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# A Review on Recent Progress in Additive Manufacturing of Nano-ceramic Materials in Dental 3D Application

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## ABSTRACT

Ceramics are high performing materials and are used in additive manufacturing (AM) in dental applications because the ceramic nanomaterial can withstand high temperatures. The advancements in ceramic additive manufacturing technology have significantly improved the manufacturing process. Additive manufacturing is still under development. The ultrasonic technique is used to detect defects in dental models produced by a 3D printing machine. Ceramic materials are widely used these days because they have promising thermal, mechanical, and electrical properties. While these processes are currently in development, significant improvements are still needed in areas such as testing methods, raw material quality, cost efficiency, and material handling. Additionally, every stage involved in AM of dental prosthetics requires further refinement to ensure consistent and reliable resultss.

**Keywords:** Additive manufacturing; Nano ceramic powders; Dental application; Mechanical properties; Layer by layer operation.

## 1. INTRODUCTION

Ceramic nanoparticles are special nonmetal materials that have great qualities because of their chemical makeup and flexible crystal structures, which can be changed by adding other elements, using different processing methods, and choosing specific ingredients (Wang *et al.* 2023). Ceramic materials are inorganic and non-metallic that are usually composed of silicates, clay minerals, and other naturally occurring raw elements. ceramics. Strong ionic and covalent connections between the component elements give ceramics their crystalline or partly crystalline structure. An additive manufacturing technique that uses high temperatures to increase the hardness, stability, and strength of materials is stereolithography (SL), which is also called vat photopolymerization. Piezoelectric, structural, bio-optical, and polymer-based ceramics are among its potential applications. Ceramics have excellent biocompatibility and chemical inertness, making them suitable for dental and medical applications (Brennan *et al.* 2020). However, their brittle nature and susceptibility to fracture are important considerations when using them in the oral cavity or as biomaterials. (Warreth and Elkareimi, 2020) have stated that ceramics and bio-glasses are promising biomaterials for bone replacement applications due to their biocompatibility, osteoconductivity and ability to promote bone regeneration. One of the current areas of biomaterials research is the fabrication of sophisticated ceramic and bioglass materials with specific characteristics. The process of additive manufacturing (AM), often known as 3D printing, has opened up new possibilities for the fabrication of micro/nanoscale mechanical metamaterials with complex structures (Punj *et al.* 2021). Man-made metamaterials possess unique properties not found in naturally occurring materials. The structures and geometries of these materials at the micro- and nano-scales may influence their properties to a large extent. (Su *et al.* 2023; Srivastava *et al.* 2022) have shown that additive printing can print complicated geometries. Since AM builds components layer by layer, it can create almost any complicated internal structure or shape, Moreover, AM significantly reduces process time by merging many production processes into one additive route. Accelerating product development timescales, AM enables faster design iterations and prototyping. Compared to subtractive manufacturing techniques, which remove material from a larger stock, design modifications may be swiftly applied without requiring considerable retooling, which also results in much less material waste. Among the most cutting-edge methods of 3D printing, direct additive manufacturing builds physical items from digital models by layering metal powders and then melting them using intense laser or electron beams (Xu, 2022; Allen *et al.* 2020). Electron beam melting, laser metal powder deposition, and selective laser melting are terms that describe the same

procedure. The operations rely on certain feedstock powder properties. Defects, residual stresses, and unique microstructures can result from these additive processes compared to traditional manufacturing. (Zhou *et al.* 2023) reported that additive manufacturing techniques are being explored for the development of bio-ceramic implants to support bone healing and regeneration. Owing to their biocompatibility, durability, and non-toxic nature, these AM-produced implants play a essential role in promoting bone repair and integration with surrounding tissues. The precision offered by AM enables the fabrication of complex and precise shapes of implants, internal pores, and interconnected networks that enhance biological performance. (Blakey-Milner *et al.* 2021) discussed how AM eliminates the need to connect parts and improves performance by merging multiple components into one. These advantages are achieved through smart design features like internal cooling channels, which not only improve functionality but also enable the production of lighter components. This results in significant savings in time and cost, while also allowing for innovative designs and the use of novel materials that are unattainable with traditional manufacturing methods.

(Javaid and Haleem, 2019) Additive manufacturing, also known as 3D printing, has unique properties that make it useful in many different sectors. Because AM enables the direct conversion of 3D CAD data into tangible items, it enables quick prototyping and production without tooling, making it suitable for one-of-a-kind products like medical implants and aircraft components. Additionally, AM allows for the creation of unique designs at any time. This technology helps manufacture components from a wide range of materials, including metals, polymers, ceramics, and composites, allowing for complex geometries, interior features, and assembly consolidation.

(Chen *et al.* 2019) Recent developments in ceramic 3D printing have opened up a world of new possibilities, including powder bed fusion (PBF), material extrusion, vat photopolymerization, material jetting, and binder jetting, among other innovative processes. The use of 3D printing to create ceramics is a natural progression from earlier methods, such as injection molding and slip casting.

(Olhero *et al.* 2022) Additive manufacturing techniques for producing dense, functional ceramic components continue to advance. AM or 3D printing technologies have been making significant inroads into the dental field in recent years, and there is a lot of enthusiasm and optimism around the potential benefits they can provide then AM allows for the production of highly customized dental devices and appliances tailored to each patient's unique oral anatomy, enabling better fit and comfort and integration of intraoral scanning, CAD/CAM, and AM creates a streamlined digital workflow for efficient dental device production and AM is utilized in the production of various dental restorations, including crowns, bridges, implants, aligners, surgical guides, dentures, and temporary restorations using various materials like ceramics, metals, and polymers. (Lakhdar *et al.* 2021) additive manufacturing (AM) is revolutionizing the ceramics industry by directly producing components from 3D digital data, eliminating the need for costly tooling like molds and dies. This can significantly reduce production costs, and the digital nature of AM enables rapid iteration and production of ceramic parts on-demand, compressing lead times compared to conventional manufacturing cycles. While lagging behind polymers and metals initially, there is now concerted research into developing AM processes capable of producing fully dense, defect-free advanced ceramic components. (Clemens *et al.* 2023) since ceramics are a broad class of materials with different compositions, characteristics, and processing demands, it is essential to match the appropriate AM method to the needs of the particular ceramic material and application. Several AM processes have produced varying outcomes when used with ceramics, due to the diversity of ceramic materials and their unique processing requirements. The nature of a given ceramic material, including its composition, particle size distribution, and sintering behavior, largely determines its compatibility with various AM methods. Certain AM methods could work better with some ceramics than others. (Singh *et al.* 2022) the development of novel microstructures for burnt ceramic material is the main goal of the use of additive manufacturing (AM) in dental applications. This has significant implications for improving clinical workflows and processes for dental professionals and AM allows for the fabrication of intricate and complex geometries that would be challenging or impossible to achieve with traditional subtractive manufacturing methods, enabling the creation of customized dental restorations and prostheses and it enables the production of patient-specific dental applications, such as crowns, bridges, and implants, by utilizing digital data from intraoral scans or CT scans, leading to improved fit and comfort so, the AM facilitates the rapid fabrication of physical models, prototypes, or even final dental restorations, streamlining the design and development process. (Branco *et al.* 2023) state that the additive manufacturing (AM) techniques for zirconia-based materials specifically for dental applications. Zirconia is a widely used ceramic material in dentistry due to its excellent mechanical properties, biocompatibility, and aesthetic qualities and zirconia which make it suitable for dental applications and material waste and improved resource efficiency than the potential for mass customization and digital dentistry workflows also the rapid prototyping and iterative design capabilities as well the zirconia helped to develop the medical field, especially in the dental area. (Punia *et al.* 2022) rapid prototyping techniques have revolutionized the creation of dental components and frameworks. These methods

improve accuracy and speed up production. Just to review, SL, digital light processing (DLP), fused deposition modeling, and selective laser sintering are the four most popular 3D printing methods. Standardly, resin-based materials are used in both SLA and DLP printing. Among them are photopolymer resins, which include acrylates and methacrylates. Dental models, crowns, bridges, and surgical guides may all benefit from these resins' ability to imitate the characteristics of natural tooth tissues like dentin and enamel. (Schwarzer *et al.* 2019) also, the AM processes are indeed gaining importance across various industries, including medical implant applications. The remarkable mechanical qualities and biological compatibility of ceramics make their use in medical implants particularly notable. Additive printing lets you fine-tune the porosity of medical implants, especially ceramic ones. This helps osseointegration, the process by which bone tissue joins with implant surfaces, and cell growth speeds up. (Marsico *et al.* 2022) lithium disilicate ceramics have long been used for dental restorations such as bridges, veneers, and crowns because of their exceptional properties. Lithium disilicate ceramics are resistant to chipping and breaking while biting or chewing due to their exceptional strength and fracture toughness. There is less chance of side effects in the mouth setting due to the fact that lithium disilicate is a very biocompatible material. (Wang *et al.* 2023) digital light processing (DLP) 3D printing technology has been successfully applied to manufacture thin dental porcelain veneers made of lithium disilicate glass ceramics and DLP can print objects with very high precision and resolution, allowing for the creation of thin veneers with accurate fit and marginal integrity as well the lithium disilicate materials used in DLP 3D printing can achieve excellent translucency, mimicking the appearance of natural tooth enamel even DLP 3D printing, the prepared thin lithium disilicate veneers can exhibit superior esthetics, with their translucent appearance blending seamlessly with the remaining natural tooth structure. This technology has streamlined the fabrication process while maintaining the high quality and lifelike appearance desired for dental restorations. (Schönherr *et al.* 2020) dentists can use glass ceramics and additive manufacturing based on lithography to make dental restorations, such as crowns. One of the most popular and extensively used 3D printing processes is lithography-based additive manufacturing (AM), which is sometimes called digital light processing (DLP), stereolithography, or just lithography. Glass ceramics processed using lithographic AM technology are the main subject of this study. The remarkable mechanical endurance, excellent precision, and outstanding optical properties (translucency) of glass ceramics make them ideal for use in dental applications. (Baumgartner *et al.* 2020) additive manufacturing (AM) based on lithography has the potential to surpass more traditional production methods like milling or casting when it comes to complex ceramic materials like dental glass ceramics. Ideal for dental restorations that need to precisely match each patient's unique anatomy, AM's layer-by-layer technique allows the simultaneous fabrication of numerous tailored components with difficult geometries. This advantage is made possible by parallelization and customization. Consequently, it is common practice to require the bespoke production of individual units or small numbers for many complex ceramics, particularly dental glass ceramics. (Zou *et al.* 2023) dental implants made of ceramic materials, such as silicon nitride, may lessen the risk of complications such as metal ion loosening and allergic reactions. Ceramic implants may also facilitate improved osseointegration, or bone integration, due to their greater biocompatibility compared to metallic implants. The capacity to 3D prints dental implants made of silicon nitride using DLP technology is a huge step forward; the capability will enable more customized implant designs that suit each patient's jaw better and may even improve the implant's ability to fuse with the jawbone. (Zhang *et al.* 2022) Furthermore, compared to the more traditional methods of casting or milling, additive manufacturing (AM) based on lithography may be more suited for sophisticated ceramic materials such as dental glass ceramics. Multiple distinct components with complicated geometries may be mass-produced at once using AM's layer-by-layer technique. Additionally, zirconia's superior mechanical and aesthetic qualities, combined with the benefits of additive manufacturing processes like vat photopolymerization and 3D printing, may make it possible to produce high-performance, bespoke dental implants made entirely of ceramic. (L. Zhang *et al.* 2024) the accuracy of multi-rooted root analog implants (RAIs) made from titanium and zirconia, manufactured using two different fabrication methods milling and 3D printing root analog implants (RAIs) are dental implant models designed to mimic the root portion of natural teeth, particularly for multi-rooted teeth like molars or premolars than the assess the influence of the material (titanium vs. zirconia) on the accuracy achievable with each manufacturing process the determination of which combination of material and fabrication method yields the highest accuracy for these complex dental implant models. (Zhao *et al.* 2021) using DLP 3D-printed zirconia ($ZrO_2$) ceramic components for dental implant applications are tested for quality using different heat treatment settings. The abutments that link dental implants to restorations or crowns are made of zirconia ($ZrO_2$) ceramic. Using DLP 3D printing technology, zirconia ceramic dental components may be customized to each patient's exact specifications, resulting in intricate designs and geometries. Compared to more conventional processes like milling or casting, producing these parts may be quicker and cheaper. (Lian *et al.* 2019) zirconia ceramic is a widely used material for dental restorations like crowns, bridges, and implant components due to its excellent properties stabilized zirconia ceramics, which typically contain yttria (Y2O3) or other stabilizing oxides, are commonly used for all-ceramic (metal-free) Zirconia all-ceramic dental

prostheses are primarily manufactured using computer-aided design and CAD/CAM techniques, which involve milling or subtractive machining of pre-sintered zirconia blocks. (Chaiamornsup *et al.* 2022) The potential advantages of using AM techniques like vat photopolymerization for fabricating casting patterns include the ability to create complex geometries, customization for patient-specific designs, and potentially improved efficiency compared to manual wax pattern creation and the technique is a common manufacturing method for partial fixed dental prostheses, such as bridges or crowns and the traditional lost-wax process, a wax pattern is first created to replicate the desired shape of the dental prosthesis. This wax pattern is then invested (encased) in a refractory material and heated, allowing the wax to burn out, leaving a mold cavity. (Sun *et al.* 2022) the discovering if various heat treatment settings impact the end quality of dental implant pieces made of DLP-printed zirconia ($ZrO_2$) is the primary objective of this study. Zirconia ($ZrO_2$) ceramic dental implant components are manufactured in this work using three-dimensional printing and Digital Light Processing (DLP). The effect of varying heat treatment parameters on the end quality of 3D-printed zirconia objects is also investigated in this study. These are the methods they use. The zirconia (ZrO2) ceramic abutment connects the implant fixture to the prosthetic crown or restoration. It plays an essential role in dental implant procedures. Dental components made of zirconia ceramic may take on complex geometries and forms thanks to direct light printing (3D printing). Compared to more traditional processes like milling or casting, making these parts could be faster and cheaper. (Ioannidis *et al.* 2020) research into the load-bearing capacities of different methods for fabricating ultrathin occlusal veneers is both necessary and intriguing since it might provide light on the longevity and possible uses of zirconia in dental restorations and 3D printing. The ability to generate and shape 3D-printed zirconia is impacted by material composition, post-processing processes, and printing circumstances, which are discussed in depth in the paper. (Ioannidis *et al.* 2022) the Vat Photopolymerization (VP) printing technique creates zirconia occlusal veneers. VP printing enables the creation of intricate features and complex geometries that are difficult or impossible to achieve with subtractive manufacturing methods like milling. This can use this design freedom to incorporate reinforcing features or optimized shapes, aiming to enhance the mechanical performance and load-bearing capacity of ultrathin veneers. Another significant advantage of this additive manufacturing technique is the ability to achieve a much tighter fit at the sharp incisal edge compared to milled veneers. (Rues *et al.* 2023) vat photopolymerization (VP) 3D printing of zirconia veneers allows for greater design freedom and shaping capabilities compared to milling. Specifically, you're highlighting that the fit at the sharp incisal edges is significantly tighter or more accurate with VP-printed veneers than with milled veneers and that VP printing can potentially achieve a superior marginal fit, particularly at challenging areas like sharp incisal edges, which are crucial for aesthetic and functional outcomes in veneer restorations. (Borlaf *et al.* 2019) mechanically robust ceramics have been developed because of recent advancements and increasing interest in photosensitive slurries for DLP printing. The use of digital light projectors and layer-by-layer photopolymerization in DLP enables the fabrication of ceramic parts with intricate details and high dimensional accuracy, making it appropriate for complex shapes and geometries. Additionally, additive manufacturing (AM) is a significant area of research and focus in the ceramics industry. (Chen *et al.* 2020) customized $ZrO_2$ all-ceramic teeth were created using photosensitive resin and DLP technology, a type of 3D printing. The thick $ZrO_2$ ceramics were produced by sintering the material for three hours at 1500°C. In terms of quality, $ZrO_2$ ceramics produced by DLP were on par with those made by conventional dry pressing methods. This study indicates that DLP and other additive manufacturing processes may make individualized $ZrO_2$ all-ceramic teeth that can be used for dental restorations. (Han *et al.* 2023) the debinding process involves removing the binder material (typically a polymer) from the green body (the as-printed part) before sintering. This step is crucial because any defects or flaws introduced during debonding can be carried over and amplified during the subsequent high-temperature sintering process, leading to defects in the final ceramic part as well Plasticizers are often used in ceramic processing to improve the flexibility and workability of the green body, making it less prone to cracking or defect formation during the debinding step when the binder is removed. By incorporating an appropriate plasticizer, you aim to produce defect-free green bodies, which can then be sintered into high-quality, dense ceramic parts without significant flaws or defects. (Li *et al.* 2018) traditional subtractive methods, which involve milling or machining a dental prosthesis from a solid block of ceramic material, remove a large amount of the ceramic block as waste during the machining process. This results in an inefficient use of materials, and the machining process frequently calls for a great deal of manual intervention, which can introduce variability and uncertainty in the final product's quality. (Zhu *et al.* 2023) also, the dental treatments using zirconia-toughened alumina (ZTA) ceramics are not without risk of stress-induced fractures and material degradation. The usual way of treating ZTA ceramics in clinics, using CAD/CAM processes, can create material waste, which could harm the economy and the environment. (Zhang *et al.* 2021) yttria-stabilized zirconia is a type of zirconia ceramic that has been stabilized in its tetragonal phase by the addition of yttria (Y2O3) and it is a biocompatible and mechanically strong material, making it suitable for dental implant applications. SLA is a 3D printing technology that involves selectively curing a photosensitive resin layer by layer using a laser or other light source it allows for

the fabrication of complex, customized shapes, and geometries, which is advantageous for dental implants that need to match the patient's specific anatomy. (Yang *et al.* 2021) despite its promise as a means for producing finely carved dental prostheses like dentures, stereolithography 3D printing of ceramics presents two significant obstacles in the dental field. SL-printed ceramic items often have worse mechanical qualities than those made using conventional farming techniques. The lengthy debinding procedure, which involves removing binders or chemicals used in the printing process, limits the clinical applicability of this technique. The study you cited focuses on using SL 3D printing to fabricate fluorapatite (FAP) glass-ceramic samples to overcome these difficulties. (Xiang *et al.* 2021) the study investigated zirconia samples fabricated via SLA in two different orientations: horizontal (H) and upright (U). A key finding was that the AM zirconia samples fabricated in the horizontal (H) orientation showed excellent dimensional accuracy. Evaluating these different orientations and properties is important for assessing the suitability of AM zirconia for potential clinical applications, where dimensional accuracy, mechanical strength, and other factors are critical. (You *et al.* 2021) on curved or sloped surfaces, the layer-by-layer nature of AM methods such as stereolithography may produce a "stair-step" impression, particularly at higher layer thicknesses. This stair-stepping may compromise the precision and surface smoothness of the finished prosthesis, which is why most AM systems offer layer thickness parameter modification. The acceptable degree of inaccuracy or surface roughness may vary depending on the particular kind of prosthesis and its clinical criteria. Using a thinner layer thickness might enhance surface quality and accuracy and lessen the stair-stepping effect, but it also comes at the expense of longer build periods. (Liu *et al.* 2018) demonstrated a reliable method for producing zirconia-based all-ceramic teeth was demonstrated using stereolithography and gel casting. The effects of zirconia particle size on stability, rheological properties, and sintering conditions were studied. (Wang *et al.* 2019) The in vitro study, conducted in a controlled laboratory environment, aimed to assess the "3D trueness" without clinical application or dimensional accuracy of the 3D printed zirconia crowns and the motivation was to investigate the potential application of 3D printing technology for fabricating dental ceramic restorations like crowns. (Wang and Sun, 2021) Such stereolithography is indeed a promising additive manufacturing technique for fabricating ceramic dental restorations with enhanced fracture resistance SLA involves selectively curing a liquid photopolymer resin layer-by-layer using a laser or other light source, building up the desired 3D structure. For ceramics, a ceramic-loaded resin is used, which is then subjected to a debinding and sintering process to remove the polymer and densify the ceramic component. (Wang *et al.* 2023) to make high-density and strong parts, and to see if stereolithography-based additive manufacturing could be used to make doped zirconia ceramics with specific color and strength properties for dental use, the study looked at making zirconia ceramic pastes with 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) as the base material and different amounts of iron (III) oxide ($Fe_2O_3$) ranging from 0 to 0.14 weight percent. This can prepare the ceramic pastes with a high solid loading of 58 vol%. (Shi and Wang, 2020) described the 3D printing of zirconia ceramic teeth using an inkjet printing method. It's an interesting application of additive manufacturing technology, and 3D printing in the dental field holds significant potential for creating personalised dental restorations and appliances. The ability to directly print high-strength zirconia ceramic could allow for the fabrication of precise dental components like crowns, bridges, implants, etc. (Arnesano *et al.* 2020) also, the 3D printing of glass-infiltrated alumina ceramics using a fused deposition modeling (FDM) process, rather than the inkjet printing of zirconia mentioned initially and extruding thermoplastic filaments loaded with different amounts of alumina powder. using these alumina-loaded filaments as feedstock for FDM 3D printing to produce "green" (unsintered) alumina parts. (Branco *et al.* 2020) also, an intriguing and pertinent research topic is assessing the appropriateness of nanostructured zirconia pieces produced using robotic additive manufacturing for dental applications. Robocasting and other additive manufacturing processes can produce intricate structures and geometries with specialized qualities, which makes them attractive for use in dentistry. For dental restorations and implants to survive the intense masticatory pressures and abrasive environment of the oral cavity, they must have sufficient mechanical strength, fracture toughness, and wear resistance. It would be essential to assess the nanostructured zirconia pieces' flexural strength, hardness, and fracture toughness. (Rodrigues *et al.* 2020) now developed zirconia pastes with high solid content for robocasting dental structures, without using organic binder additives and creating high solid load zirconia pastes for dental robocasting also maximizing zirconia content while maintaining proper rheological properties for robocasting, likely to achieve better final properties in the printed structures. (Kriegseis *et al.* 2022) the growing trends in dental implant technology and personalized care and dental implants are becoming more popular as well as the growing desire for patient-specific, esthetic implant-supported reconstructions also, direct Inkjet Printing, an additive manufacturing process, can produce accurate and individualized abutments. This method involves layer-by-layer printing of ceramic suspensions and the use of Direct Inkjet Printing for creating implant abutments is particularly interesting as it allows for precise, patient-specific designs. (Zhang *et al.* 2022) a significant shift in dental implant manufacturing, moving from traditional subtractive methods to more advanced additive techniques. The use of nano-particle ink-jetting to create zirconia implants with integrated lamellar surface topography is particularly noteworthy, as it

combines material choice (zirconia) with a specific surface structure designed to promote osseointegration. (Lüchtenborg *et al.* 2022) In the field of dental prosthetics, compare traditional subtractive methods with newer additive manufacturing technologies and it provides valuable insights into the viability of additive manufacturing for complex dental prostheses like four-unit FDPs. It may help inform dental professionals about the best manufacturing methods for achieving high accuracy in these restorations. (Chen *et al.* 2018) the use of 3Y-TZP (3 mol% Yttria-stabilized Tetragonal Zirconia Polycrystal) ceramics and digital dentistry is becoming more popular. AM is showing a lot of promise for dental restorations. Dental restorations frequently utilize this material due to its exceptional mechanical qualities and biocompatibility. The AM method blends cold isostatic pressing (CIP) and laser sintering of powdered material. This technique aims to increase the density and consistency of the green body. Combining AM technology (SLS) with the conventional ceramic processing technique (CIP) may enhance 3Y-TZP's qualities for use in dental applications. (Camargo *et al.* 2021) then the vat photopolymerization for ceramic parts. This is indeed a critical area in advanced ceramic manufacturing and This is an additive manufacturing process capable of producing high-performance ceramic parts it's known for its ability to generate intricate, high-resolution geometries by employing bimodal or multimodal particle size distributions to enhance packing density while maintaining flowability and exploring different dispersant and binder combinations to optimize rheology at high loadings than investigating the use of shear-thinning additives to aid recoating while maintaining suspension stability. (Wu *et al.* 2023) ceramic vat photopolymerization has the potential to transform the manufacturing of complex and functional ceramic parts and the technology allows for the creation of intricate geometries that are difficult or impossible to achieve with traditional ceramic manufacturing methods. This inherent aspect of the process can lead to anisotropic properties and visible layer lines. (Li *et al.* 2022) also, the development of advanced turbine blades with complex internal structures is crucial for modern high-performance aircraft engines, especially for fifth-generation and beyond fighter jets advanced engines operate at extremely high temperatures to maximize efficiency and thrust. This requires sophisticated cooling systems within the blades. Also, the double-walled and multi-layer designs allow for more effective distribution of cooling air throughout the blade then the hollow cavity structures helping minimize blade weight while maintaining strength. Complex internal geometries help manage heat distribution and thermal stresses. (Zhang *et al.* 2020) the fabrication of 3Y-TZP strengthened ZrO2 ceramics using digital light processing (DLP) additive manufacturing. This is an interesting application of advanced manufacturing techniques to produce high-performance ceramic materials. This study is important because it investigates the connection between the composition more especially, the amount of 3Y-TZP, and the properties that are produced when the ceramic is made using DLP. Making ceramics with DLP is a relatively new technique. It allows for the creation of complex geometries that might be difficult to achieve with traditional ceramic processing methods and the focus on density, shrinkage, microstructure, and mechanical properties provides a comprehensive view of how 3Y-TZP concentration affects the final product. (Westbeek *et al.* 2020) vat photopolymerization (VP), particularly focusing on particle-filled resins. This is indeed an important area of study in advanced manufacturing and most VP research has been empirical, focusing on experimental investigations also, these studies mainly look at the influence of process and material parameters. It moves beyond empirical observations to develop a more fundamental understanding of the VP process for particle-filled resins and a successful simulation model could allow for better prediction of final material properties based on input parameters also, with a detailed model, it becomes possible to optimize process parameters more efficiently than through trial-and-error experimentation. (Li *et al.* 2019) thus the interlayer bonding strength in ceramic parts manufactured by stereolithography also, Weak bonding strength between interlayers in stereolithography-manufactured ceramic parts and the weakness can seriously affect the overall quality of the parts. Interlayer bonding is often a limiting factor in the mechanical properties of additively manufactured parts, especially in ceramics, and the chemical bonds to strengthen interlayer adhesion could potentially lead to significant improvements in part quality and performance. The multi-exposure model provides a way to quantify the degree of chemical bonding, which is crucial for optimizing the process. (Westbeek *et al.* 2019) additive manufacturing of ceramics using vat photopolymerization and VP offers significant advantages for ceramic manufacturing, particularly in terms of resolution and reduced internal stresses. This could lead to the production of ceramic parts with complex geometries and improved mechanical properties. The addition of ceramic particles to the photopolymer resin introduces new variables and interactions that need to be understood and controlled. (Qian *et al.* 2021) provide deeper insights into the complex light-material interactions during ceramic stereolithography, which is crucial for process optimization and combining theoretical modeling, simulation, and experimental validation, the study offers a comprehensive view of the light scattering phenomena also, the research highlights key factors (particle distribution, input energy, refractive index) that affect light scattering, which can guide future process improvements. (Cai *et al.* 2022) the novel method for preparing silica glass using pressure-less spark plasma sintering (PL-SPS) in combination with stereolithography 3D printing and combining PL-SPS with stereolithography offers a new way to produce glass

parts, potentially opening up new design possibilities as well as the ability to rapidly manufacture glass parts could lead to significant time and cost savings in production. The capability to create complex structures expands the potential applications for glass components in various industries and the sintering temperature and dwelling time are the main factors affecting the process and are crucial for controlling and optimizing the manufacturing process. (Hossain and Lu, 2023) an alumina (Al2O3) ceramic and the growing importance of 3D printing technologies, particularly direct ink writing (DIW), in their fabrication and a clear need for advanced manufacturing techniques that can produce alumina ceramics with complex geometries and high precision. This demand is likely driven by the evolving requirements of industries such as electronics, aerospace, and medical devices and traditional ceramic forming techniques (like slip casting, tape casting, or pressing) are struggling to keep up with the increasing complexity of part designs. This limitation is pushing the industry towards more flexible manufacturing methods. (Duarte and Phark, 2024) the modern fixed restorative dentistry makes use of a diverse array of restorations, each with its grade, thanks to developments in digital technology and materials. In this work, four distinct ceramic materials to microhardness and surface roughness testing after three separate manufacturing procedures. Depending on the materials and manufacturing processes used, the surface qualities of restorations might vary. Therefore, while deciding on a restoration type as a therapeutic intervention, it is important to take these distinctions into account. (Duarte and Phark, 2025) the mechanical strength and wear rates of 3D-printed CRCs are lower than those of CAD-CAM CRCs and conventional ceramics, but these materials provide more customization options. Also, it's hard to determine when to use these materials in clinical settings because the guidelines for colorectal cancer (CRC) are unclear, and the ADA categories do not separate CRCs from ceramics. (Fouad *et al.* 2024) this method of investigates the impact of reinforcing heat-cured acrylic resin dentures with nano-ceramic aluminum oxide ($Al_2O_3$). A weight percentage of 1, 3, 5, and 10 of $Al_2O_3$ was added to the PMMA in order to enhance it. Just to give you an idea, PMMA may also be made without adding any ceramic. By observing changes in color, density, hardness, and strength under compression, the researchers were able to determine how the addition of $Al_2O_3$ nanoceramic affected the mechanical and physical characteristics of the PMMA resin and its composites. (Alghauli and Alqutaibi, 2024) this method achieves a very thin coating, about 0.1 to 0.2 mm thick. Additionally, this method effectively stops caries from developing because of the accuracy it provides, which enables exceptional adaptation and adherence. (Spina and Morfini, 2024) a growing number of people are turning to additive manufacturing to create products and parts from high-performance materials. The filament-based 3D printing of ceramics has gained a lot of interest due to the recent advances in ceramic material extrusion technology. (Campos *et al.* 2025) also, the composites of alumina-toughened zirconia (ATZ) with 10% $Al_2O_3$ whiskers were made and studied using glass infiltration. The XRD patterns of the control group only showed peaks for tetragonal zirconia and α-alumina, but the glass-infiltrated groups did not show any peaks for solid materials. Compared to regular ATZ, ATZ containing alumina whiskers showed significantly higher fracture toughness and characteristic strength. (Sivaraman and Bharathiraja, 2025) the 3D printing using aluminum ceramic nanoparticles is a viable option for many biomedical device designs, including blades, sutures, dental equipment, and more. Ceramics and other nonmetal materials serve as heat sources in cutting tools, medicines, biotechnology, and abrasive applications. A considerable paradigm shift has occurred due to the principal uses of ceramic powder, which are most prominent in the dental, skeletal, and biological domains. (Panyasuksri *et al.* 2025) more people are opting for resin-bonded fixed dental prostheses (RBFDPs), which are less intrusive, to replace lost front teeth. Finding out the different bridge designs influenced success rates and failure risks of anterior ceramic RBFDPs was the goal of the systematic review and meta-analysis. (Bertoni *et al.* 2024) a high-performance ceramic material that can only be made via computer-aided manufacturing (CAM) techniques, zirconia has skyrocketed in popularity because of its mechanical strength, biocompatibility, aesthetics, and flexibility. After getting the tooth ready with the right glue, the enamel was smoothed with 40-micron aluminum oxide, the tooth was treated with 37% orthophosphoric acid, and the zirconia veneers were attached using a rubber dam. (Saini *et al.* 2024) the dental cosmetic crowns made of alumina and yttrium-stabilized zirconia (YSZ) are the most popular. This study thoroughly examined the optical and dynamic stability, band structures, refractive indices, and mechanical characteristics of alumina and YSZ.



**Fig. 1: Ceramic teeth**

## 2. CERAMIC MATERIAL FOR THE AM PROCESS

The literature on AM ceramic dental restorations uses five of the seven classifications described by ISO 17296e2, although the inconsistent and non-standardised nomenclature sometimes requires explanation. The biocompatibility, attractive aesthetics, and exceptional mechanical strength of ceramics contribute to their increasing use in dentistry. One of the applications of AM technology in dentistry is the fabrication of ceramic dental restorations.

Ceramic materials like zirconia and lithium disilicate often form dental crowns and veneers. In addition to looking and feeling much like real teeth, these restorations are very resistant to wear and discolouration and have a good compressive strength. Zirconia or alumina ceramic implants are used as an alternative to titanium implants. Ceramic teeth (Fig. 1) are biocompatible and offer excellent esthetic results, particularly in cases where the implant is visible in the smile zone. However, they are more brittle than metal alloys and may require special handling and bonding techniques, and the development in ceramic materials and manufacturing techniques has led to improved strength, esthetics, and bonding capabilities of ceramic dental restorations. In this process, the material jetting is one of the best processes to make the teeth in AM technology because the process is simple that requires only aluminium oxide powder.

### 2.1 Vat Polymerisation (VP)

Vat polymerisation is a type of three-dimensional AM that makes use of a liquid-based photopolymerization process. This process requires a construction platform and a controlled light source to cure liquid photopolymer resin in layers. A controlled light source, such as a laser exposes and cures the resin in a pattern that fits the cross-section of desired 3D item. Ceramics used in dentistry make use of the technologies detailed .Ceramic VP involves combining ceramic powders with liquid photopolymers to form a suspension. Digital light processing is more efficient than SL. Common materials used in dental additive manufacturing include zirconium oxide, aluminium oxide, glass-ceramics, and silicon nitride. Fig. 2 shows the vat polymerization method to obtain the product using laser process. These materials are often utilized in dental implants and restorations because of their high strength, fracture toughness, and biocompatibility. Nano alumina, which mixes glass and ceramics, is a material that has both functional and ornamental applications.

The additive manufacturing procedures, like stereolithography and selective laser sintering, enhance precision while decreasing waste. The AM method and post-processing steps used could alter the unique properties and functionalities of material. The size of the laser spot, the thickness of the layers, and the positioning accuracy of the AM machine are all factors that might affect how well the printed object matches the digital model. Stereolithography and other photopolymer-based AM processes may have their cured geometry produced to varying degrees according the extent of exposure to the light source as well as its wavelength and intensity. Light scattering within the resin or powder composition can cause over- or under-curing, thereby affecting the dimensional accuracy of the printed part. Precision refers to the consistency and repeatability of measurements or prints within a given set. Environmental variables, such as temperature and humidity, may also impact the reliability of the printing process, resulting in differences in accuracy. The accuracy of the printed components is also susceptible to process variables, including laser power, scan speed and layer thickness. The raw materials (such as powder or resin) composition or distribution might also alter as a consequence of these modifications. The constant and correct production of dental restorations, implants, and other medical equipment using AM technologies relies on very precise and accurate processes. Manufacturers often conduct extensive testing and calibration to optimise these parameters and ensure the desired level of accuracy and precision in their AM processes.

Digital Light Processing additive manufacturing produces $ZrO_2$ crowns with Vickers hardness and fracture toughness comparable to those made by traditional dry pressing. This finding is significant, as it confirms that DLP-printed dental restorations can match the strength and durability of conventionally manufactured ceramics, potentially enabling more precise and efficient production without compromising mechanical performance.

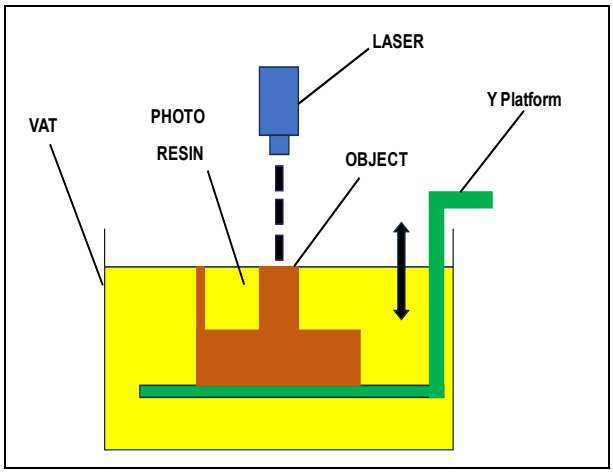



**Fig. 2: Vat polymerisation**

### 2.2 Material Extrusion (ME)

Ceramics, being biocompatible and extremely strong, find application in dental restorations

and implants due to their resistance to fractures. Alumina nano powder combines the aesthetic and technical qualities of ceramics and glass. Fig. 3 shows the process of material extrusion in which a wire material is melted, filled in the mould and shaped.

Ceramic, PLA, ABS, and PETG are common thermoplastic filaments used in ME, along with high-performance polymers like PEEK. The filament is melted and placed on a construction platform along a preset route after being fed into the extruder from a spool. The platform travels vertically while the nozzle builds the item layer by layer in an exact horizontal pattern. Because of its adaptability, cheap equipment cost, and user-friendliness, material extrusion has gained immense popularity. Prototyping, low-volume manufacturing, teaching, and the creation of bespoke components are common uses for it. Sintering and debinding are two examples of the complicated post-processing operations that have recently made use of metal and ceramic filaments. Paper speed, layer height, and nozzle diameter are just a few of the several variables that impact ME's surface polish and resolution. Anisotropic mechanical properties and visible layer lines are rare side effects of ME, even though it can provide very precise dimensions. After printing, it is common to need to remove the support structures for pieces that hang over.

## 2.3 Material Jetting (MJ)

Material jetting (MJ) is an alternative method of additive manufacturing that deposits the built material like material extrusion; however, it uses a different approach. The method applies the construction material layer by layer, using tiny droplets instead of a continuous thread. The droplets are typically dispensed from print heads with multiple nozzles or *via* printheads that can eject droplets on demand. Also, the build materials used in MJ are typically photocurable resins or waxes that can be melted and deposited as droplets. Unlike ME, where the feedstock requires specific viscoelastic properties for extrusion, MJ feedstocks must have suitable jetting properties, such as appropriate viscosity and surface tension to form stable droplets. In MJ, each layer is formed by depositing droplets of the building material in the desired pattern. The droplets then coalesce and solidify (either through UV curing or cooling, depending on the material) to form the solid layer. Both ME and MJ require support structures for overhanging geometries or internal cavities. These supports are typically printed using the same or a different sacrificial material.

Material extrusion uses a nozzle-extrusion method for viscoelastic feedstock, while MJ employs a droplet-based method for building material, offering higher resolution, material choice, and complex geometries. Both methods are additive manufacturing technologies, differing in material deposition mechanism, feedstock requirements, and processing range. Build platforms are heated or UV-treated immediately after droplet deposit.

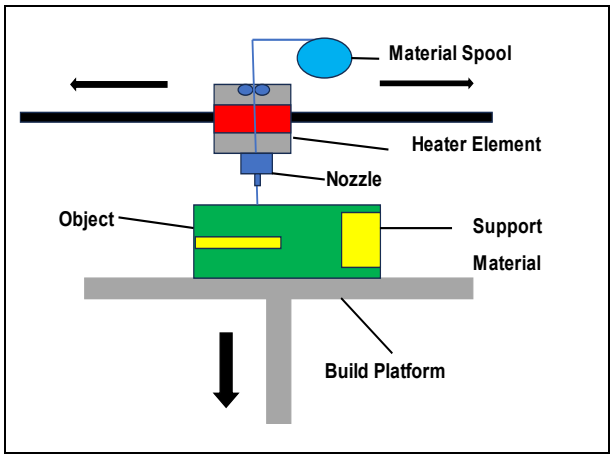



**Fig. 3: Material extrusion**

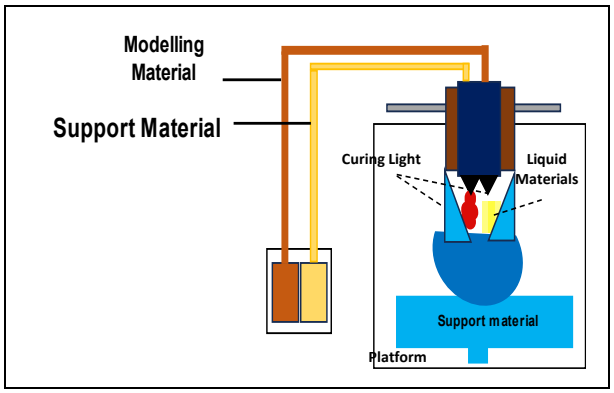



**Fig. 4: Material jetting**

Additional post-processing steps, such as sintering or debinding, may be required to remove the wax binder or liquid carrier after the jetted ink has cured or solidified. The MJ has the potential to provide outstanding resolution by creating picoliter-sized droplets. The solvent-based MJ inks allow for the production of green components with little organic matter. The nozzle diameters range from 10 to 60 µm. This improves sintering and reduces shrinkage when subjected to heat or densification. Fig. 4 shows the material jetting process, in which the liquid material is deposited, cured using a light source and solidified into the desired shape. The curing occurs from above, while support material is applied at the base to prevent sticking and ensure easy separation from the build platform.

Material jetting is an effective AM technology and direct inkjet printing is a key component of MJ. This method achieves printing by simultaneously depositing droplets of several materials. A feature of MJ is the ability to control the deposition of different materials, resulting in the formation of functionally graded materials (FGMs) These FGMs can be used for specific applications by displaying gradients in functional properties, such as

mechanical, thermal or electrical properties. Voxel-wise microstructure manipulation enables localized material distributions, enhancing properties like strength, hardness, and thermal conductivity.

It is possible to exert fine-grained control over the microstructure and material composition of individual voxels in MJ because deposition happens at the voxel level, which is like a 3D pixel. This is the main differentiating factor between MJ and other AM techniques that deposit components sequentially. Changing the microstructure and composition at the voxel level and concurrently depositing several materials opens up new opportunities for sophisticated manufacturing. Insufficient heating of the build platform or printed layers would prevent the hardening of the ceramic particles and the evaporation of the liquid carrier. For the construction of dental bridges, the MJ system deposits ceramic ink droplets selectively according to the design. The continued printing is achieved by covering the areas with carbon black support material. For instance, additional post-processing steps, such as using heat or chemicals, may be necessary to remove the carbon black support material. A debinding method is used to eliminate any remaining organic components or binders from the ceramic ink. By putting the 3Y-TZP ceramic material through high-temperature sintering, which makes it denser and stronger, MJ technology can fabricate intricate dental restorations out of ceramic ink. Using an aqueous-based ink makes the process eco-friendly since it is free from organic solvents.

## 2.4 Binder Jetting (BJ)

A thin layer of powder material is spread across the build platform, and a liquid bonding agent (binder) is selectively deposited onto the powder layer according to the cross-sectional data of the part being built. Also, the binder joins the powder particles together where it was deposited. The build platform is lowered, a new layer of powder is spread on top, and these steps are repeated until the entire object is built. After printing, the object is typically cured to strengthen the bonds and remove excess powder. A binder can jettison a variety of materials, including polymers, metals, and ceramics. It is recognized for its relatively quick turnaround time and its ability to produce full-color objects using colored binding inks. Spraying the binder over each layer of powder starts the drying portion of the printing process. The curing stage strengthens the bond between the binder and the ceramic particles, increases cross-linking, and enhances the green strength of the printed components before they go through further processing steps like sintering and debinding. The parameters affect the product quality, dimensional accuracy, and surface polish, while the interaction between the binder droplets and ceramic powder determines its resolution and detail. Binder jetting can handle nearly any powdered material. Due to its customizable binder and post-processing techniques, binder jetting is a versatile material treatment technology that finds significant usage in a range of industries, including consumer items, automotive, aerospace, and medical.

In binder jetting, inconsistent material distribution and weak bonding between particles can lead to reduced green strength, resulting in varied mechanical properties across the printed part and defects that compromise the structural integrity and performance of ceramic components. The inkjet head design is also improved, which can lead to more precise deposition of the binder, potentially improving density and uniformity, and the sintering can help reduce porosity and increase density. Even higher-quality powders can improve the overall printing process and final product characteristics. This technology for ceramics is still in its early stages. The challenges mentioned are significant hurdles that researchers are actively working to overcome. Fig. 6 shows the components of binder jetting equipment.

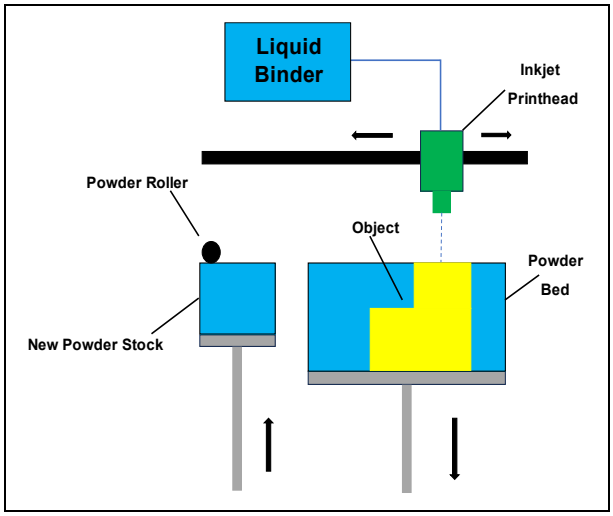



**Fig. 5: Binder jetting**

The potential of binder jetting (BJ) for ceramics, including its ability to create complex geometries and support mass customization, makes it a promising focus for ongoing research. Advancements are needed in refining printing parameters, improving post-processing techniques, and developing reliable methods for real-time quality assessment and control during the printing process.

## 2.5 Powder Bed Fusion

Laser melting and sintering are the two most often used laser-based PBF techniques. Powder bed fusion uses thermal energy from lasers or electron beams. Selective Laser Melting (SLM) is a preferred option for metal and ceramic materials because it produces denser parts with better mechanical properties than Selective Laser Sintering (SLS). Fig. 6 illustrates the PBF process to fill the bed layer by layer. In this process, the roller

spreads the material during each layer formation as the build bed moves downward after each printed layer. Additionally, the machining and subsequent manufacturing of ceramic teeth involve various methods and ceramic materials.

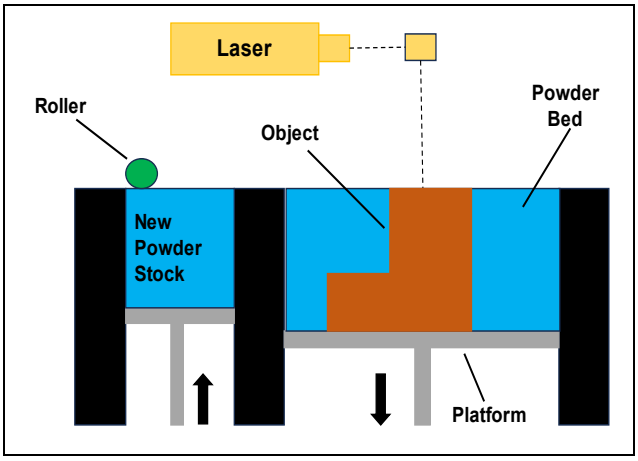



**Fig. 6: Powder bed fusion**

### 2.5.1 Selective Laser Melting

Selective Laser Melting produces denser objects with superior mechanical properties due to complete melting of powder particles. A model is first created in CAD before being sent to the SLM machine. The 3D model is then sliced into 2D layers, which are transmitted to the SLM system. Each 2D slice is treated as a cross-section of the component, and powder is selectively melted by the laser based on each slice. Metals commonly used include stainless steel and superalloys based on nickel, titanium, and aluminium nanopowders. By using high-energy laser beams, SLM eliminates the need for bonding chemicals and complex components are directly formed within the powder bed. Time and energy are saved during solidification, which is especially advantageous for ceramic materials as it removes the need for densification treatment.

This technology offers significant advantages in the production of intricate parts, particularly those involving complex metal components. This is due to its exceptional accuracy and ability to rapidly produce components with near-net shapes. Although it is challenging to produce high-performance ceramics like $ZrO_2$ and $Al_2O_3$ directly from metal powder without expensive moulds and little post-processing, this method offers fast turnaround times for small batches. The use of SLM allows production of interior structures that would not have been possible with traditional methods while also reducing material waste. Ceramics are known for their excellent resistance to high temperatures but are generally more susceptible to thermal shock compared to metals. This is due to their low thermal conductivity and brittleness, which make them less able to absorb and dissipate sudden thermal stresses. Unlike metals, which can deform plastically, or polymers, which may have higher thermal shock resistance at low temperatures, ceramics tend to fracture when subjected to rapid temperature variations.

Yttria-stabilised $ZrO_2$ made using stereolithography has a density of 56%, but is not viable for utilisation due to its poor mechanical and density properties. Many oxide ceramics have poor sintering capabilities because they absorb very little laser light, making the transfer of energy to ceramic powders difficult. The use of TiC as an absorbance enhancer has significantly enhanced the properties of 8YSZ, and notable advancements have been made in ceramic SLM to support this development. This technology has successfully produced 8YSZ components with a relative density of 97%, even in the absence of post-treatment. This makes them just as robust as traditional 8YSZ. Adding TiC to the powder mix likely increases the total energy absorption, as zirconia alone has low absorption efficiency at the wavelengths used by most SLM systems. When absorption improves, processing at lower laser power reduces thermal strains and leads to more uniform heating of the powder bed. This shows that it is possible to make high-quality ceramic parts directly, and it makes complex 8YSZ parts useful situations, like solid oxide fuel cells and thermal barrier coatings. It also provides a blueprint that other ceramic materials may use to improve their SLM processes. Selective laser melting has run into problems in dental ceramic applications because of a dimensional issue. Printing dental restorations using SLM puts the printed structural integrity of ceramics at risk because of its inability to produce precise and complicated shapes and thus, not meeting the strength requirements needed for dental applications.

### 2.5.2 Selective Laser Sintering

Selective Laser Sintering (SLS) is a 3D printing process that uses high-powered lasers to sinter or bind the powdered material together into a solid structure. The ceramic powders are mixed with binders or additives, and the laser melts the binder, which then acts to sinter the ceramic particles. It generally operates at lower temperatures due to the low melting point of the binder. The ceramic powder is evenly spread in each layer. A high-power laser like, the $CO_2$ laser and materials like plastic, metal, ceramics, and glass are used in the SLS process.

Post-processing procedures, including the application of a hot binder to eliminate fragments, are necessary for ceramic components created with SLS. Careful monitoring is required to prevent warping or breakage during the removal of unfused particles from both the surface and internal cavities. To achieve this, methods like chemical treatments, ultrasonic cleaning, brushing, and compressed air are used.

Selective laser sintering can work with various ceramic powders, including alumina, zirconia, silicon nitride, and hydroxyapatite (for biomedical applications). Also, this process produces minimal wastage where complex moulds or tooling are avoided.

In this process, a combination of a polymer binder and ceramic powder ($Al_2O_3$ in this case) is used, where polymer acts as a temporary binder to hold the ceramic particles together. Also, SLS produces green bodies with randomly distributed pore structures, which are beneficial for applications requiring controlled porosity.

The SLS parameters can affect the final structure and allow for tuning of properties like porosity, density, and strength. This technology has been widely investigated for complex ceramic structures. SiC has low thermal expansion and strong thermal conductivity, $ZrO_2$ has high strength and toughness, $SiO_2$ is frequently used in high-temperature applications, and $Al_2O_3$ has excellent hardness, wear resistance, and thermal stability. These developments demonstrate the adaptability of SLS for ceramic processing and make it possible to create complicated forms that are difficult to achieve using traditional methods.

Fig. 7 shows the tooth implant (a), tooth crown (b) and teeth bridge (c). Implant looks like natural tooth and the bridge helps to assemble an even and good look for the teeth line. Good powder flow ensures consistent packing density throughout the part, allowing the fine powders to fill small gaps and achieve intricate and finer details. This minimises the risk of voids or inconsistencies in the final component. The formation of green bodies at lower temperatures improves component integrity during the build process and can enhance both resolution and surface finish. The laser selectively melts the binder, which then flows between the ceramic particles to hold them together.

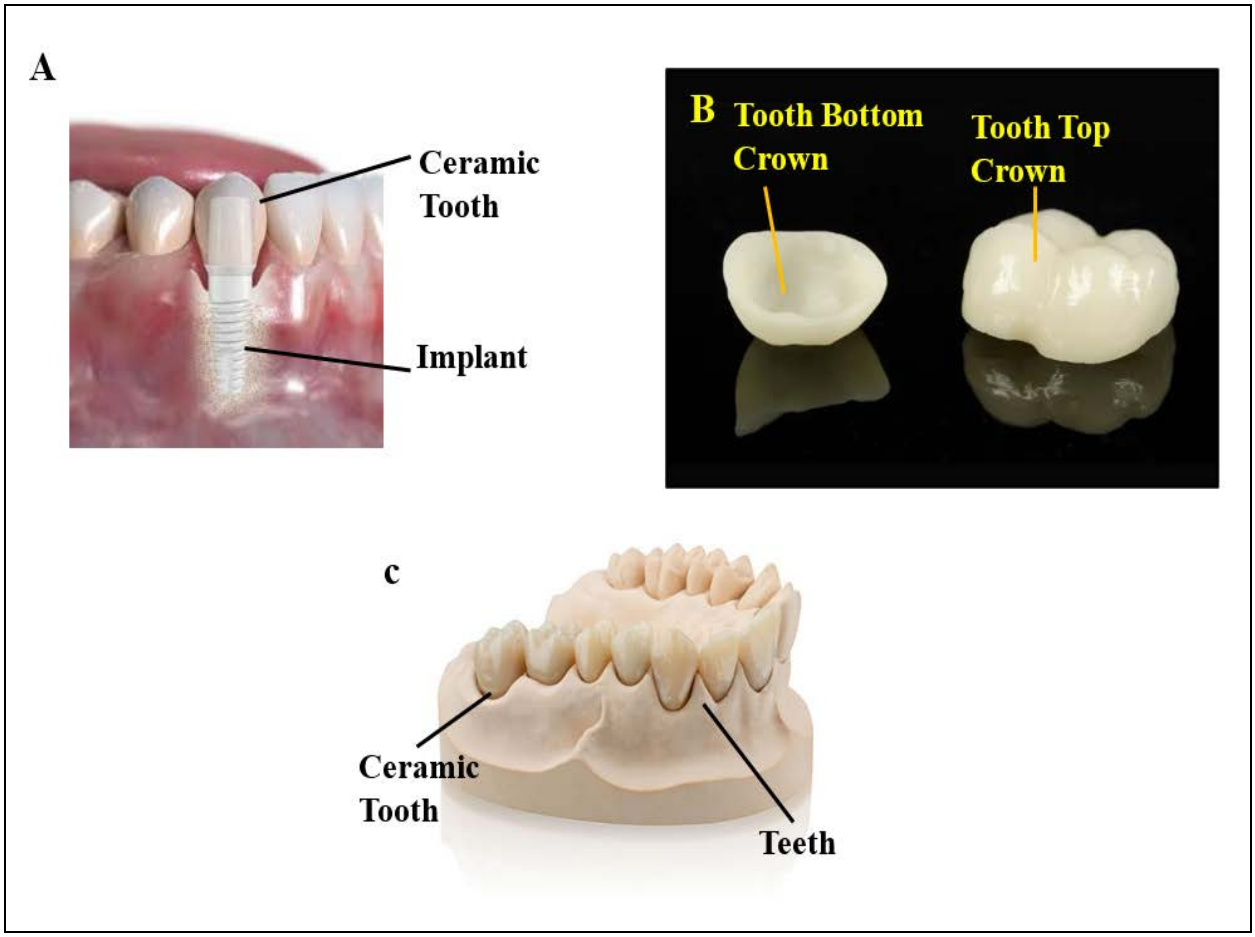



**Fig. 7: (a) Implant, (b) Tooth crown, and (c) Teeth bridge**

The SLM and SLS processes worked with 3Y and 3YTZP (3 mol% Yttria-stabilised Tetragonal Zirconia Polycrystal) materials to make the dental restoration. Because of this, the process of fabricating dental restorations may advance. When compared to SLM, SLS offers more accuracy and better surface quality. A modern alternative to traditional dental fillings, alumina ceramic teeth are both strong and aesthetically pleasing. These ceramics, which are composed of very pure aluminum oxide, are safe to use for long periods of

time within the human body since they are biocompatible. Alumina ceramic dental work involves various techniques and components, as seen in the figure.

Fig. 7a depicts a dental implant, which consists of a metal post embedded in the gum and a ceramic crown that is fastened to it. This setup replaces both the visible portion of a tooth and its root. Both the top and bottom views of the ceramic crown are shown in Fig. 7b. These crowns are made with excellent attention to detail so that they fit and seem completely natural. Their translucence and lifelike look mimic those of real teeth. The arrangement of ceramic teeth in a dental model is shown in Fig. 7c. Due to their strength, durability, and resistance to oral conditions, alumina ceramics are widely preferred.

These materials, combined with the SLS method yield promising results for dental applications. The SLS process improved the material's mechanical properties and density compared to the SLM method.

## 3. CERAMIC MATERIAL FOR DENTAL APPLICATIONS

The usage of bioceramics is on the rise in bioengineering, especially in the fields of dentistry and orthopaedics, due to their biocompatibility and outstanding mechanical properties. Scientists are looking at the possibility of making ceramic parts for use in dental restorations. Commonly used ceramics include nanomaterials like $ZrO_2$ and $Al_2O_3$, as well as glass ceramics and ceramic composites. Table 2 shows the mechanical properties of ceramic materials used in dental applications.

### 3.1 $ZrO_2$

$ZrO_2$ (zirconium dioxide, or zirconia), a biomedical-grade oxide bioceramic has exceptional mechanical properties such as high fracture toughness, flexural strength, and compressive strength, making it a popular 'ceramic steel.' $ZrO_2$ indeed has important industrial applications, but its polymorphism poses challenges. $ZrO_2$ has three main crystalline phases that are all monoclinic (room temperature to ~1170°C), tetragonal (~1170°C to ~2370°C), and cubic (above ~2370°C to melting point). The transitions between these phases involve volume changes, which can cause stress and cracking in the material. These potential failures in high-stress or high-temperature applications restrict the use of pure $ZrO_2$ in applications requiring high-temperature stability or mechanical strength. Doping with stabilising agents (e.g., yttria, magnesia, or ceria) to maintain the cubic or tetragonal phase at room temperature created a new composite material with controlled grain sizes and the microstructure. The mechanical strength of $ZrO_2$ nanomaterial is enhanced by its ability to undergo a phase transformation from tetragonal to monoclinic crystal structure under stress, thereby improving fracture toughness.

Phase transitions in $ZrO_2$ behaviour are crucial for applications, as they can cause stress and failure. Pure zirconia is stabilised or alloyed for high-temperature applications to maintain a single phase. The reversible phase transitions in $ZrO_2$, especially between the monoclinic and tetragonal phases, cause significant volume changes that can lead to structural failure. This is a crucial limitation for many applications. Common dopants include $Y_2O_3$ (yttria), CaO, MgO, and $CeO_2$. These create oxygen vacancies in the crystal structure, stabilising the tetragonal or cubic phase at room temperature. Also, the nanostructured $ZrO_2$ can exhibit phase stability due to surface energy effects, and the critical grain sizes can be maintained to preserve the tetragonal phase. Zirconia-toughened alumina finds widespread usage in biomedical applications due to its ability to form composites with better properties when combined with other materials. Applying pressure could stabilise the tetragonal phase in some instances. More applications are possible as a result of the enhanced mechanical characteristics, chemical inertness, and biocompatibility of pure nano $ZrO_2$.

3Y-TZP (3 mol% yttria-stabilized tetragonal zirconia polycrystal) is indeed the most common formulation for biomedical applications, and other concentrations like 5Y-TZP or 8Y-TZP exist for different applications as well as the mixture of polymorphs. The presence of multiple phases contributes to the material's unique properties. The metastable tetragonal phase, with its high fracture toughness, flexural strength, and mechanical performance, plays a crucial role in transformation toughening processes. For long-term stability and resistance to corrosion and wear, the biocompatibility of the metastable tetragonal phase is essential for its utilisation in the human body.

Zirconium dioxide nanopowder is utilised in advanced dental restorations, producing dental prosthetics such as crowns, bridges, veneers, implants, and abutments. These restorations offer comparable mechanical properties to traditional ones and meet clinical dimensional accuracy requirements, making them a viable and potentially superior alternative. The nano of $ZrO_2$ is mostly used in dental applications but the zirconia is expensive material compared to alumina and glass ceramics.

### 3.2 $Al_2O_3$

$Al_2O_3$, a popular ingredient in ceramics, is a distinctive solid aluminium oxide. It has exceptional chemical, mechanical, thermal, and electrical properties, as well as hardness, high melting point, and is inexpensive. Addition of zirconium oxide, chromium oxide, or magnesium oxide to $Al_2O_3$ increases the tensile

and fracture strength of the material. The porosity, grain size, and sintering process of $Al_2O_3$ can be regulated to suit the need by adding additives.

### 3.3 Glass-ceramic

Glass-ceramics, with their crystalline reinforcement and optical translucency, are ideal for stylishly replacing unsightly dentures. By altering the type and composition of the crystal, its properties including translucency and strength, can be utilised for specific dental applications. Glass ceramics offer numerous varieties with varying reinforcement types and crystal content rates (17-70 vol%), allowing for customization of properties for various dental applications, where different restorations require different strengths, aesthetics, and other properties.

Glass-ceramic materials, including leucite, lithium disilicate, and fluorapatite, are commonly utilised in clinical practice, especially in dentistry. Fluorapatite glass ceramic has a bending strength of 70-120 MPa, demonstrating its unique mechanical property suitable for various dental applications.

Researchers are investigating dental glass-ceramic AM, which uses VP techniques, for dental restorations such as crowns and veneers. Glass-ceramic materials can improve accuracy and material qualities compared to traditional procedures. They help to build the product with more shine and a glassy finish. Glass ceramics can withstand high temperatures and exhibit controlled surface roughness. They have revolutionized dental materials through their exceptional combination of strength, biocompatibility, and aesthetics. With ongoing advancements in digital manufacturing and material science, their role in restorative dentistry continues to grow significantly.

Ceramics have an important role in both restorative and prosthodontic dentistry. Majority of its applications use CAD/CAM software for dental restorations, like crowns and bridges.

## 4. DENTAL RESTORATION by CERAMIC ADDITIVE MANUFACTURING

Dental restoration involves replacing damaged or missing teeth using removable and fixed prosthetics. Ceramic materials, known for their versatility and biocompatibility, are commonly used in restorations such as crowns and onlays.

### 4.1 Crown and Bridge

Dental crowns are custom-made restorations that safeguard damaged teeth, bolster weak ones, and rehabilitate their shape, size, function, and appearance. They are crucial in restorative dentistry, offering functional and aesthetic benefits. The precision of their manufacture ensures they blend seamlessly with the patient's other teeth.

**Table 2. Mechanical performance of ceramic materials in dental restoration**

| Mechanical properties of the primary ceramic materials | | | | | |
|---|---|---|---|---|---|
| | **Mechanical Performance** | **Main applications** | | **Mechanical Performance** | **Main applications** |
| $ZrO_2$ | Modulus of elasticity: 210GPa<br>Flexural strength: 300e1200 MPa<br>Fracture toughness: 5e20 MPa m1/2<br>Hardness: 5e15 GPa | Crowns, Bridges, Veneers, Implants, abutments | $ZrO_2$ | Modulus of elasticity: 220GPa<br>Flexural strength: 900e1200 MPa<br>Fracture toughness: 5e20 MPa m1/2<br>Hardness: 5e15 GPa | Crowns, Bridges, Veneers, Implants, abutments |
| $Al_2O_3$ | Modulus of elasticity: 340GPa<br>Flexural strength: 300e600 MPa<br>Fracture toughness: 3.5e20 MPa m1/2 | Crowns, Bridges, Implants, abutments | $Al_2O_3$ | Modulus of elasticity: 380GPa<br>Flexural strength: 400e600 MPa<br>Fracture toughness: 3.5e20 MPa m1/2 | Crowns, Bridges, Implants, abutments |

Dental bridges are dental restorations that replace missing teeth in restorative dentistry. They are fixed, comfortable, and blend naturally with existing teeth, allowing for normal eating and speaking. They consist of artificial teeth anchored to natural teeth or dental implants, promoting oral health. The bi-layered design structure uses high-strength ceramics like zirconium dioxide or aluminium oxide for restorations, while a glass-ceramic veneering layer mimics natural teeth. This approach ensures strong, structural integrity, load-bearing capacity, and aesthetic appeal, allowing dentists to create restorations that meet both functional and aesthetic demands.

### 4.2 Inlay and Outlay

Dental glass-ceramic AM is studying crowns and veneers made of glass ceramics based on fluorapatite and lithium disilicate. These materials may have improved material properties and precision when treated using vat photopolymerization procedures. Improved materials and techniques make them suitable alternatives. Getting an inlay or outlay typically involves multiple dental visits. During the first visit, dentist prepares the tooth, takes an impression, and places a temporary restoration. The inlay or outlay is then custom-made in a dental lab and bonded to the tooth during subsequent visit. Fig. 8 a shows that the ceramic inlay and outlay help to protect the inner and outer layer of teeth and 4(B) shows the natural teeth and ceramic teeth arranged in the human mouth to complete the teeth line and it shows the fine design helped to cover the complete teeth set by the teeth bridge.

Inlays and outlays are two types of dental restorations that repair decaying or fractured teeth using glass ceramics and resin. The use of additive manufacturing technology to create wax patterns for pressed inlays and outlays, 3D printing and mould creation offers advantages over traditional fabrication processes in terms of precision, personalisation, and speed.

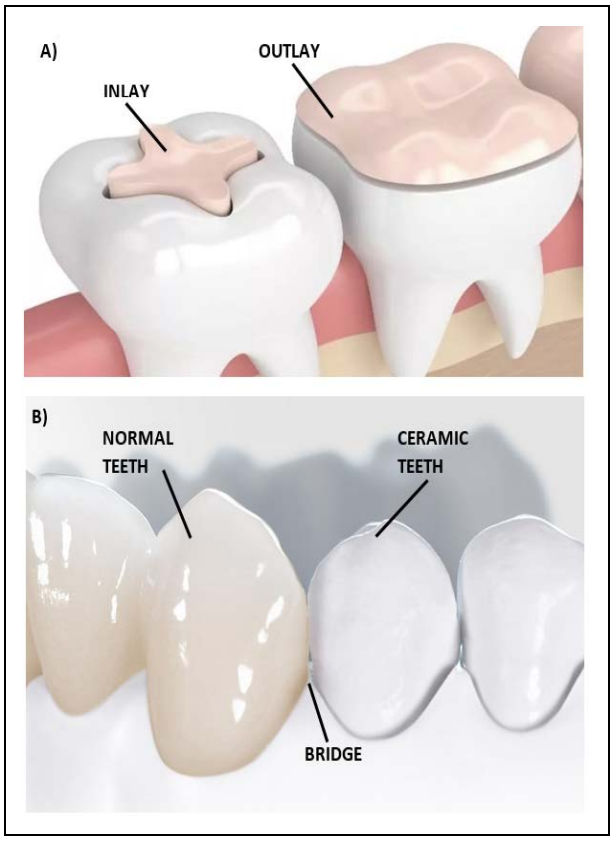



**Fig. 8: (a) Inlay and outlay and (b) Normal teeth with ceramic teeth**

### 4.3 Implant

Dental implants have been a reliable method for replacing missing teeth for over five decades. They are surgically placed into the jawbone, providing a secure foundation for prosthetic teeth, bridges, or dentures. An abutment, a connector piece, serves as a bridge between the implant and the artificial tooth or dental restoration. The implant fixture connects to the artificial tooth, bridge, or denture, enabling natural chewing function. The abutment is attached after healing and integrates with the jawbone. Dental implants are designed to withstand biting forces and fluids, and materials like titanium are biocompatible, preventing adverse reactions.

Additive manufacturing technology simplifies zirconia implant fabrication, making them a more cost-effective and biocompatible alternative to titanium. With ongoing research and clinical evidence, zirconia implants could become a popular choice for patients with metal allergies or aesthetic concerns. Dental implants, like crowns, bridges, and veneers, are surgically placed within the jawbone, requiring specific properties for successful tooth replacement. Osseointegration is crucial for implant stability and to withstand chewing forces, preventing failure.

## 5. FUTURE SCOPE

### 5.1 Forming Quality

Higher print efficiency in AM technologies often comes with reduced accuracy, resolution, quality, and mechanical properties. Striking the right balance between print quality and efficiency is essential for manufacturers and users, allowing them to optimize performance according to specific application needs

For example, using smaller nozzles can increase accuracy but also lead to longer print times and reduced energy consumption. Increased ceramic particle content in slurry increases solid loading, requiring consistent flow characteristics and careful adjustment of dispersants or additives. This leads to less shrinkage during sintering and increased solid loading.

The development of sintering involves managing heating and cooling rates, using stress relief heat treatments, gradient sintering approaches, controlling particle size distribution and packing. This process starts with CAD design, an accurate shrinkage model-based, and iterative design processes that refine dimensions based on actual sintering results.

### 5.2 Mechanical Performance

Ink/slurry-based AM techniques for ceramic parts involve dispersing particles, adding binders, printing, thermal processes, and high-temperature

treatment to strengthen and densify the part. The ceramic AM process optimises particle sizes for high-packing density, flowability, and strength, with uniform distribution reducing porosity. High-performance powder material with uniform distribution ensures good mechanical properties. Particle size distribution, dopant addition, particle rearrangement, and hot isostatic pressing during sintering can enhance packing density, flowability, and mechanical properties of viscous liquids.

### 5.3 Artistic Distinctive

Further research is needed to enhance the visual appeal of dental restorations using advanced micromanufacturing processes. Zirconium dioxide and glass ceramic are popular materials due to their strength, durability, and ability to match natural teeth. The AM techniques replicate the optical properties of natural teeth, including colour gradients, translucency, and surface texture.

$ZrO_2$ has three crystalline phases: monoclinic, tetragonal, and cubic. Its optical properties, including transparency, are closely linked to these structures. Manufacturers can influence the final optical properties of AM-formed restorations by choosing powders with specific crystalline phases. Research into AM processes and treatments like heat cycling or controlled cooling rates can refine the crystalline structure and optical properties.

Glass ceramics, formed from glasses and partially crystallised through heat treatments, offer unique properties like optical transparency and translucency. They mimic translucency and opalescence of natural teeth, making them ideal for dental restorations. However, their mechanical properties are often inferior to high-strength ceramics like zirconia, limiting their use in high-stress areas.

### 5.4 Cost and Time

Ceramic advanced manufacturing processes rely on slurry, which can be improved through debinding and sintering. Machine learning and AI can optimise process parameters and predict optimal conditions. Hybrid manufacturing, combining AM with subtractive methods, and batch processing can reduce post-processing. A multidisciplinary approach combining material science, process engineering, and automation is crucial for making AM economically viable on an industrial scale. The expansion of AM in ceramic dental restorations is mainly attributable to the improvement of debinding and sintering equipment. These innovations may improve restoration quality, decrease handling and transfer times, and simplify the process. Because of this, AM would have a better chance of competing with more traditional methods, which may lead to its increased use in the dental industry.

## 6. CONCLUSION

The article delves into techniques including stereolithography, digital light processing, and selective laser sintering that are part of the additive manufacturing technology used to make dental restorations. The article discusses the properties, uses, and processing capabilities of several materials, including glass ceramics, zirconia nanopowders, alumina nanopowders, and hybrids. Additionally, it discusses about dental items such as crowns, bridges, veneers, and implant components. New ceramic advanced materials can transform the restorative industry and dental practice, according to the research. Vat Photopolymerization and Material Jetting technologies are producing ceramic dental restorations that meet clinical standards in accuracy, mechanical performance, and biocompatibility. However, the high costs and time required for printing, post-processing, and finishing may hinder widespread adoption. Innovations could bridge this gap, potentially leading to a significant shift in dental manufacturing practices. The methods of ME, MJ, BJ, and PBF in dentistry offer inherent advantages such as high resolution, smooth surface finish, and compatibility with biocompatible resins. These cyclic process technologies can work with a wider range of materials, potentially enabling new composite structures or multi-material dental restorations.

Dental restorations increasingly utilise zirconia and other ceramics due to their biocompatibility, beauty, and durability. The AM treatments make use of aluminium nanopowder to produce highly adaptive restorations that are comparable to those using conventional techniques. Dental research should aim to develop restorations that closely mimic the appearance and function of natural teeth, that are durable, patient-friendly, and effective. Materials must replicate natural color shades, offer translucency, resist staining, and provide flexibility without stressing adjacent teeth.

## CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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