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(Review)

Advancements in Glass-Ceramic Production Processes and Diverse Applications: An Article Review

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ABSTRACT

This study evaluates glass ceramics' production methods, properties, and applications, focusing on techniques such as two-stage heat treatments, single-stage processes, petrurgic methods, powder methods, and sol-gel precursor glasses. It examines each method's benefits and limitations and suitability for different applications in sectors like construction, optics, medicine, electronics, military, kitchenware, and thermal applications. The conventional two-stage heat treatment involves nucleation at lower temperatures and crystal growth at higher temperatures, which is critical for achieving desired properties such as strength and thermal shock resistance. Alternatives like single-stage heat treatments, such as those used for Silceram, offer cost benefits but may not always achieve optimal properties. The petrologic method provides a more economical approach but poses challenges in microstructure control. Sintering processes combine densification and crystallization, and powder technology methods are also explored. The sol-gel method, though promising for high-purity applications, faces challenges in scalability and cost. Recycling waste materials for glass-ceramic production offers environmental benefits, including reducing landfill waste and conserving resources. Various waste materials, such as coal fly ash and steel slag, can be utilized, though there are trade-offs between waste reuse and product performance. Glass ceramics exhibit a range of useful properties, including transparency, low thermal expansion, toughness, and biocompatibility. These characteristics make them suitable for diverse applications, from the military to the medical fields. Advanced types like lithium aluminosilicate glass-ceramics offer specific advantages for high-performance applications but may have limitations based on temperature and machinability. Overall, the study underscores the versatility of glass ceramics and highlights ongoing developments and optimizations in their production and applications.

Keywords: *Glass-ceramics, Preparation, Application.*

1. Introduction

Glass-ceramics are materials that have the properties of both glass and ceramics. They are hard and durable, like ceramics, but they can also be transparent, like glass. The crystals are evenly distributed throughout the glass, giving it the strength and durability of a ceramic. The type of crystals that form in the glass depends on its composition. Some common crystals found in glass-ceramics include quartz and feldspar. The properties of glass-ceramics can be tailored by controlling the composition of the glass and the heat treatment process. This makes glass-ceramics a versatile material that can be used for a variety of applications, such as cookware, dental implants, and optical components [1-4]. Glass-ceramics were unintentionally found. Since then, research organizations, academic institutions, and businesses have published a number of fascinating papers and awarded patents pertaining to glass-ceramics globally. Glass-ceramics, sometimes referred to as vitrocerams, pyrocerams, vitrocerâmicos, vitroceramiques, and sittals, are made when specific glasses crystallize under regulated conditions; this process is typically started by adding additives that nucleate.

In contrast, spontaneous surface crystallization is typically undesirable in the production of glass. They always have one or more embedded crystalline and residual glassy phases. There is a range of 0.5 to 99.5 % crystallinity, with the most common range being between 30 and 70 %. Ceramization under control produces a variety of materials with intriguing occasionally distinct combinations of characteristics [5-8]. Only specific glass compositions are suitable precursors for glass-ceramics. The composition of the glass determines the type of crystals that will form during the heat treatment, and the properties of the resulting glass-ceramic. The heat treatment is also critical to the attainment of an acceptable and reproducible product. The heat treatment must be carefully controlled to ensure that the crystals form in the desired way and that the desired properties are achieved [9,10]. A heat treatment program for glass-ceramics should take into account a number of aspects, some of which are listed as, the composition of the glass, the desired properties of the glass-ceramic, the desired size and distribution of the crystals, the rate of heating and cooling and the atmosphere in which the glass is heated. The heat treatment schedule is typically developed through trial and error, and it is often necessary to modify the schedule for different glass compositions [11,12]. The production of glass-ceramics is a complex process that requires a good understanding of the properties of glasses and ceramics. However, the potential benefits of glass-ceramics make them a worthwhile material to study and develop.

Glass-ceramics are not fully crystalline. The amount of crystalline phase in a glass-ceramic can vary depending on the composition of the glass and the heat treatment process. However, the residual glass typically makes up 50-95% of the glass-ceramic volume. The composition of the residual glass is different from the parent glass because the crystals that form during the heat treatment extract some of the components from the glass. This can change the properties of the residual glass, such as its refractive index and its coefficient of thermal expansion. The composition of the residual glass can also be affected by the presence of nucleating agents [13-15]. Nucleating agents are substances that promote the formation of crystals. They are often added to glass-ceramics to ensure that the crystals form in a controlled way. The composition of the residual glass is an important factor in determining the properties of the glass-ceramic. By controlling the composition of the residual glass, it is possible to tailor the properties of the glass-ceramic to meet specific needs [3, 13,15].

The mechanical properties of glass-ceramics are superior to those of the parent glass. This is because the crystals in the glass-ceramic provide reinforcement, making it stronger and more durable. Glass-ceramics can also exhibit other distinct properties that are beneficial for particular applications. For example, the extremely small coefficient of thermal expansion of certain compositions in the Li_2O-Al_2O_3-SiO_2 system makes them suitable for thermal shock resistant applications. Thermal shock resistance is the ability of a material to withstand sudden changes in temperature without breaking. Glass-ceramics with an extremely small coefficient of thermal expansion are less likely to crack when exposed to sudden temperature changes. This is because the crystals in the glass-ceramic prevent the material from expanding or contracting too much.

Glass-ceramics with an extremely small coefficient of thermal expansion are used in a variety of applications where thermal shock resistance is important. For example, they are used in cookware, ovenware, and laboratory glassware [4,11,12].

Additional characteristics of glass-ceramics that make them appropriate for many applications include the following: Transparency: Glass-ceramics can be transparent, making them suitable for applications where visibility is important, such as optical components and jewelry. Glass-ceramics are a versatile material with a wide range of properties. They are strong, durable, and transparent, making them a good choice for a variety of uses [16,17].

This study explores and evaluates the production processes, properties, and diverse applications of glass-ceramics. This includes investigating conventional and modified production methods, such as two-stage heat treatments, single-stage approaches, petrurgic methods, powder methods, and sol-gel precursor glasses. Additionally, the study aims to analyze the advantages and disadvantages of each production technique and assess their suitability for different applications. Furthermore, the study aims to highlight the potential of glass-ceramics in various sectors, including construction, optics, medicine, electronics, military, kitchenware, and thermal applications, with a focus on their unique properties and benefits. Ultimately, the aim is to provide insights that contribute to advancing and optimizing glass-ceramic production processes and their utilization across diverse industries.

2. Production processes for glass-ceramics:

2.1. Conventional process (two-stage):

The conventional method for producing glass-ceramic is to devitrify a glass by a two-stage heat treatment. The first stage is called the nucleation stage, where the glass is heated to a temperature below its melting point, but high enough to allow the formation of nuclei, which are small crystals that serve as the starting points for crystallization. The second stage is called the growth stage, where the glass is heated to a higher temperature, allowing the nuclei to grow into larger crystals. The temperature and time of the heat treatments are carefully controlled to achieve the desired microstructure of the glass-ceramic. A high density of nuclei is important, as it leads to a desirable microstructure consisting of a large number of small crystals [18-20]. This microstructure gives the glass-ceramic its characteristic properties, such as strength, toughness, and thermal shock resistance.

The parent glass may be fabricated before crystallization using well-established, traditional glass-making methods, such as casting and forming. However, some glass-ceramics, such as those used in dental applications, are made by sintering powdered glass. Glass production and subsequent heat treatments are generally energy-intensive and therefore expensive. However, the unique properties of glass-ceramics make them suitable for a wide range of applications, such as cookware, dental implants, and optical components [5]. The two-stage heat treatment procedure is described in more detail below: The nucleation stage is typically carried out at a temperature of 500-700 degrees Celsius [21,22]. The exact temperature depends on the composition of the glass.

- The growth stage is typically carried out at a temperature of 700-900 degrees Celsius. The exact temperature also depends on the composition of the glass.
- The duration of the heat treatments can vary from a few hours to several days. Again, the exact duration depends on the composition of the glass and the desired microstructure. The nucleation stage is the most critical step in the glass-ceramic production process. The glass will not crystallize properly if the number of nuclei is too low. The glass will become cloudy if the number of nuclei is too high. The growth stage is also important but less critical than the nucleation stage. The size and shape of the crystals can be controlled by the temperature and time of the growth stage. The two-stage heat treatment process is complex and delicate. However, it is essential to produce high-quality glass-ceramics with the desired properties.

2.2. Modified conventional method (single-stage):

The two-stage heat treatment is necessary because the nucleation and growth rate curves do not overlap significantly. This means that if we only heat the glass to a temperature where the nucleation rate is high, the crystals will not have enough time to grow before the glass melts. On the other hand, if we heat the glass to a temperature where the growth rate is high, the nucleation rate will be too low and the glass will not devitrify properly. The overlap between the nucleation and growth rate curves can be increased by optimizing the glass composition. This can be done by adding nucleating agents to the glass. Nucleating agents are substances that promote the formation of nuclei in the glass.

Adding the right amount of nucleating agents makes it possible to achieve the necessary overlap between the nucleation and growth rate curves and allow for a single-stage heat treatment. The glass-ceramic system known as "Silceram" is an example of a glass-ceramic that can be produced using a single-stage heat treatment. Silceram is a lithium aluminosilicate glass-ceramic that is used in dental applications. The nucleating agent for Silceram is a small amount of titania (TiO_2). The addition of titania to the glass increases the nucleation rate and allows for a single-stage heat treatment at a temperature of around 700 degrees Celsius [23]. The single-stage heat treatment process is more economical than the two-stage heat treatment process. However, it is not always possible to achieve the desired properties of the glass-ceramic using a single-stage heat treatment. In some cases, the two-stage heat treatment is still necessary to produce a high-quality glass-ceramic with the desired properties [24-25].

2.3. Petrurgic method:

It was found with Silceram that there was little difference between whether the glass was heated up to TNG from room temperature or whether the molten glass was cooled to TNG. This is because the nucleation and growth rate curves for Silceram have a significant overlap, meaning that nucleation and growth can occur during a single-stage heat treatment. The petrurgic method is a type of single-stage heat treatment used to produce glass-ceramics. In the petrurgic method, the parent glass is cooled slowly from the molten state. The cooling rate is carefully controlled to achieve the desired microstructure [26]. The petrurgic method is more economical than the conventional two-stage heat treatment method. This is because it does not require a separate heating step. Additionally, the petrurgic method can be used to produce glass-ceramics with a wider range of properties than the conventional method.

The advantages of the petrurgic method can be summarized as follows: 1) It is more economical than the conventional two-stage heat treatment method, 2) It can be used to produce glass-ceramics with a wider range of properties, and 3) It is a simpler process, which can lead to fewer defects in the final product. Its disadvantages are as follows: 1) It can be more difficult to control the microstructure of the final product. And 2) It may not be suitable for all types of glass-ceramics. Overall, the petrurgic method is a promising technique for the production of glass-ceramics. It is more economical and versatile than the conventional two-stage heat treatment method. However, it is important to control the cooling rate to achieve the desired microstructure carefully

2.4. Powder methods:

The technological significance of the sintering process in which both densification and crystallization occur simultaneously at the same temperature is that it can produce dense glass-ceramics with a controlled microstructure. This is because the rate of densification can be adjusted to match the rate of crystallization, which allows for the formation of a fine-grained microstructure with good mechanical properties [27]. The sintering process is a complex phenomenon that is influenced by a number of factors, including the composition of the glass, the particle size, the temperature, and the time. The viscosity of the glass typically controls the rate of densification. As the glass is heated, the viscosity decreases and the particles can move closer together. The nucleation and growth rates of the crystals typically control the crystallization rate.

In the sintering process in which densification and crystallization take place simultaneously, the rate of densification must be greater than the rate of crystallization. This is because if the crystallization rate is too high, the crystals will form before the particles can move closer together. This will result in a porous material with poor mechanical properties. The sintering process in which densification and crystallization take place simultaneously, can be used to produce a variety of glass-ceramics with different properties. For example, the microstructure of the glass-ceramic can be controlled by adjusting the temperature and time of the sintering process. The composition of the glass can also be adjusted to influence the properties of the glass-ceramic [28]. The sintering process in which densification and crystallization occur simultaneously, is a promising technique for producing dense glass-ceramics with a controlled microstructure. This technique can produce glass-ceramics with various properties, making it a versatile and useful tool for the manufacturing industry.

In the case of the advantages of the sintering process, it can be used to produce dense glass-ceramics with a controlled microstructure, it is a versatile technique that can be used to produce a variety of glass-ceramics with different properties, and it is a relatively simple process that can be easily scaled up for industrial production. While in the case of the disadvantages of the sintering process**, i**t can be sensitive to the composition of the glass and the sintering conditions, it can be more expensive than other methods of producing glass-ceramics, and it may not be suitable for all types of glass-ceramics. Overall, the sintering process in which densification and crystallization occur simultaneously is a promising technique for producing dense glass-ceramics with a controlled microstructure. This technique is versatile and can be used to produce a variety of glass-ceramics with different properties. However, it is important to carefully consider the composition of the glass and the sintering conditions to ensure that the desired results are achieved. The most common method is to cold-compact the powder and then sinter it at a high temperature. This method is relatively simple and inexpensive, but it can be difficult to achieve full densification. Another method is to use pressure-assisted densification methods such as hot pressing or HIP ping. These methods can achieve near full densification but are more expensive than cold-pressing and sintering.

A third method is to use powder technology to produce dispersion-reinforced glass-ceramic matrix composites. These composites are made by mixing the powdered parent glass with the reinforcement in the required proportions. The mixture is then shaped, sintered, and crystallized. The production of continuous fiber-reinforced glass-ceramics is more complex and requires dedicated apparatus. For both particulate- and fiber-reinforced glass-ceramics, the densification is usually carried out by hot pressing, and a final heat treatment is required to achieve crystallization of the glass matrix. The choice of which method to use depends on the specific application and the desired properties of the glass-ceramic [27,28].

2.5. Sol-gel precursor glass:

The sol-gel method requires the use of pure chemicals, which can be expensive and difficult to obtain from waste materials. Additionally, the sol-gel method can be more difficult to scale up for industrial production [29]. However, I think it is important to note that the sol-gel method is a promising technique for the production of glass-ceramics from waste materials. The sol-gel method can be used to produce glasses with a controlled microstructure and a high purity. This could be useful for applications where the purity of the glass is important, such as medical applications [30]

Sol-gel method is promising for producing glass-ceramics with a controlled microstructure and high purity. However, the sol-gel method is also more expensive and more difficult to scale up than the traditional melt-quenching method. In the case of the advantages of the sol-gel method for producing glass-ceramics, it is a low-temperature process, which can be a benefit for some applications. It can be used to produce glass-ceramics with a controlled microstructure, and it can be used to produce glass-ceramics with various properties. While in the case of the disadvantages of the sol-gel method for producing glass-ceramics, it can be more expensive than the conventional method, it can be more difficult to control the process, and it is not yet widely used, so there is less information available about the technique. Overall, the sol-gel method is a promising technique for producing glass-ceramics. It has some advantages over the conventional method, but it also has some disadvantages. The sol-gel method may become more common in the future as the technology continues to develop.

2.6. Glass-ceramics from wastes:

The statement that there cannot be zero waste from any manufacturing, industrial or energy conversion process. No matter how efficient the process is, some waste will always be produced. That's why it's important to recycle and reuse waste whenever possible. Recycling is the process of converting waste materials into new materials and objects. It is an alternative to conventional waste disposal that can save material and help lower greenhouse gas emissions. Recycling can benefit your community and the environment. Reuse is the process of using a product or material again for its original purpose or for a new purpose. It is a more sustainable alternative to recycling, as it requires less energy and resources. The reuse of waste materials to produce glass-ceramics is a promising way to reduce waste and conserve resources. Glass-ceramics are materials that have the properties of both glass and ceramics. They are hard and durable, like ceramics, but they can also be transparent, like glass [31,32]. Many different types of waste materials can be used to produce glass-ceramics.

Some of the most common include [33]

- Coal fly ash: This is a waste product from coal-fired power plants. It is a fine, powdery material that is rich in silicon dioxide.
- Mud from zinc hydrometallurgy: This is a waste product from zinc production. It is a sludge rich in zinc, iron, and sulfur.
- Slag from steel production: This is a waste product from steel production. It is a hard, brittle material that is rich in iron oxide.
- Ash and slag from waste incinerators: This is a waste product from municipal solid waste incineration. It is a mixture of ash and slag rich in silica and calcium oxide.

- Red mud from alumina production: Red mud is a waste product from alumina production. It is a highly alkaline sludge that is rich in aluminum oxide.
- Waste glass: This is a waste product from the production and use of glass. It is a mixture of glass fragments and impurities.

The reuse of waste materials to produce glass-ceramics can have a number of benefits, including:

- It can reduce the amount of waste sent to landfills.
- It can conserve natural resources.
- It can help to reduce greenhouse gas emissions.
- It can create jobs in the recycling and manufacturing industries.

The reuse of waste materials to produce glass-ceramics is a promising way to reduce waste and conserve resources. It is a sustainable and environmentally friendly alternative to conventional waste disposal. There is always a trade-off between the amount of waste recycled and the optimization of properties of the new products. In general, minimizing the amount of pure materials or non-waste additions introduced is important to improve performance, as the main objective is to reuse the waste material [34].

3. Application of glass ceramic:

3.1. Construction applications:

Glass-ceramics can be made from a variety of waste materials, including ashes, blast furnace residue, and steel residue. The glass-ceramic's composition and predominant crystal phases will vary depending on the waste material used. However, all glass-ceramics are generally strong, hard, and chemically resistant [35]. Neopari's is a unique type of glass-ceramic made from recycled glass. It is an ideal alternative to stone for interior and exterior walls, interior floors, counters, and table tops, as shown in figure 1. Neopari's is marble-like and is available in large, flat or curved panels [36].

Figure. 1: Four colors, White, light beige, light gray, and black of neopari's (glass-ceramic). Adapted from: (https://www.tgpamerica.com/products/glass/neoparies/)

The benefits of using glass-ceramics made from waste materials:

- They are a sustainable alternative to traditional materials, such as stone and ceramic.
- They are low-cost and easy to produce.

- They are strong, hard, and chemically resistant.
- They have a variety of applications.

3.2. Optical applications:

Glass-ceramics are used in various optical applications because they can be made transparent or translucent and have low thermal expansion. This makes them ideal for applications with critical dimensional stability, such as in telescope mirrors, laser gyroscopes and Sodium-Vapour lamp bulb (Figure 2) [37].

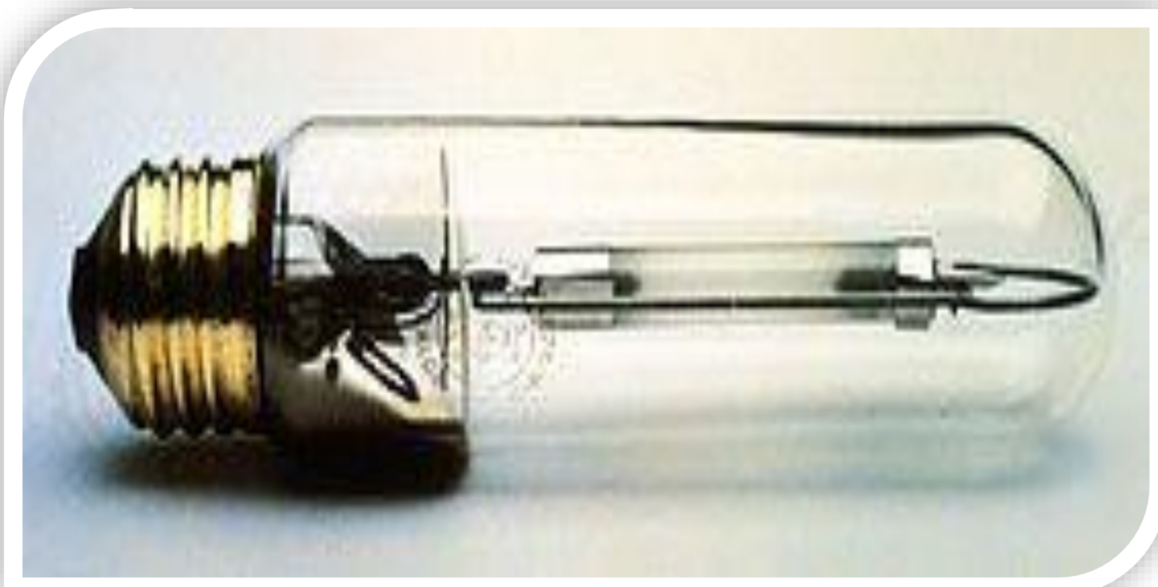

Figure. 2: Sodium-Vapour lamp bulb. Adapted from (https://www.britannica.com/technology/optical-ceramics/images-videos)

The advantages of using glass-ceramics in optical applications:

- High translucency or transparency: Glass-ceramics can be very transparent, making them ideal for applications where light transmission is important.

- Low thermal expansion: Glass-ceramics have low thermal expansion, which means that they will not expand or contract significantly when exposed to changes in temperature. This makes them ideal for applications where dimensional stability is critical.
- Toughness: Glass-ceramics can be made to be tough, which means that they are resistant to breakage. This makes them ideal for applications where the material may be exposed to impact or vibration.
- Biocompatibility: Some glass-ceramics are biocompatible, which means they can be used in medical applications without causing adverse reactions.

Examples of optical applications of glass-ceramics:

- Telescope mirror blanks: Glass-ceramics are used to make telescope mirror blanks because they are very transparent and have low thermal expansion. This ensures that the mirror will not distort when exposed to changes in temperature.
- Laser gyroscopes: Glass-ceramics are used to make laser gyroscopes because they are very stable and vibration-resistant. This ensures that the laser gyroscope will be able to measure rotation accurately.
- Broadband optical amplification: Glass-ceramics doped with transition metal ions can be used to amplify light over a broad range of wavelengths. This makes them ideal for applications such as fiber optic telecommunications.
- Tunable and infrared lasers: Glass-ceramics doped with transition metal ions can be used to create tunable and infrared lasers. This makes them ideal for applications such as spectroscopy and medical diagnostics.
- Phosphor with tunable UV/blue luminescence behavior: Glass-ceramics doped with rare earth ions can be used to create phosphors with tunable UV/blue luminescence behavior. This makes them ideal for applications such as lighting and display technology.
- Solar collectors: Glass-ceramics can be used to make solar collectors because they are very transparent and have low thermal expansion. This ensures that the solar collector will be able to collect and transmit sunlight efficiently.

Overall, glass-ceramics are versatile materials that can be used in a wide range of optical applications. Their high translucency or transparency, low thermal expansion, toughness, and biocompatibility make them ideal for applications where dimensional stability, light transmission, and resistance to breakage are important.

3.3. Medicine applications:

Bioglass is a type of bioactive glass that has been used in the medical field for many years. It is made from a combination of materials, including silicon dioxide, calcium oxide, sodium oxide, and phosphorus oxide. Bioglass is biocompatible, meaning that the body does not reject it. It is also bioactive, bonding to bone and promoting bone growth. However, bioglass has some limitations. It is not as strong as other materials, such as metals or ceramics. This makes it difficult to use bioglass in load-bearing applications. Glass-ceramics are a type of material that combines the properties of glass and ceramics. They are made by melting glass and then rapidly cooling it to form a glassy matrix. The glassy matrix is then heat-treated to form crystalline phases. The crystalline phases give the material strength and toughness, while the glassy matrix gives it biocompatibility [38,39].

A-W glass-ceramic is a type of glass-ceramic used for hard tissue repair. It contains apatite and β-wollastonite crystals, which are similar to the minerals found in bone. A-W glass-ceramic is biocompatible and bioactive and has been shown to promote bone growth. Researchers are still working to improve the properties of glass-ceramic biomaterials. One way to do this is to incorporate specific ions into the material. For example, the addition of Cu^{2+}, Sr^{2+}, and Zn^{2+} ions can enhance the bioactivity and antimicrobial activity of glass-ceramics. Overall, glass-ceramics are promising materials for hard tissue repair. They are biocompatible, bioactive, and strong. Researchers continue improving the properties of glass-ceramics, which may become the preferred material for hard tissue repair. By the way, the code you generated is correct. The bioactivity of an ion is a measure of its ability to promote bone growth. The ions you listed, Cu^{2+}, Sr^{2+}, and Zn^{2+}, are all known to be bioactive.

The specific bioactivity of each ion will depend on the concentration of the ion and the other ions present in the material. Lithium disilicate glass-ceramic is one of the most popular materials used in dental restorations today. It is known for its excellent aesthetics, strength, and durability.

Lithium disilicate is made by first melting a glass containing lithium oxide, silicon dioxide, and other oxides. The molten glass is then cooled rapidly, which creates a glassy matrix with small crystals of lithium disilicate embedded in it. The crystals give the material strength and durability, while the glassy matrix gives it its translucency and esthetic properties **[39].** Lithium disilicate is used to make a variety of dental restorations, including crowns, bridges, and veneers. It is also used to make inlays, which are used to repair chipped or broken teeth.

The advantages of using lithium disilicate glass-ceramic in dental restorations are

- Excellent esthetics: Lithium disilicate is very translucent, which makes it a good choice for restorations that need to match the color of natural teeth.
- Strong and durable: Lithium disilicate is two to three times stronger than other dental glass-ceramics, making it a good choice for restorations that must withstand chewing forces.
- Biocompatible: Lithium disilicate is biocompatible, which means it is unlikely to cause any allergic reactions or other problems in the mouth.
- Easy to work with: Lithium disilicate can be milled and shaped using computer-aided design/computer-aided manufacturing (CAD/CAM) technology, making it a good choice for restorations that must be customized to fit the individual patient.

Lithium disilicate glass-ceramic is a versatile and reliable material ideal for a wide range of dental restorations.

3.4. Electronic applications:

All-solid-state secondary batteries with inorganic solid electrolytes are expected to be the next generation of high-output batteries. The crucial requirements for appropriate solid electrolytes are high ionic conductivity and good formability as (Figure 3) [40]. Glass-ceramics are a promising material for solid electrolytes because they can be made to have high ionic conductivity and good formability. In addition, glass-ceramics are more stable in the open atmosphere and even to exposure to moist air than liquid electrolytes [41].

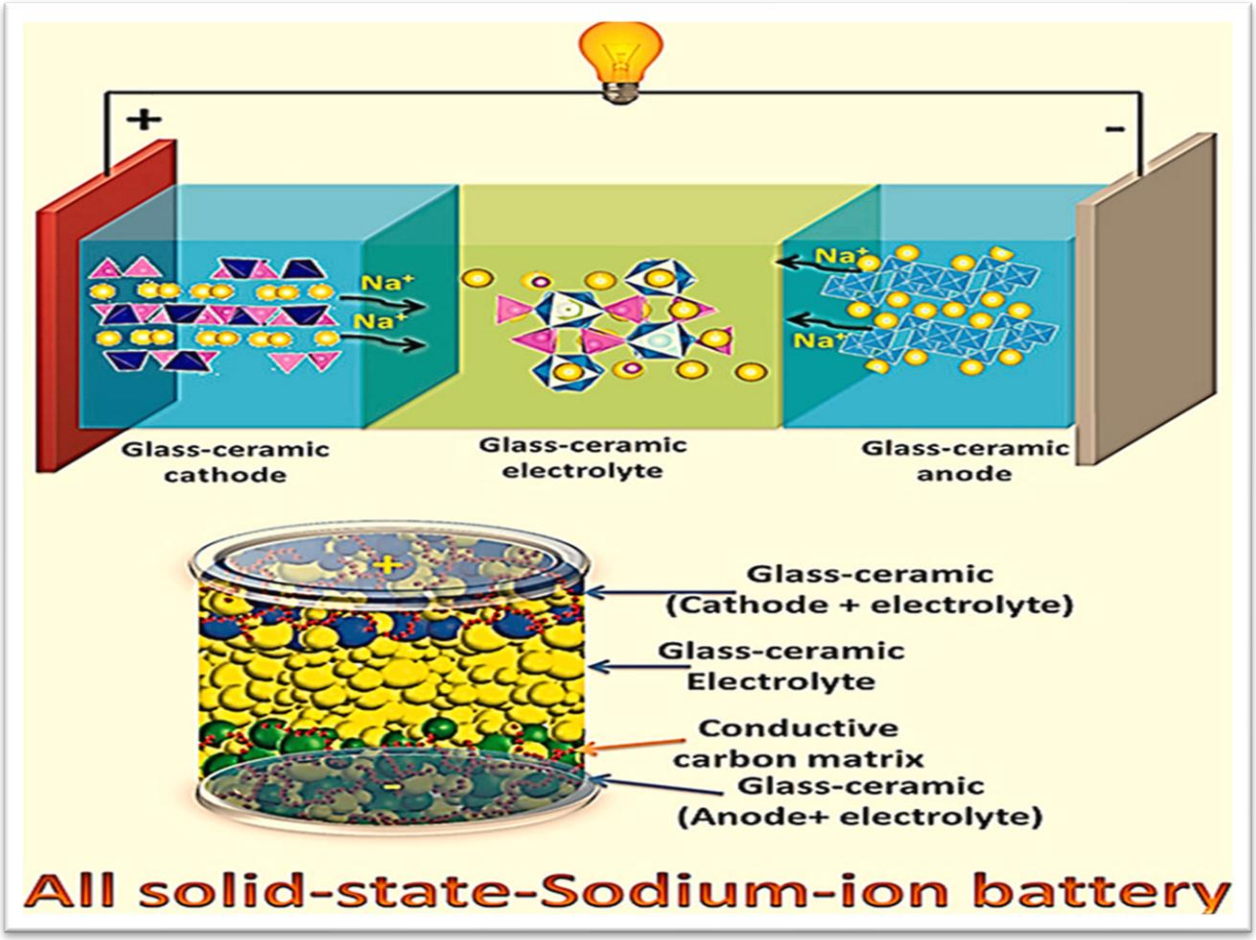

Figure. 3: All solid –State-Sodium- ion battery. Adapted from (https://ars.els-cdn.com/content/image/1-s2.0-S0378775321014130-ga1_lrg.jpg)

The advantages of using glass-ceramics as solid electrolytes in batteries:

- High ionic conductivity: Glass-ceramics can have high ionic conductivity, essential for high-performance batteries.
- Good formability: Glass-ceramics can be easily formed into different shapes, making them suitable for use in various battery designs.

- Stability in the open atmosphere: Glass-ceramics are more stable in the open atmosphere than liquid electrolytes, which means that they can be stored and used without the need for special precautions.
- Stability to moist air: Glass-ceramics are also more stable to moist air than liquid electrolytes, which makes them suitable for use in a humid environment

Overall, glass-ceramics are a promising material for solid electrolytes in batteries. They offer a number of advantages over liquid electrolytes, including high ionic conductivity, good formability, and stability in the open atmosphere. As research in this area continues, glass-ceramics are likely to play an increasingly important role in developing next-generation batteries [42,43].

3. 5. Military applications:

Glass-ceramics are used in various military applications because they offer a unique combination of properties that are essential for these applications [44,45]. The properties that make glass-ceramics ideal for military applications:

- Low coefficient of thermal expansion: This property makes glass-ceramics resistant to thermal shock, which is a phenomenon that occurs when a material is rapidly heated or cooled. Thermal shock can cause materials to crack or shatter, but glass-ceramics can withstand it.
- High mechanical strength: Glass-ceramics are strong and durable, which makes them ideal for applications where they will be exposed to impact or vibration.
- High abrasion resistance: Glass-ceramics are resistant to abrasion, which means they can withstand being scratched or rubbed against other surfaces.
- High transparency: Some glass-ceramics are transparent, which makes them ideal for applications where visibility is important, such as in view-windows for armored vehicles or tanks.
- Radar transparency: Some glass-ceramics are transparent to radar waves, which makes them ideal for applications where stealth is important, such as in the nosecones of high-performance aircraft and missiles.

Figure. 4: Aircraft. Adapted from (https://www.elantechnology.com/glass/glass-suppliers-industries/glass-industry-for-military-applications/)

Examples of military applications of glass-ceramics:

- Nosecones of high-performance aircraft and missiles: The nosecone is the front part of an aircraft or missile. It is responsible for protecting the aircraft or missile from the heat and friction of the air as it travels at high speeds. Glass-ceramics are used in the nosecones of high-performance aircraft as (Figure 5) and missiles because they can withstand the high temperatures and pressures encountered at these speeds.
- View-windows for armored vehicles or tank: The view-window is the part of an armored vehicle or tank that allows the crew to see outside. Glass-ceramics are used in view-windows because they are strong, durable, and transparent.

- Radar windows: Radar windows are used in radar systems to allow radar waves to pass through. Glass-ceramics are used in radar windows because they are transparent to radar waves. Overall, glass-ceramics are a versatile material that can be used in a wide range of military applications. Their unique properties make them ideal for applications where high strength, durability, transparency, and radar transparency are important [46,47].

3.6. Kitchenware applications:

Glass-ceramics are a great material for kitchenware (Figure 5) because of their superior robustness (relative to glass), appealing appearance, and extremely low thermal expansion coefficient [46]. Glass-ceramics are a good choice for kitchenware because

- Robustness: Glass-ceramics are more robust than glass, making them less likely to break or chip. This is important for kitchenware, which is often exposed to heat, cold, and impact.
- Appealing appearance: Glass-ceramics can be made in various colors and finishes, making them a versatile material for kitchenware. They can also be made to be smooth and non-porous, which makes them easy to clean.
- Low thermal expansion coefficient: The thermal expansion coefficient of glass-ceramics is very low, which means they are resistant to thermal shock. Thermal shock is a phenomenon that occurs when a material is rapidly heated or cooled, and it can cause materials to crack or shatter. Glass-ceramics are less likely to experience thermal shock than glass, making them a safer kitchenware choice.

Overall, glass-ceramics are a versatile material that can be used in a wide range of kitchenware applications. Their unique properties make them a safe and durable choice for kitchenware.

Figure. 5: kitchenware products. Adapted from (https://www.nytimes.com/wirecutter/reviews/how-to-shop-for-dinnerware/)

3.7. Thermal applications:

Lithium aluminosilicate glass-ceramic is a very important material due to its extremely low coefficient of thermal expansion (CTE). This means that it will not expand or contract significantly when exposed to changes in temperature. This makes it ideal for applications with critical dimensional stability, such as in optical components, precision instruments, and thermal shock-resistant materials [48-51]. Other unique characteristics of lithium aluminosilicate glass-ceramic include:

- Good homogeneity: This means the material is free of defects such as bubbles or inclusions, which can lead to stress concentrations and premature failure.
- Good transparency: This allows the material to be used in optical applications.

- High melting temperature: This makes it possible to process the material using conventional manufacturing techniques.
- Good machinability: This makes fabricating the material into complex shapes possible.

The limiting use temperature of lithium aluminosilicate glass-ceramic is typically below about 700 degrees Celsius. However, some varieties of this material can be used at higher temperatures. Machinable glass-ceramics are a type of lithium aluminosilicate glass-ceramic that contains mica crystals. These crystals provide the material with good machinability and high CTE, making it suitable for applications where it needs to be bonded to metal or other materials. Lithium aluminosilicate glass-ceramic is a versatile material with a wide range of applications. Its low CTE, good homogeneity, and high melting temperature make it ideal for demanding applications with critical dimensional stability [52-55].

Figure 6: Application of a leucite-based glass-ceramic. Adapted from (https://www.researchgate.net/publication/45267367_Properties_and_Clinical_Application_of_Three_Types_of_Dental_Glass-Ceramics_and_Ceramics_for_CAD-CAM_Technologies/figures?lo=1)

4. Conclusion:

Glass-ceramics production has evolved significantly, with various innovative methods and techniques being developed to enhance efficiency and properties. Conventional two-stage heat treatments have been augmented by single-stage methods like the modified conventional approach and the petrurgic method, offering cost-effective alternatives with controlled microstructures. Additionally, powder methods and sol-gel precursor glasses demonstrate the potential for sustainable production and customization of glass-ceramics. Furthermore, the diverse applications of glass-ceramics across construction, optical, medical, electronic, military, kitchenware, and thermal sectors underscore their versatility and significance in modern technology. As research continues to refine production processes and explore new applications, glass-ceramics are poised to play an increasingly pivotal role in various industries, offering tailored solutions to meet evolving needs.

Conflict of Interest

The authors declare that they have no conflicts of interest to disclose.

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