sol-Gel and molar ratio system of TEOS, TEP, $LiNO_3$, $Zr(NO_3)2$•$5H_2O$, KNO_3 and $Al(NO_3)_3$•$9H_2O$ in conjunction with the $50SiO_2$-$36LiO_2$-$8ZrO_2$-$3K_2O$-$2P_2O_5$-Al_2O_3 (mol. percent) system. Schematic representation for SBG, MBG and Glass-ceramic processing. Flexural strength and bioactivity were studied. The findings show that the Glass-ceramic 8M2S (MBG: SBG=8:2) has the highest crystallinity and flexural strength consistent with the unique cross-linked interlocking microstructures of all obtained Glass-ceramic products. The flexural strength of the samples can first be shown to rise progressively and then decrease with rising MBG content. The 0M10S sample exhibits the lowest flexural resistance (84.64 ± 8.89 MPa), and the 8M2S sample has the highest flexural strength of all Glass-ceramics with apparent intertwined $Li_2Si_2O_5$ grain colonies (153.06 ± 10.28 MPa)[54]. These findings indicated that in this analysis, the Glass-ceramics obtained have potential mechanical and bioactive performance. This knowledge can be useful for more study and practical applications for the restorative dental medicinal use of these Glass-ceramics.

Molla et al. [79] Studied in dry and artificial saliva (AS) conditions, the K_2O-B_2O_3-Al_2O_3-SiO_2-MgO-F Glass-ceramic device with 70% mica crystals was thermally treated at 1040 °C for 12 hours and subjected to fretting wear against steel. The initial contact stress of Hertzian was 196MPa for the selected operating parameters. During the initial run-in cycle, the coefficient of friction increased and then entered a phase of steady state, independent of the fretting environment. However, at dry contact, a higher value of steady state COF-0.88 was calculated, while much lower COF 0.67 was reported in the AS medium. In atmospheric conditions, higher COF is well suited to the intensity of abrasion.

The wear rate ranged from 10^{-4} to 10^{-5} mm^3/Nm and a systematic decrease in the wear rate with test period was recorded in both test medium cases. Table. 3 Description of the findings of the tribology test obtained from some of the GCs previously produced as well as human teeth and compared with the GC currently tested. The difference in the rate of friction/wear depends on the variation in conditions of operation.

Table. 3 Description of the findings of the Tribology test obtained for some of the GCs previously produced as well as human teeth and compared with the GC currently tested.

Tribocouple	*Operating conditions*	*COF*	*Wear rate (mm^3/Nm)*	*Wear mechanisms*	*Reference*
Human teeth vs. steel	20 N, dry/AS, 0.002 m/s	0.8–1.2 (dry) 1.0 (AS)	–	Oxidative wear and microfracture	[80]
Human teeth vs Al_2O_3 .	1N, AS, 0.0005 m/s, 8000 cycles	0.12–0.55	–	Fretting fatigue; adhesive wear	[81]
Dicor vs. Al_2O_3	4.9 N, 0.0014 m/s, dry	0.7–0.077	2.6×10^{-3}	Microfracture	[82]
Dicor vs. Al_2O_3	1N, 0.0025 m/s, distilled water	0.4–0.6	10^{-3} to 10^{-4}	Localized fracture	[83]
CaO–MgO–Al_2O_3–SiO_2 (self-mated)	0.01–0.5 m/s, dry, contact Pressure 0.1–1.4MPa	0.05–0.65	10^{-3} to 10^{-4}	Microcracking, abrasion	[84]
MgO–CaO–SiO_2–P_2O_5–F vs. ZrO_2	10 N, 0.025 m/s, dry	0.75	0.7×10^{-4}	Abrasive and adhesive wear	[85]
K_2O–B_2O_3–Al_2O_3–SiO_2–MgO–F vs. steel	1N, 0.0016 m/s, dry/AS, 100,000 cycles	0.88 (dry); 0.67 (AS)	12×10^{-5} (dry); 2×10^{-5} (AS)	Tribomechanical wear (dry); tribochemical wear (AS)	[79]

Shibayan et al.[81] Studied the mechanical properties studied show variations in hardness. On the outer surface (near 3.5 GPa), the enamel is the toughest and dentin is softer than enamel. With the depth of the base, the steadily diminishing hardness was assessed. This variation is partly dependent on the abundance of enamel and dentin minerals, with a possible reliance even on local microstructural characteristics, such as the orientation of the enamel rod and the density of the dentinal tubule. Human tooth/alumina tribocouple exhibits steady state COF in tribological testing, varying under the unlubricated fretting conditions for various times in the range of 0.12–0.55. It was not possible to definitively associate the observed steady state COF and the number of cycles.

VI. CONCLUSION

An effort has been prepared in this review article to address recent advances in the synthesis, reinforcement, microstructure and mechanical features of Glass-ceramics. With regard to doping of Glass-ceramics, an analysis of available literature shows that crystallization of the bulk; promote the addition of nucleating agents such as TiO_2 to the composition of Glass.

1- Titanium Dioxide, in appropriate quantity, can be useful as a coating component, from a thermochemical point of view, in the crystallization of Glass-ceramics.
2- Tensile strength, hardness, wear resistance, and elastic modulus, mechanical characteristics have been reported to improve dramatically with an improvement in reinforcement material, but at the cost of ductility.
3- With increasing reinforcing content, the fracture strength also decreases, particularly for particle reinforced Glass-ceramics.
4- Glass-ceramics has been a promising material for engineering applications and research is still going on to explore the promise of this flexible material.

REFERENCES

1. P. Sooksaen, S. Suttiruengwong, K. Oniem, and K. Ngamlamiad, “Fabrication of porous bioactive Glass-Ceramics via decomposition of natural fibres,” *J. Met. Mater. Miner.*, vol. 18, no. 2, 2008.
2. A. Yadav *et al.*, “Melt property variation in $GeSe_2$-As_2Se_3-PbSe glass ceramics for infrared gradient refractive index (GRIN) applications,” *Int. J. Appl. Glas. Sci.*, vol. 10, no. 1, pp. 27–40, 2019.
3. M. A. Binhussain, M. Marangoni, E. Bernardo, and P. Colombo, “Sintered and glazed glass-ceramics from natural and waste raw materials,” *Ceram. Int.*, vol. 40, no. 2, pp. 3543–3551, 2014.
4. D. M. Ayala Valderrama, J. A. Gómez Cuaspud, J. A. Roether, and A. R. Boccaccini, “Development and characterization of glass-ceramics from combinations of slag, fly ash, and glass cullet without adding nucleating agents,” *Materials (Basel).*, vol. 12, no. 12, p. 2032, 2019.
5. W. Holland and G. Beall, “Glass-ceramic technology (American ceramic society),” *Westerville, OH*, 2002.
6. M. Stoica, “Theoretical Consideration about Metallic Glasses,” in *Fe-Based Bulk Metallic Glasses*, Springer, 2017, pp. 1–20.
7. G. A. Sycheva, “Crystal growth and nucleation in glasses in the lithium silicate system,” *J. Cryst. Process Technol.*, vol. 6, no. 4, pp. 29–55, 2016.
8. M. Allix and L. Cormier, “Crystallization and Glass-Ceramics,” in *Springer Handbook of Glass*, Springer, 2019, pp. 113–167.
9. J.-W. Lee, Y.-I. Jang, W.-S. Park, S.-W. Kim, and B.-J. Lee, “Photocatalytic and Pozzolanic Properties of Nano-SiO_2/Al_2O_3-TiO_2 Powder for Functional Mortar,” *Materials (Basel).*, vol. 12, no. 7, p. 1037, 2019.
10. A. Hoppe, E. Boccardi, F. E. Ciraldo, A. R. Boccaccini, and R. G. Hill, “1.10 bioactive glass-ceramics,” *Compr. Biomater. II*, pp. 235–243, 2017.

11. L. Chen, C. Yu, L. Hu, and W. Chen, "Effect of La_2O_3 on the physical and crystallization properties of Co2+-doped $MgO–Al_2O_3–SiO_2$ glass," *J. Non. Cryst. Solids*, vol. 360, pp. 4–8, 2013.
12. S. H. Din, "Nano-Composites and their Applications: A review," *Charact. Appl. Nanomater.*, vol. 2, no. 1, 2019.
13. C. M. Thompson, H. M. Herring, T. S. Gates, and J. W. Connell, "Preparation and characterization of metal oxide/polyimide nanocomposites," *Compos. Sci. Technol.*, vol. 63, no. 11, pp. 1591–1598, 2003.
14. M. Kozłowski, G. Khater, P. Olesik, and M. Mahmoud, "Preparation and characterization of lightweight glass–ceramics based on industrial wastes," *J. Aust. Ceram. Soc.*, vol. 56, no. 1, pp. 11–20, 2020.
15. J. Kang, J. Wang, J. Cheng, X. Peng, Y. Hou, and S. Qian, "Structure and properties of $CaO–MgO–Al_2O_3–SiO_2$ glasses obtained by vitrification of granite wastes," *Phys. Chem. Glas. J. Glas. Sci. Technol. Part B*, vol. 58, no. 6, pp. 249–255, 2017.
16. D.-G. Kim, B. Konar, and I.-H. Jung, "Thermodynamic optimization of the K2O-Al2O3-SiO2 system," *Ceram. Int.*, vol. 44, no. 14, pp. 16712–16724, 2018.
17. R. Mishra, M. Goswami, A. Dixit, and M. Krishnan, "Study on thermophysical properties and phase evolution in Nd doped Li_2O-Al_2O_3-SiO_2 glass nucleated by multiple nucleating agents," *J. Non. Cryst. Solids*, vol. 447, pp. 66–73, 2016.
18. K.-D. Kim, S.-H. Lee, and H.-K. Ahn, "Observation of nucleation effect on crystallization in lithium aluminosilicate glass by viscosity measurement," *J. Non. Cryst. Solids*, vol. 336, no. 3, pp. 195–201, 2004.
19. S. Xu, J. Liu, K. Li, Y. Zhou, and D. Xu, "The role of TiO_2 on the microstructure and the electrochemical behavior of Ce0. 8Gd0. 2O2-δ for solid oxide fuel cell electrolyte," *J. Alloys Compd.*, vol. 780, pp. 711–717, 2019.
20. N. S. Canarslan and Ö. S. Canarslan, "Combustion synthesis of SiC-$MoSi_2$-Al_2O_3 composites," *Ceram. Int.*, vol. 45, no. 12, pp. 14505–14509, 2019.
21. Q. L. Wang, X. Y. Huang, J. Yin, J. F. Sun, M. X. Feng, and L. Chen, "Influence of CeO_2 Doping on Property of SnO_2 Ceramics," in *Key Engineering Materials*, 2017, vol. 726, pp. 287–291.
22. P. Fielitz, S. Ganschow, K. Kelm, and G. Borchardt, "Aluminium self diffusion in high-purity α-Al_2O_3: Comparison of Ti-doped and undoped single crystals," *Acta Mater.*, 2020.
23. R. A. Gado, M. Hebda, M. Łach, and J. Mikuła, "Alkali Activation of Waste Clay Bricks: Influence of The Silica Modulus, SiO_2/Na_2O, H_2O/Na_2O Molar Ratio, and Liquid/Solid Ratio," *Materials (Basel).*, vol. 13, no. 2, p. 383, 2020.
24. C. Goswami, A. Patnaik, I. K. Bhat, and T. Singh, "Synthesis and Characterization of Composites Al_2O_3–Cr for $2O_3$ Artificial-Based Ceramic Hip Joint," *Innov. Des. Anal. Dev. Pract. Aerosp. Automot. Eng. (I-DAD 2018)*, vol. 2, p. 21, 2018.
25. A. Vereschaka *et al.*, "Investigation of the influence of the thickness of nanolayers in wear-resistant layers of Ti-TiN-(Ti, Cr, Al) N coating on destruction in the cutting and wear of carbide cutting tools," *Surf. Coatings Technol.*, vol. 385, p. 125402, 2020.
26. J. Lu, Q. F. Luo, X. Y. Mao, X. P. Xu, Y. H. Wang, and H. Guo, "Fabrication of a resin-bonded ultra-fine diamond abrasive polishing tool by electrophoretic co-deposition for SiC processing," *Precis. Eng.*, vol. 47, pp. 353–361, 2017.
27. B. Henriques *et al.*, "Copper–nickel-based diamond cutting tools: stone cutting evaluation," *Int. J. Adv. Manuf. Technol.*, vol. 92, no. 1–4, pp. 1339–1348, 2017.
28. B. R. Arellano, S. W. Stafford, D. M. Cone, and M. Contreras, "Characterization of Deposits Found on Carrier Panel Tiles Recovered from the Space Shuttle Columbia," *Process. Prop. Des. Adv. Ceram. Compos. II*, vol. 261, p. 293, 2017.
29. W. Q. Lim, M. Devarajan, and S. Subramani, "Performance of Cu-Al_2O_3 thin film as thermal interface material in LED package: thermal transient and optical output analysis," *Microelectron. Int.*, 2018.
30. I. Alekseeva *et al.*, "Optical applications of glass-ceramics," *J. Non. Cryst. Solids*, vol. 356, no. 52–54, pp. 3042–3058, 2010.
31. E. Kleebusch, C. Patzig, T. Hoeche, and C. Ruessel, "The evidence of phase separation droplets in the crystallization process of a Li_2O-Al_2O_3-SiO_2 glass with TiO_2 as nucleating agent–An X-ray diffraction and (S) TEM-study supported by EDX-analysis," *Ceram. Int.*, vol. 44, no. 3, pp. 2919–2926, 2018.
32. F. C. Serbena, I. Mathias, C. E. Foerster, and E. D. Zanotto, "Crystallization toughening of a model glass-ceramic," *Acta Mater.*, vol. 86, pp. 216–228, 2015.
33. [33] G. H. Beall, "Milestones in glass-ceramics: a personal perspective," *Int. J. Appl. Glas. Sci.*, vol. 5, no. 2, pp. 93–103, 2014.
34. M. Dittmer, C. Ritzberger, M. Schweiger, V. Rheinberger, M. Wörle, and W. Höland, "Phase and microstructure formation and their influence on the strength of two types of glass-ceramics," *J. Non. Cryst. Solids*, vol. 384, pp. 55–60, 2014.
35. J. C. Mauro and E. D. Zanotto, "Two centuries of glass research: historical trends, current status, and grand challenges for the future," *Int. J. Appl. Glas. Sci.*, vol. 5, no. 3, pp. 313–327, 2014.
36. X. Guo *et al.*, "Synthesis and application of several sol–gel-derived materials via sol–gel process combining with other technologies: a review," *J. Sol-Gel Sci. Technol.*, vol. 79, no. 2, pp. 328–358, 2016.
37. J. Ye, C. Wen, J. Wu, N. Wen, B. Sa, and T. Zhang, "Mechanical and bioactive properties of lithium disilicate glass-ceramic mixtures synthesized by two different methods," *J. Non. Cryst. Solids*, vol. 509, pp. 1–9, 2019.
38. W. Lien, H. W. Roberts, J. A. Platt, K. S. Vandewalle, T. J. Hill, and T.-M. G. Chu, "Microstructural evolution and physical behavior of a lithium disilicate glass–ceramic," *Dent. Mater.*, vol. 31, no. 8, pp. 928–940, 2015.
39. X.-F. Song, H.-T. Ren, and L. Yin, "Machinability of lithium disilicate glass ceramic in in vitro dental diamond bur adjusting process," *J. Mech. Behav. Biomed. Mater.*, vol. 53, pp. 78–92, 2016.
40. F. H. ElBatal, M. A. Ouis, A. M. Abdelghany, and N. A. Ghoneim, "Structural and optical correlation of gamma-irradiated 3d transition metals-doped lithium disilicate glasses," *Silicon*, vol. 7, no. 4, pp. 409–417, 2015.
41. A. Ashery, A. A. M. Farag, M. A. Moussa, and G. M. Turky, "Enhancement of electrical and dielectrically performance of graphene-based promise electronic devices," *Synth. Met.*, vol. 261, p. 116303, 2020.
42. H.-H. Huang, R. K. Joshi, K. K. H. De Silva, R. Badam, and M. Yoshimura, "Fabrication of reduced graphene oxide membranes for water desalination," *J. Memb. Sci.*, vol. 572, pp. 12–19, 2019.
43. M. Yalcin and F. Yakuphanoglu, "Voltage and frequency dependence of negative capacitance behavior in a Graphene-TiO_2 nanocomposite photoanode based on quantum dot sensitized solar cells," *Optik (Stuttg).*, vol. 183, pp. 1099–1105, 2019.
44. G. Fan, G. Shi, H. Ren, Y. Liu, and R. Fan, "Graphene/polyphenylene sulfide composites for tailorable negative permittivity media by plasmonic oscillation," *Mater. Lett.*, vol. 257, p. 126683, 2019.
45. L.-Y. Zhang and S.-Q. Liu, "Dielectric Properties of Melt and Heat Treated K_2O-Al_2O_3-SiO_2-CaO-CuO-TiO_2 Samples," in *2nd 2016 International Conference on Sustainable Development (ICSD 2016)*, 2016.
46. A. R. Molla *et al.*, "Crystallization, mechanical, and optical properties of transparent, nanocrystalline gahnite glass-ceramics," *J. Am. Ceram. Soc.*, vol. 100, no. 5, pp. 1963–1975, 2017.
47. W. Zhu, H. Jiang, H. Zhang, S. Jia, and Y. Liu, "Effect of TiO_2 and CaF_2 on the crystallization behavior of Y_2O_3-Al_2O_3-SiO_2 glass ceramics," *Ceram. Int.*, vol. 44, no. 6, pp. 6653–6658, 2018.
48. R. I. Webster and E. J. Opila, "The effect of TiO2 additions on CaO–MgO–Al2O3–SiO2 (CMAS) crystallization behavior from the melt," *J. Am. Ceram. Soc.*, vol. 102, no. 6, pp. 3354–3367, 2019.
49. A. Aldaadaa, M. Al Qaysi, G. Georgiou, R. MA Leeson, and J. C. Knowles, "Physical properties and biocompatibility effects of doping SiO2 and TiO2 into phosphate-based glass for bone tissue engineering," *J. Biomater. Appl.*, vol. 33, no. 2, pp. 271–280, 2018.
50. A. Aygun, A. L. Vasiliev, N. P. Padture, and X. Ma, "Novel thermal barrier coatings that are resistant to high-temperature attack by glassy deposits," *Acta Mater.*, vol. 55, no. 20, pp. 6734–6745, 2007.
51. M. Chavoutier *et al.*, "Effect of TiO_2 content on the crystallization and the color of (ZrO2, TiO2)-doped $Li_2O–Al_2O_3–SiO_2$ glasses," *J. Non. Cryst. Solids*, vol. 384, pp. 15–24, 2014.
52. S. A. BhaskarRaju, K. C. Hemanth, and S. L. N. Jayasimha, "Mechanical characterization of ZA-27 reinforced with SiCp MMCs," in *Proc Of Int Conf on Current Trends in Eng Sci and Tech*, 2017, pp. 228–232.
53. K. K. Alaneme, K. O. Adeoye, and S. R. Oke, "Mechanical and wear behaviour of steel chips reinforced Zn27Al composites," *Leonardo Electron. J. Pract. Technol.*, vol. 29, pp. 1–16, 2016.
54. R. Dalmis, H. Cuvalci, A. Canakci, and O. Guler, "Investigation of graphite nano particle addition on the physical and mechanical properties of Za27 composites," *Adv. Compos. Lett.*, vol. 25, no. 2, p. 096369351602500202, 2016.
55. S. C. Sharma, K. H. W. Seah, B. M. Satish, and B. M. Girish, "Effect of short glass fibers on the mechanical properties of cast ZA-27 alloy composites," *Mater. Des.*, vol. 17, no. 5–6, pp. 245–250, 1996.

56. K. K. Alaneme, "Mechanical behaviour of cold deformed and solution heat-treated Alumina reinforced AA 6063 metal matrix composites," *West Indian J. Eng.*, vol. 35, no. 2, pp. 31–35, 2013.
57. K. K. Alaneme, "Influence of thermo-mechanical treatment on the tensile behaviour and CNT evaluated fracture toughness of borax premixed SiCp reinforced aluminum (6063) composites," *Int. J. Mech. Mater. Eng.*, vol. 7, no. 1, pp. 96–100, 2012.
58. M. A. Zalapa-Garibay, D. Torres-Torres, A. M. Arizmendi-Morquecho, and S. Y. Reyes-López, "Effect of NiO and MoO_3 addition on the crystallinity and mechanical properties of α-cordierite and β-cordierite in the MgO-Al2O3-SiO2 system," *Results Phys.*, vol. 13, p. 102227, 2019.
59. D. P. Mukherjee, A. R. Molla, and S. K. Das, "The influence of MgF_2 content on the characteristic improvement of machinable glass ceramics," *J. Non. Cryst. Solids*, vol. 433, pp. 51–59, 2016.
60. S. Mollazadeh, B. E. Yekta, J. Javadpour, A. Yusefi, and T. S. Jafarzadeh, "The role of TiO2, ZrO2, BaO and SiO2 on the mechanical properties and crystallization behavior of fluorapatite–mullite glass–ceramics," *J. Non. Cryst. Solids*, vol. 361, pp. 70–77, 2013.
61. W. Luo *et al.*, "Effect of B_2O_3 on the crystallization, structure and properties of $MgO–Al_2O_3–SiO_2$ glass-ceramics," *Ceram. Int.*, vol. 45, no. 18, pp. 24750–24756, 2019.
62. Y. Muroya *et al.*, "Densification of SiO_2-Al_2O_3-TiO_2 based ceramic film coated on steel for high thermal stabilty and mechanical properties," *Surf. Coatings Technol.*, vol. 201, no. 3–4, pp. 880–885, 2006, doi: 10.1016/j.surfcoat.2005.12.045.
63. J. Yang, S. Zhang, B. Liu, D. Pan, C. Wu, and A. A. Volinsky, "Sr^{2+}/Y^{3+} co-doped MgO-Al," *J. Iron Steel Res. Int.*, vol. 22, no. 12, pp. 1113–1117, 2015.
64. H. Shao, "K? M. Liang, F. Zhou, G? L. Wang, A? M. Hu," *Mater. Res. Bull*, vol. 40, p. 499G506, 2005.
65. G. L. Paraschiv, S. Gomez, J. C. Mauro, L. Wondraczek, Y. Yue, and M. M. Smedskjaer, "Hardness of oxynitride glasses: topological origin," *J. Phys. Chem. B*, vol. 119, no. 10, pp. 4109–4115, 2015.
66. M. Feng *et al.*, "Crystallization and wear behavior of SiO_2-Al_2O_3-ZrO_2-Ba (Sr, Ca) O glass-ceramics added with Cr_2O_3 by different methods," *Ceram. Int.*, vol. 45, no. 17, pp. 22617–22624, 2019.
67. J. H. Ouyang, S. Sasaki, T. Murakami, and K. Umeda, "Spark-plasma-sintered ZrO_2 (Y_2O_3)-$BaCrO_4$ self-lubricating composites for high temperature tribological applications," *Ceram. Int.*, vol. 31, no. 4, pp. 543–553, 2005.
68. D. Herman, T. Okupski, and W. Walkowiak, "Wear resistance glass-ceramics with a gahnite phase obtained in CaO-MgO-ZnO-Al_2O_3-B_2O_3-SiO_2 system," *J. Eur. Ceram. Soc.*, vol. 31, no. 4, pp. 485–492, 2011.
69. G. Wang, K. Fu, S. Wang, and B. Yang, "Optimization of mechanical and tribological properties of a dental $SiO_2–Al_2O_3–K_2O–CaO–P_2O_5$ glass-ceramic," *J. Mech. Behav. Biomed. Mater.*, vol. 102, p. 103523, 2020.
70. K. Fu, S. Wang, G. Wang, and Y. Wang, "The effects of calcium oxide on fluorapatite crystal morphology and mechanical property of functional glass-ceramics," *Ceram. Int.*, vol. 44, no. 16, pp. 20531–20538, 2018.
71. H. R. Fernandes, D. U. Tulyaganov, M. J. Pascual, V. V Kharton, A. A. Yaremchenko, and J. M. F. Ferreira, "The role of K_2O on sintering and crystallization of glass powder compacts in the $Li_2O–K_2O–Al_2O_3–SiO_2$ system," *J. Eur. Ceram. Soc.*, vol. 32, no. 10, pp. 2283–2292, 2012.
72. H. R. Fernandes, D. U. Tulyaganov, A. Goel, and J. M. F. Ferreira, "Effect of K_2O on structure–property relationships and phase transformations in $Li_2O–SiO_2$ glasses," *J. Eur. Ceram. Soc.*, vol. 32, no. 2, pp. 291–298, 2012.
73. K. Tsuru, C. Ohtsuki, A. Osaka, T. Iwamoto, and J. D MACKENZIE, "Bioactivity of sol–gel derived organically modified silicates: Part I: In vitro examination," *J. Mater. Sci. Mater. Med.*, vol. 8, no. 3, pp. 157–161, 1997.
74. T. Yabuta, E. P. Bescher, J. D. Mackenzie, K. Tsuru, S. Hayakawa, and A. Osaka, "Synthesis of PDMS-based porous materials for biomedical applications," *J. sol-gel Sci. Technol.*, vol. 26, no. 1–3, pp. 1219–1222, 2003.
75. Q. Chen, F. Miyaji, T. Kokubo, and T. Nakamura, "Apatite formation on PDMS-modified $CaO–SiO_2–TiO_2$ hybrids prepared by sol–gel process," *Biomaterials*, vol. 20, no. 12, pp. 1127–1132, 1999.
76. Q. Chen, N. Miyata, T. Kokubo, and T. Nakamura, "Bioactivity and mechanical properties of PDMS-modified $CaO–SiO_2–TiO_2$ hybrids prepared by sol-gel process," *J. Biomed. Mater. Res.*, vol. 51, no. 4, pp. 605–611, 2000.
77. Y. Aburatani, K. Tsuru, S. Hayakawa, and A. Osaka, "Mechanical properties and microstructure of bioactive ORMOSILs containing silica particles," *Mater. Sci. Eng. C*, vol. 20, no. 1–2, pp. 195–198, 2002.
78. Y. Guo, D. Bian, and Y. Zhao, "Preparation and Properties of Chemically Bonded Ceramic Coatings Reinforced by GO-TiO_2 composites," *Russ. J. Appl. Chem.*, vol. 92, no. 6, pp. 842–847, 2019.
79. A. R. Molla, B. V. M. Kumar, and B. Basu, "Friction and wear mechanisms of $K_2O–B_2O_3–Al_2O_3–SiO_2$–MgO–F glass-ceramics," *J. Eur. Ceram. Soc.*, vol. 29, no. 12, pp. 2481–2489, 2009.
80. H. Li and Z. R. Zhou, "Wear behaviour of human teeth in dry and artificial saliva conditions," *Wear*, vol. 249, no. 10–11, pp. 980–984, 2001.
81. S. Roy and B. Basu, "Mechanical and tribological characterization of human tooth," *Mater. Charact.*, vol. 59, no. 6, pp. 747–756, 2008.
82. S. Jahanmir and X. Dong, "Wear mechanism of a dental glass-ceramic," *Wear*, vol. 181, pp. 821–825, 1995.
83. V. S. Nagarajan and S. Jahanmir, "The relationship between microstructure and wear of mica-containing glass-ceramics," *Wear*, vol. 200, no. 1–2, pp. 176–185, 1996.
84. H. Xiao, Y. Cheng, Q. Yang, and T. Senda, "Mechanical and tribological properties of calcia–magnesia–alumina–silica-based glass–ceramics prepared by in situ crystallization," *Mater. Sci. Eng. A*, vol. 423, no. 1–2, pp. 170–174, 2006.
85. J. Park and A. Ozturk, "Tribological properties of $MgO–CaO–SiO_2–P_2O_5$–F-based glass-ceramic for dental applications," *Mater. Lett.*, vol. 61, no. 8–9, pp. 1916–1921, 2007.