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Review Article

Additive Manufacturing of Ceramic Components: A Review of 3D Printing Technologies for Industrial Applications

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Abstract

Additive manufacturing (AM), also known as 3D printing, has emerged as a transformative technology across various manufacturing sectors. It enables the fabrication of complex geometries, high-volume customization, significant material savings through layer-by-layer manufacturing methods, and the potential for the use of Eco-friendly materials. This technology offers significant freedom in the design and fabrication of complex geometric parts, with the potential to reduce costs in both prototyping and final product manufacturing, as well as reduce waste through the recycling of materials lost during manufacturing processes. Although its adoption in the ceramics industry has lagged that of polymers and metals, its unique capabilities in fabricating complex geometries of high-performance ceramics are receiving significant attention. This review provides a comprehensive overview of the current landscape of AM technologies specifically designed for ceramic materials. It explores the underlying principles of various ceramic 3D printing processes, highlighting their advantages and disadvantages in producing high-density, defect-free components with customized properties. Furthermore, this paper examines the transformative impact of AM on ceramics in various structural and functional industrial applications, including aerospace, biomedicine, electronics, energy, and more. By bringing together the latest developments and addressing the inherent challenges associated with ceramic processing via additive manufacturing, this review highlights the tremendous potential of this technology to revolutionize conventional ceramic manufacturing and enable the production of advanced ceramic components with enhanced performance and functionality.

Keywords: Additive Manufacturing AM, 3D Printing, Ceramics, Mechanical Properties, Density.

1. INTRODUCTION

Additive manufacturing (AM) is a technology for fabricating three-dimensional (3D) objects, using metals, ceramics, or plastics, which may be used in various applications. AM is defined by International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM)as the "process of joining materials to make parts from 3Dmodeldata, usually layer upon layer, as opposed to subtractive and formative manufacturing methodologies". The processes encompassed in AM are the 3D analog of the very common 2D digital printers; therefore, AM is also commonly referred as 3D printing. However, in the last 30 years, AM has also been referred to as direct digital manufacturing, additive layer manufacturing, additive fabrication, additive techniques, additive processes, free-formed fabrication, solid free-formed fabrication, rapid manufacturing, and rapid prototyping. The term additive manufacturing has been accepted by the ASTM F42 Technical Committee and the ISO Technical Committee TC261 and this has contributed to the international adoption of this term [1]. 3Dprinting or additive manufacturing constructs parts and products additively, layer by layer, allowing the realization of complex and sophisticated designs. 3D printing offers high efficiency, customizability, and a low cost when compared to traditional manufacturing and printed parts dimensions can be tiny as few micrometers, as in the case of microelectromechanical systems (MEMS), or as large as a few meters, as in the case of printing complete houses [2].

Ceramics are solid materials that consist of inorganic, non-metallic substances. They can exist in two forms: crystalline, which has a structured arrangement, and non-crystalline (amorphous), which lacks a specific pattern [2]. Owing to their various excellent properties, ceramics are used in a wide range of applications, including the chemical industry, machinery, electronics, aerospace and biomedical engineering. The properties that make them such versatile materials include high mechanical strength and hardness, good thermal and chemical stability and viable thermal, optical, electrical and magnetic performance [3]. Nevertheless, the shaping process of ceramic materials cannot be performed using conventional forging and machining formation. To this aim, they are usually shaped through multi-step methods [16], including powder mixture (binder and stabilizers) and shape forming such as extrusion, slip casting, pressing, tape casting, gel casting and inkjet molding. Thereafter, the green body that has been shaped should undergo a sintering process to perform the final consolidation. It is well reported that the traditional methods are rather expensive since they include molding, heat treatment and, sometimes, post-sintering machines [17]. Additive manufacturing (AM), originally developed for use with plastics, polymers, and metals, has recently expanded to include ceramic materials, unlocking new opportunities for advanced manufacturing and broadening the scope of industrial applications. This technological evolution allows for the fabrication of intricate structures and the utilization of diverse raw materials, overcoming many of the limitations inherent in traditional ceramic processing techniques [4]. The process of 3D printing ceramics follows the core principles of additive manufacturing. It begins with the design of a digital model using computer-aided design (CAD) software, followed by slicing and toolpath generation using computer-aided manufacturing (CAM) software, which also defines essential printing parameters and generates the G-code. This code is then executed by a 3D printer, whose configuration may vary depending on the type of ceramic feedstock employed. After printing, additional post-processing steps, including sintering, glazing, or machining, are often necessary to achieve the final properties and usability of the ceramic component. Note that slurry-based technologies use ceramic/polymer mixtures with viscosities ranging from low-viscosity (~mPa·s) inks with a low ceramic loading (up to 30vol %) to high-viscosity (~Pa·s) pastes with a much greater ceramic loading (up to 60vol %) [3]. The integration of 3D printing into ceramic manufacturing has significantly advanced the field by enabling greater design freedom, improving control over process variables, and broadening the selection of usable materials. These capabilities have addressed longstanding challenges such as the fabrication of complex geometries, material limitations, and inefficiencies in production. As technology continues to evolve, 3D printing is driving the ceramics industry toward enhanced performance, reduced material waste, improved productivity, and faster turnaround times [3-5]. This review examines the transformative role of additive manufacturing in various sectors, with a particular emphasis on ceramic materials and the diverse technologies enabling their production.

2. Additive Manufacturing Technologies

Additive Manufacturing (AM) was first commercialized by Charles Hull in the 1980s using stereolithography, and since 2009 it has been widely applied in engineering and industry.

1. Design are created using CAD models or data from 3D scanners and medical imaging.
2. The CAD model is optimized (e.g., via FEA) and converted to STL or newer formats such as AMF or 3MF.
3. The model is sliced into layers, and G-code is generated to control the AM machine.
4. The machine fabricates the object layer by layer, followed by support and material removal.
5. Post-processing (e.g., polishing, coating, heat treatment) produces the final part [4].

Table 1: Displays the timeline of the landmark achievements in AM from the 1980 s to 2025

Year	Milestone / Event	Technology / Material	Organization / Person
1983	Invention of stereolithography (SLA)	SLA, Photopolymers	Chuck Hull, 3D Systems
1986	SLA patent granted, 3D Systems founded	SLA	Chuck Hull
1987	First commercial SLA printer (SLA-1) released	SLA	3D Systems
1988	FDM invented and patented	FDM, Thermoplastics	S. Scott Crump
1989	First SLS printers sold	SLS, Nylon	Carl Deckard, DTM
1992	Stratasys releases first FDM machine	FDM	Stratasys
1993	MIT patents 3DP (binder jetting)	Binder Jetting	MIT
1994	ZCorp founded to commercialize 3DP	Color Binder Jetting	Z Corporation
1995	EOS releases metal PBF (DMLS) systems	DMLS	EOS GmbH
1998	First commercial metal binder jet printer	Metal Binder Jetting	ExOne (Extrude Hone)
2003	RepRap project initiated	FFF / Open-source AM	Adrian Bowyer
2003	First bioprinter created	Bioprinting	Thomas Boland
2006	First RepRap self-replicates	FFF	RepRap community
2009	First 3D-printed blood vessels	Bioprinting	Wake Forest Institute
2010	SLA/SLS patent expiration sparks desktop revolution	SLA, SLS	Industry-wide
2012	Organovo prints liver-like tissues	Bioprinting	Organovo

Year	Milestone / Event	Technology / Material	Organization / Person
2014	First 3D-printed object manufactured in space	Polymer Extrusion	NASA / Made in Space
2015	FDA approves first 3D-printed pill (Spritam)	Binder Jetting (Pharma)	Aprecia Pharmaceuticals
2016	ISO/ASTM 52900 AM terminology standard released	Industry Standard	ISO/ASTM
2017	FAA certifies titanium structural 3D-printed part in Boeing 787	Metal AM (Titanium)	Boeing, Norsk Titanium
2018	First 3D-printed human corneas	Bioprinting	Newcastle University
2019	HP launches Multi Jet Fusion for mass production	Polymer PBF	HP Inc.
2020	FAA certifies flight-critical engine part via AM	Metal AM	Honeywell
2021	Desktop Metal acquires ExOne	Metal Binder Jetting	Desktop Metal
2022	Roboze launches circular economy AM recycling program	High-Temp Polymers / Recycling	Roboze
2023	AI-driven generative design + in-situ quality control gain industry use	AI + AM Integration	Industry-wide
2024–2025	AM exceeds $20B market size; AM integrates with Industry 4.0 and AI tools; sustainability becomes a priority	All AM technologies	Global industry

Table 2 provides a detailed overview of 3D printing technologies, their standard abbreviations, and a brief description of each [7-9].

Table 2: 3D printing technologies

Abbreviation	Full Name	AM Process Category	Description / Notes
SLA	Stereolithography	Vat Photopolymerization	Uses a UV laser to cure liquid resin layer by layer. High resolution, smooth surfaces.
DLP	Digital Light Processing	Vat Photopolymerization	Like SLA but uses a projector to cure entire layers at once. Faster than SLA.
FDM / FFF	Fused Deposition Modeling	Material Extrusion	Melt and extrude thermoplastic filament. Widely used, especially in desktop printers.
	Fused Filament Fabrication		
LDM	Liquid Deposition Modeling	Material Extrusion	Extrusion is based on a pneumatic system where the pump sends the ceramic paste materials to the depositing head or arm.
SLS	Selective Laser Sintering	Powder Bed Fusion	Use a laser to sinter powdered thermoplastics. No need for support structures.
DMLS	Direct Metal Laser Sintering	Powder Bed Fusion	Like SLS but for metal powders. Produces functional metal parts.
SLM	Selective Laser Melting	Powder Bed Fusion	Fully melts metal powders for dense parts. Used in aerospace and medical applications.
EBM	Electron Beam Melting	Powder Bed Fusion	Uses an electron beam (instead of a laser) to melt metal powders in a vacuum chamber.
BJ / 3DP	Binder Jetting / 3D Printing	Binder Jetting	Binds powder materials (metal, sand, ceramics) with a liquid binder. Fast, scalable.
IBP	Inkjet Bioprinting	Bio-inks, hydrogels	Inkjet-like printing of biological fluids
MJF	Multi Jet Fusion	Powder Fusion (HP proprietary)	Uses inkjet arrays to selectively fuse polymer powder with heat. High strength and speed.
LENS	Laser Engineered Net Shaping	Directed Energy Deposition (DED)	Blows metal powder into a laser melt pool. Good for repair and hybrid manufacturing.
DED	Directed Energy Deposition	Directed Energy Deposition	Melt material as it's deposited. Used for metals and large parts.
DIW	Direct Ink Writing / Robocasting	Material Extrusion	Extrudes paste/slurry through nozzle

Abbreviation	Full Name	AM Process Category	Description / Notes
TPP / DLW	two-photon polymerization Direct Laser Writing	Vat Photopolymerization	uses a focused, ultrafast laser beam to locally solidify a photo-reactive resin, creating complex micro- and nano-scale structures.
LOM	Laminated Object Manufacturing	Sheet Lamination	Cuts and bonds layers of material sheets (paper, plastic, metal foil).
PJP / MJM	PolyJet Printing / MultiJet Modeling	Material Jetting	Jets photopolymer droplets cured by UV light. High resolution, full-color printing.
CDLP / CLIP	Continuous Digital Light Processing / Continuous Liquid Interface Production	Vat Photopolymerization	Continuous SLA method for faster printing (developed by Carbon).
T3DP	Tomographic 3D Printing	Volumetric Additive Manufacturing	Uses light projections to form entire objects simultaneously inside resin. Experimental.

AM offers an alternative approach to conventional formative processes, making it possible to manufacture geometrically complex near-net-shape 3D ceramic parts without using expensive tooling. The first obvious advantage of AM for the ceramic industry lies in its ability to enable the economic manufacturing of prototypes, low-volume productions and even individual customized parts, without the use of high-cost dedicated mold tooling. Indeed, because molds used in injection molding are extremely expensive, large production volumes are usually required to amortize the high tooling costs, although this does not necessarily apply to all conventional formative technologies such as, for instance, plasters of Paris molds used in slip casting are relatively inexpensive [12].

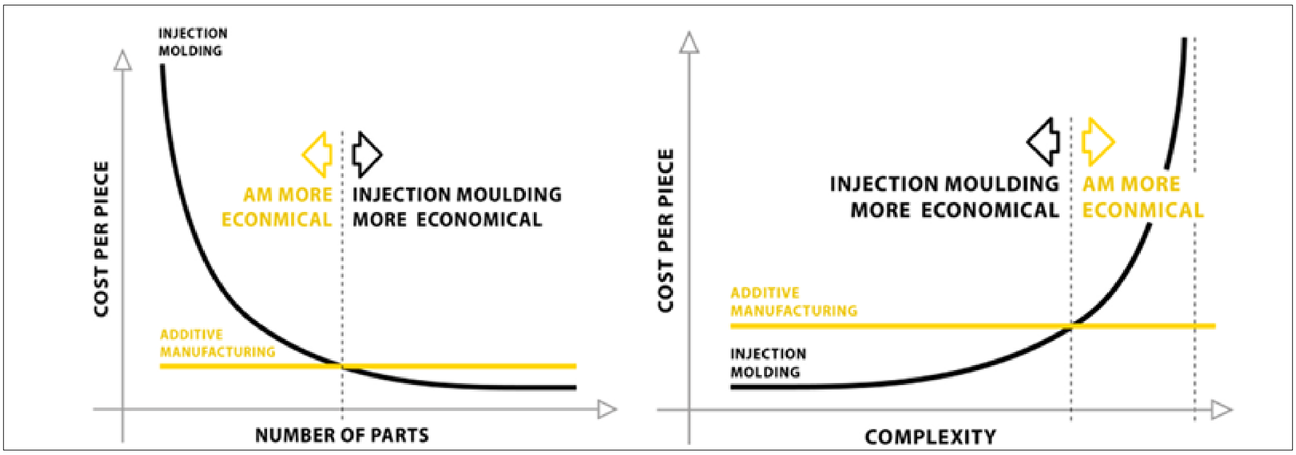

Fig. 2: AM vs. Injection Molding Economics

Fig. 2. Graphs show that AM is more economical than injection molding when working with small production volumes due to the lack of economies of scale and/or when manufacturing highly complex parts since hardware and tooling modifications are not required when increasing part complexity [12].

There are Several 3D printing techniques exist on both research and industrial levels. The different and diverse 3D printing technologies can be classified according to the nature of the raw printing materials: Liquid / Slurry, powder, and Bulk Solid [5], Table 3-1 shows the classification of different 3D printing technologies based on the form of raw material [11, 12].

Table 3-1: Classifies different 3D printing technologies based on the form of raw material

Material Form	3D Printing Technique (Abbreviation)	Common Materials
	SLA	Photopolymer resins
	DLP	Photopolymer resins
Liquid / Slurry Based	CLIP	Photopolymer resins
	MJ	Photopolymers, waxes
	DIW	Ceramic slurries, biomaterials
	IBP	Bio-inks, hydrogels
	SLS	Nylon, polyamide
Powder-Based	SLM	Metal powders (steel, titanium)
	EBM	Titanium, cobalt-chrome

Material Form	**3D Printing Technique (Abbreviation)**	**Common Materials**
	SLA	Photopolymer resins
	DLP	Photopolymer resins
	BJ	Sand, ceramics, metal powders
	MJF	Nylon, TPU
	FDM / FFF	PLA, ABS, Carbon fiber, TPU, PETG
Bulk Solid-Based	PGF (Pellet Granular Fabrication)	Thermoplastic pellets
	LOM	Paper, plastic, metal sheets
	WAAM (Wire Arc Additive Manufacturing)	Metal wires (steel, titanium)

3. Additive Manufacturing of Ceramics

Ceramics in general are the most challenging materials to fabricate due to their brittle nature [10], Ceramic AM has been extensively developed during the last years to overcome conventional manufacturing disadvantages, specifically concerning size shrinkage, generation of parts with complex structures, and high tool wear. Ceramic AM is mainly utilized in the aerospace, automotive, and healthcare sectors. Furthermore, 3D printing has been considered an essential method to print advanced ceramics for biomaterials and bone tissue engineering, e.g., scaffolds for bones and teeth. Compared to traditional methods like casting and sintering, 3D- printed ceramic scaffolds utilized in tissue engineering are more convenient and faster [4]. On the other hand, ceramic materials possess a low thermal expansion coefficient so that by varying temperatures, they expand negligibly and present a good shape consistency [15, 16].

3.1. Classification of Ceramics

Advanced ceramics are classified by their chemical composition into oxides (e.g., alumina Al_2O_3, zirconia ZrO_2) and non-oxides (e.g., carbides, nitrides, borides) [21].

They are also categorized by application into structural, electro, optical, chemical, bio, and superconducting ceramics [22, 23]. Among oxide ceramics, Al_2O_3 is valued for low cost and easy sintering, while ZrO_2 offers high toughness and industrial versatility [24].

Ceramics are thus classified in two main ways: by composition and by application.

(A) Based on Composition: three groups exist—oxides, non-oxides, and composites [5].

i. Oxide ceramics (Al_2O_3, ZrO_2, TiO_2) feature high strength, chemical stability, and oxidation resistance.
ii. Non-oxide ceramics (Si_3N_4, SiC) endure extreme temperatures (up to 2400 °C) and resist corrosion. Si_3N_4 is tough, lightweight, and used in bearings, cutting tools, and engines. SiC is acid-resistant with excellent heat conduction, used in turbines and heat exchangers.
iii. Composite ceramics, such as fiber-reinforced types, enhance toughness and are used in heat shields and gas ducts [18].

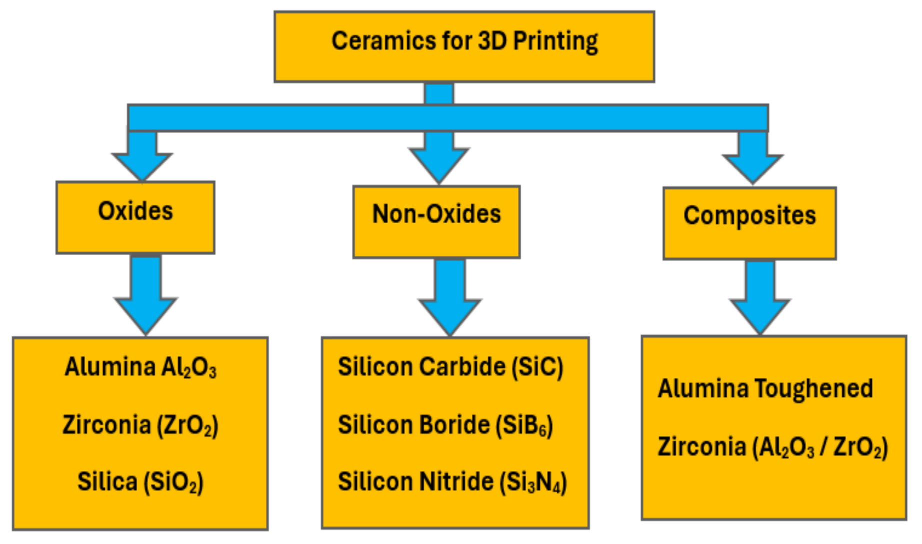

Figure 3: Ceramic materials classification based on composition [18].

B. Classification Based on Applications

The following table 4 outlines various types of ceramics categorized by their applications.

Table 4: Application-Based Classification of Ceramics

Type	Key Properties	Common Uses
Structural Ceramics	Molded from clay; good insulation	Bricks, tiles, dinnerware, statues
Refractory Ceramics	Heat-resistant, oxide-based	Furnaces, kilns
Electrical Ceramics	Conductivity increases with temperature	Capacitors, insulators, fast ion conductors
Magnetic Ceramics	Ferrimagnetic, made of ferrites	Transformers, data storage, telecommunications
Abrasive Ceramics	Very hard and tough; used for cutting/grinding	Diamond, SiC, WC – tools, polishing, machining

4. The Processing Stages in 3D-Printed Ceramic Fabrication

The 3D printing process follows a systematic sequence of steps, beginning with the creation of a digital model using computer-aided design (CAD) software. Once the model is finalized, it is exported in STL (stereolithography) format, which is compatible with computer-aided manufacturing (CAM) software. This file is then processed using slicing software to generate the G-code, which contains the specific instructions required for the 3D printer to fabricate the object layer by layer. Before printing begins, the machine setup involves calibrating the printer, including resetting the axes to the machine's origin (home position) and loading the appropriate raw material. After these preparations, the printing process is carried out, during which the physical object is built based on the digital design. Following fabrication, the printed part undergoes post-processing steps to enhance its final properties and remove any support structures or imperfections.

The Ceramics 3D printing involves a series of sequential processes that convert raw materials into a final ceramic component. The process begins with the preparation of the starting material, which can involve mixing ceramic powders with binders, solvents, or other additives to form a printable paste, or using pre-prepared resins or slurries, depending on the printing method. Once the feedstock is ready, it is loaded into the printer, and the printing parameters—such as viscosity, extrusion pressure, layer height, or curing intensity—are adjusted to suit the material properties and the selected 3D printing technique. Following the printing phase, the produced green body (unfired ceramic) typically undergoes a post-processing stage, which may include drying, cleaning, or binder removal, depending on the material system and printing method. The duration and specific steps in this phase vary based on the technology used. Afterward, a finishing stage may be applied to remove any residual material, correct surface defects, or improve dimensional accuracy. Figure 4 below illustrates the stages of 3D ceramic printing.

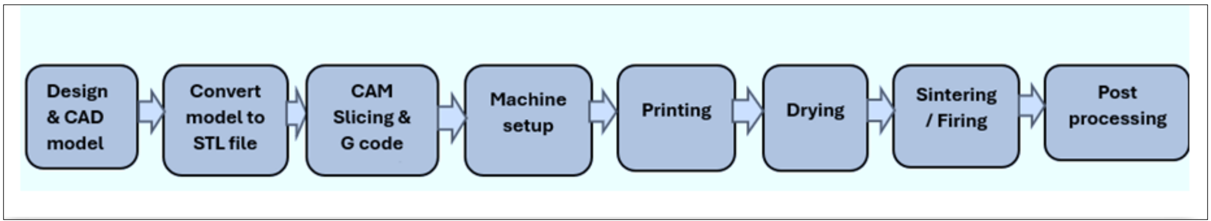

Figure 4: Stages of 3D printing of ceramics

5. Ceramic 3D printing methods / techniques

This section provides a detailed discussion of various 3D printing technologies for ceramics, categorized according to the form of the raw material, as summarized in Table 3-1.

5.1 Liquid / Slurry-Based Technologies

Liquid/Slurry-based ceramic 3D printing technologies utilize liquid or semi-liquid feedstocks composed of fine ceramic particles dispersed within a carrier medium, typically in the form of inks or pastes, depending on the system's solid loading and viscosity. These slurries can be processed through various additive manufacturing methods, including photopolymerization, inkjet printing, and extrusion. Recent advances in materials science have also enabled the use of photo-polymerizable pre-ceramic polymers (PCPs), which can be converted into polymer-derived ceramics (PDCs) through subsequent pyrolysis. This section will specifically explore photopolymerization-based techniques such as stereolithography (SLA) and its derivatives—digital light processing (DLP) and two-photon polymerization (TPP)as well as inkjet-based inkjet printing (IJP) and extrusion-based direct ink writing (DIW).

5.1.1 Stereolithography (SLA)

The SLA technique is believed to be the most prominent and popular 3D printing technology that has been extensively used worldwide. It was first proposed and developed by Hull in 1986[3]. Stereolithography (SLA) is a vat-photopolymerization-based additive manufacturing technique that employs a photosensitive liquid resin, which solidifies upon exposure to a specific wavelength of light, typically ultraviolet (UV). The process begins with the preparation of a 3D model using CAD software, which is then sliced into thin horizontal layers and converted into a machine-readable format (STL). During printing, a UV light source commonly a laser in SLA or a digital projector in digital light processing (DLP) selectively cures the resin layer-by-layer based on the sliced model data. This initiates a photopolymerization reaction that solidifies the resin at defined locations. After each layer is cured, the building platform moves up to allow a fresh layer of resin to be exposed and cured, repeating the process until the complete object is formed. SLA is renowned for its high precision and resolution, attributed to the fine laser spot size and accurate control of the light path, making it particularly suitable for fabricating intricate geometries, microstructures, and porous architectures in bio ceramic applications. Figure 4 illustrates the working principle of SLA.

The size and number of produced objects affect their speed. The SLA approach needs less resin, the excess resin can be drained and reused after creating the sample [25].

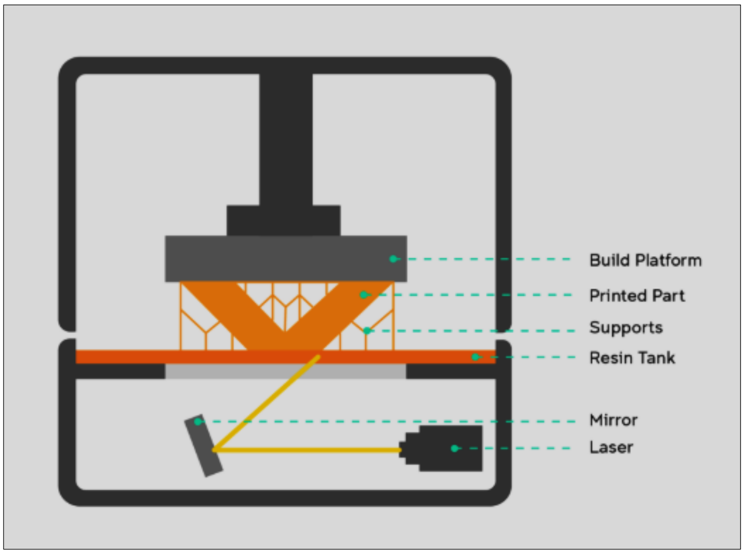

Figure 5: Stereolithography (SLA) process

The SLA of ceramics proceeds with the addition of fine ceramic particles, down to micro/nanometer size, into the photocurable medium, which can be aqueous or non-aqueous [3]. The liquid becomes a ceramic suspension after it has been well dispersed in the medium with the aid of essential surfactants and additives. Similarly, polymerization only takes effect in the organic monomer phase under light irradiation as ceramic particles are inert to light emission. The ceramic particles are then uniformly surrounded by the cross-linked organic network being polymerized to form the pre-designed shape of each layer until the entire 3D ceramic part is built up. The green parts must be processed with further treatments, typically pyrolysis to remove organics followed by sintering at high temperatures to reach the packed density, much the same as in conventional ceramic processing routes such as injection molding. There is also an indirect SL method, in which SL resin molds are prepared for investment casting of complex ceramic parts [3-19].

SLA is widely favored for manufacturing elaborate prototypes and objects featuring smooth surface textures. SLA 3D printed ceramics printing resin/solution is prepared by mixing the light curable resin with ceramic powder and then post-processing the printed green parts through sintering and debinding processes. Stereolithography (SLA)-based 3D printing enables the fabrication of highly precise bio ceramic scaffolds with intricate porous architectures. In a notable study, Duong and colleagues from the National Key Laboratory of Sclerotherapy at Northwestern Polytechnical University, China, successfully fabricated BCP bio ceramics with enhanced density and mechanical properties using SLA 3D printing. Porous biphasic calcium phosphate (BCP) bio ceramics are considered among the most promising materials for bone repair in clinical medicine due to their excellent biocompatibility and Oste conductivity. At the optimized procedure of sintering temperature 1250 °C for 2 h, the 3D printed BCP bio ceramics showed uniform shrinkage in all directions, and especially the mechanical properties were close to that of human cortical bone. They achieved complex porous BCP scaffolds exhibiting high porosity (51.49%) and significant compressive strength (8.14 MPa) [20].

5.1.2 Digital Light Processing (DLP)

The digital light processing or digital light projection (DLP) technique is in fact a mask-based SLA, in which an integral image is transferred to the photopolymerizable liquid surface by exposing the light source through a patterned mask once only. The original concept was first proposed by Nakamoto and Yamaguchi in 1996 using physical masks [3]. Figure 5 illustrates the working principle of DLP.

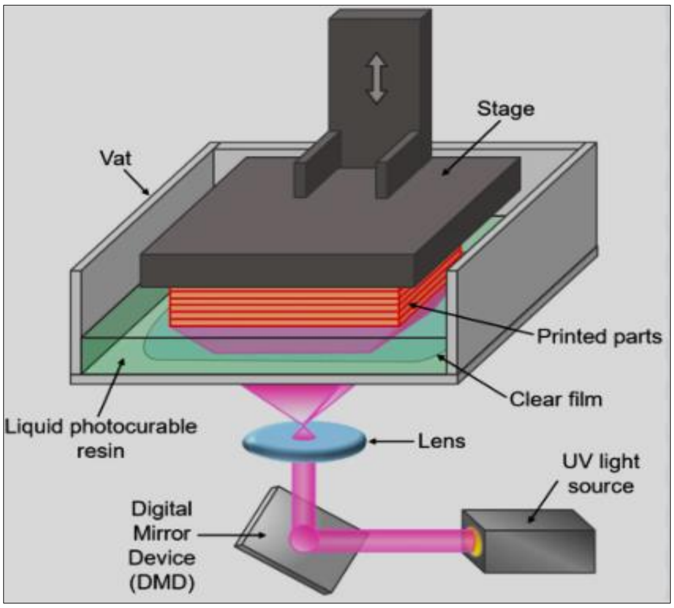

Figure 7: DLP working principle

It was further developed and improved on by Bertsch *et al*., in 1997 with the use of a liquid crystal display (LCD) as the dynamic mask generator. Since 2001, progress has been made by replacing LCDs with digital micromirror devices (DMDs) from Texas Instruments owing to their competitive fill factor and reflectivity (resulting in higher re solution and contrast in the light display) [40, 41]. The ultra-fast light switching and integral projection allow the DLP 3D printing process to be dramatically reduced as it is much faster than the conventional SLA point-line-layer scanning process. Moreover, very good feature resolution can be ob tained, to several micrometers. These remarkable advantages of DLP technology have attracted considerable attention in the 3D printing industries, and it has been explored for fabricating parts with even higher accuracy and speed [3-31].

Yao'sgroup fabricated high-performance hydroxyapatite (HA) ceramics using digital light processing (DLP)3Dprintingtechnology [28]. Guo's group has effectively showcased the capability of Digital Light Processing (DLP) 3D printing to create intricate titanium dioxide ceramic lattice structures This pioneering work significantly broadens the scope for utilizing titanium dioxide ceramics in fields that require porous architecture, such as bone tissue engineering and catalytic systems [32].

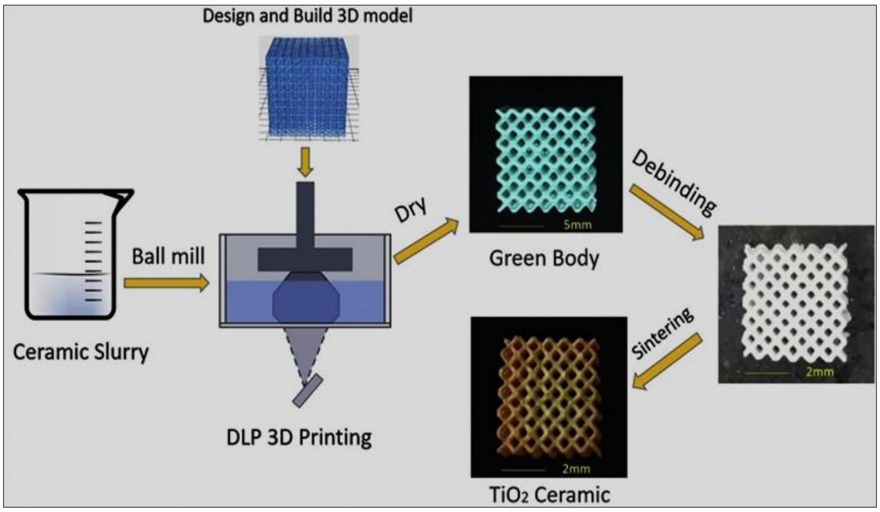

Figure 8: Schematic of the preparation of fine 3DP LatticestructuralTiO2ceramic [32]

5.1.3 Direct-Ink-Writing (DIW)

Direct-Ink-Writing (DIW), also known as Robocasting, is an advanced 3D printing technique that builds complex structures by precisely placing materials layer by layer. In this additive manufacturing process, a nozzle or a pen-like tool releases a liquid or semi-liquid substance, often a mix of polymers and other components, onto a base. The material is then squeezed out of the nozzle and quickly solidifies upon deposition, forming the desired 3D structure.

DIW is widely used to create ceramic or metal components, which are then hardened through a process in an oven. It's also commonly used for bioprinting various materials, allowing for the creation of intricate biological structures. Fig 9 illustrates a Schematic process of Direct Ink Writing (DIW).

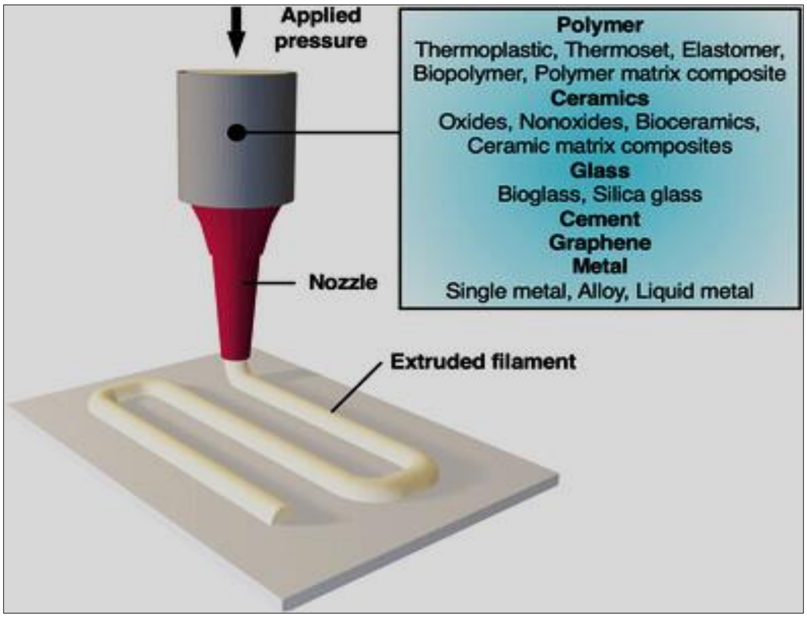

Fig. 9: Schematic process of Direct Ink Writing (DIW) [35]

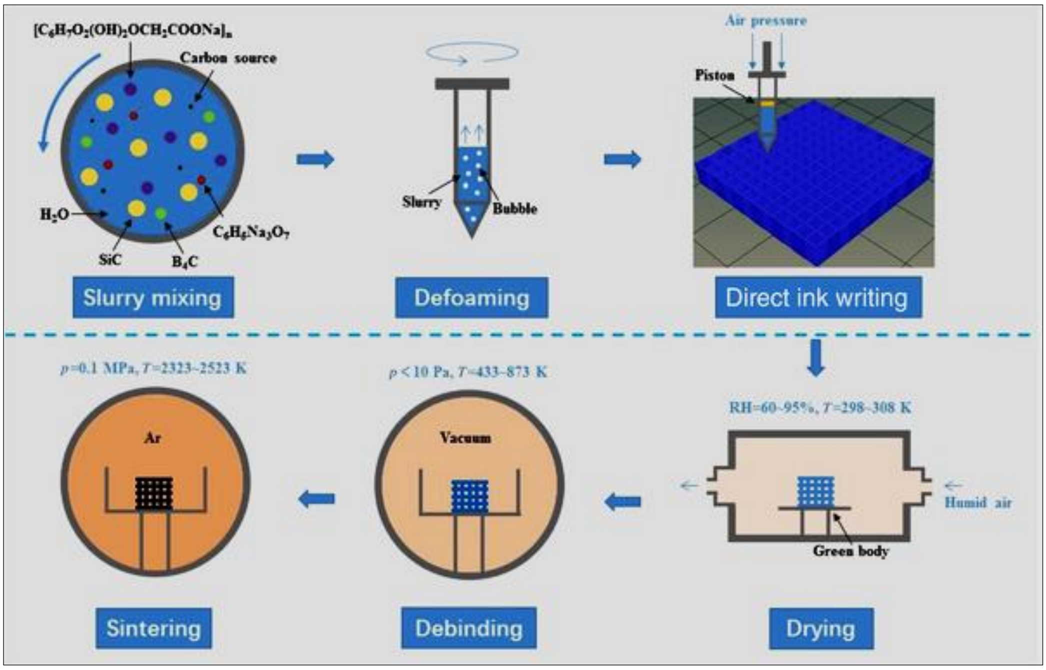

Fig. 10: Schematic of the preparation process of SiC ceramics by Direct Ink Writing (DIW) [49]

This technique was first patented in 1997 by Cesarano and colleagues at Sandia National Laboratories. Initially, it was developed for working with concentrated materials, like ceramic slurries, that had very little organic content. Some researchers [33], view DIW as a broad term for various 3D printing technologies that use an "ink" (either as droplets or a paste) to create designed objects. Smay and his team at Harvard University have made significant strides in using DIW to produce 3D structures with repeating patterns, ranging from micro- to millimeter scales [36-37]. These structures, often made from special gel-based pastes, Figure 10 shows examples of these 3D structures, which were made using a special gel-based paste [33], serve as active components in piezoelectric-polymer composites, highlighting DIW's potential for intricate 3D fabrication.

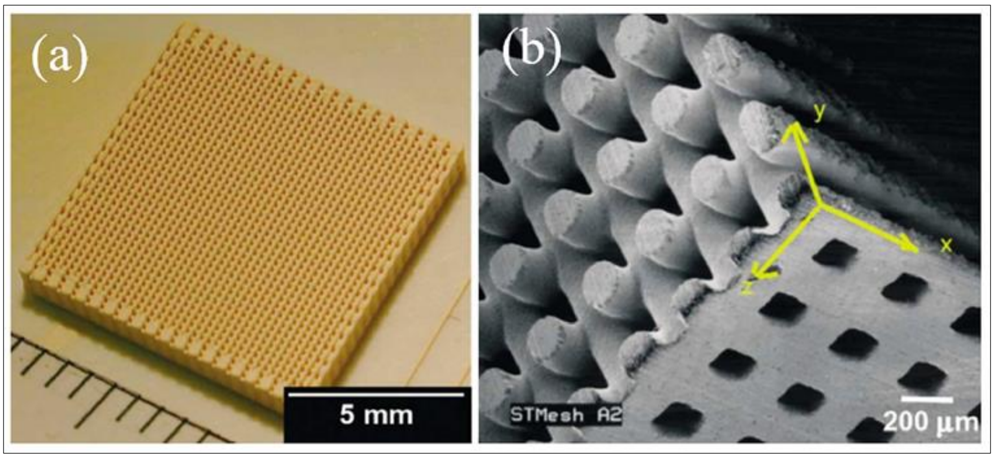

Fig. 11: (a) 3D periodic PZT structures made by DIW with concentrated ceramic paste; (b) SEM image showing the detailed microstructure [33]

5.1.4 Inkjet Printing (IJP)

Inkjet printing (IJP) has emerged as a compelling technology for patterning functional materials, offering significant advantages over conventional ceramic prototyping techniques like stereolithography, fused deposition modeling, and selective laser sintering, which are limited around 150 µm and single-material deposition [39].

Beyond its traditional uses, IJP has evolved into a versatile material deposition technique for thin-layer applications. Its material versatility now extends to polymers and metals for electronic patterning [40, 41], solder paste for microelectronics [42], and even cells for tissue engineering [43], often forming 2D structures. However, the current limitation of IJP is its restriction to miniaturized parts due to the minute volume of ink (picolitres to nanoliters) ejected per droplet.

Despite this, recent advancements have transformed IJP into a promising manufacturing process for 3D multilayered parts, particularly with ceramic inks. This involves dispersing ceramic particles within a liquid solvent for direct and selective deposition onto a substrate via a printhead. The high-precision, computer-aided positioning of droplets facilitates a precise point-line-layer-part building process, enabling the creation of solid ceramic phases after drying and sintering of the printed materials.

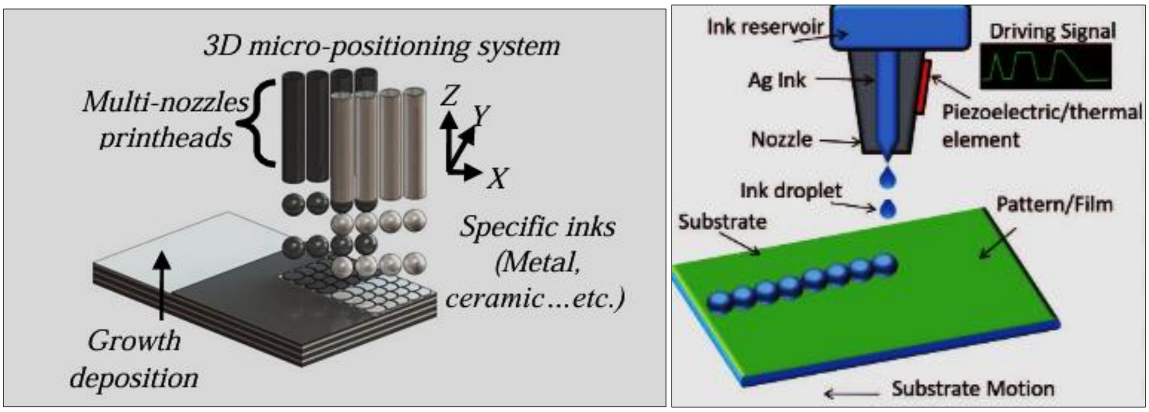

Fig. 13: 3D multi material inkjet printing principle

The performance of IJP of ceramics very many hinges on the critical factors of the ceramic powder and ink formulation as well as their properties, in particular the rheological characteristics such as dispersivity, stability, viscosity and surface tension. In addition, a moderate pH value must be maintained to prevent possible corrosion of the jetting system by the ink. A uniform particle size distribution with particles less than 1/100 of the nozzle diameter (at the micron scale) can prevent the clogging and blockage of nozzles and capillaries, as required by the printer manufacturers [41]. Dense structural ceramic parts have been successfully fabricated by Cappi *et al*., [44], using an aqueous Si3N4 ink with a 30vol% solid loading (Fig. 14). Mechanical properties comparable with those of dry pressed ones were achieved, suggesting the potential for IJP to fabricate high-performance non-oxide engineering ceramics. Research [45], has also reported that pre-ceramic polymers loaded with 10vol% SiC particles and 7vol% poly carbosilane generated low-viscosity inks suitable for IJP. Their results showed that 3D parts can be fabricated with low shrinkage and that no macro defects were detected.

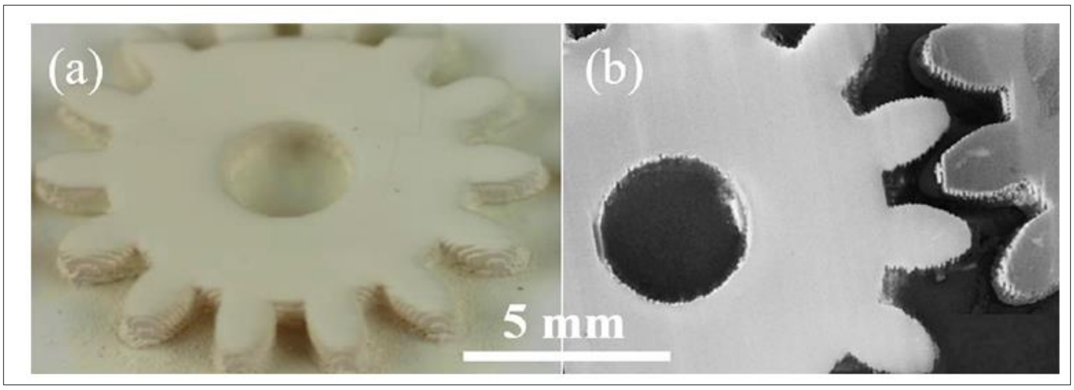

Fig. 14: Si3N4 gearwheel fabricated by IJP: (a) green part; (b) sintered part [44].

Overall, Inkjet Printing (IJP) is a versatile 3D printing technique well-suited for creating small ceramic parts. While it offers less flexibility for complex designs, like those with overhangs or hollow sections due to support challenges, its benefits are significant. IJP boasts low cost, a simple processing route, and a wide range of material choices. These advantages have greatly boosted its use in advanced ceramic manufacturing, especially in microelectronics and energy devices.

5.1.5 Two-Photon Polymerization (TPP)

Two-photon polymerization has emerged as a versatile and powerful technique for fabricating highly precise, three-dimensional micro- and nanostructures, particularly in fields that demand high-resolution patterning, such as photonics, biomedical engineering, and micro-optics [72]. This method relies on the localized excitation of photosensitive materials, typically photoresists or specialized resins, through focused femtosecond laser pulses, facilitating polymerization with high spatial control [47, 48]. 2PP is a nonlinear optical lithography technique in which photo initiator molecules simultaneously absorb two photons to reach an excited electronic state, thereby initiating localized polymerization. The probability of two-photon absorption is proportional to the square of the incident light intensity, confining the polymerization process to the focal volume of a tightly focused femtosecond laser beam. This spatial confinement enables feature sizes well below the diffraction limit, making 2PP a powerful tool for high-resolution, three-dimensional micro- and nanofabrication [46]. Fig 15 illustrates schematic diagram for 2PP fabricating system [49].

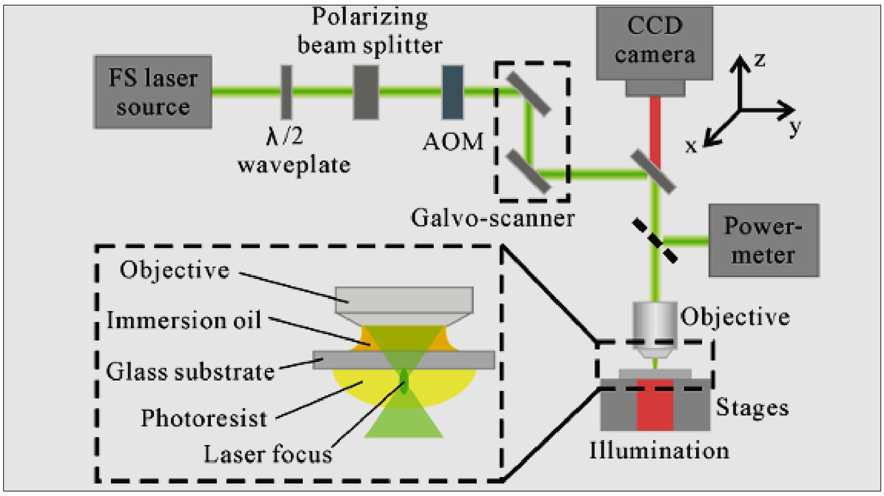

Fig. 15: schematic diagram for 2PP fabricating system [49]

More recently, Colombo and his team [50], also used TPP to create a complex, very porous SiOC diamond-shaped structure at the micron scale, as shown in Figure 16 (i). This was also done using a pre-ceramic polymer. Additionally, TPP has been used to build 3D Zr–Si polymer ceramic scaffolds. These scaffolds are designed for growing bone tissue from a patient's own cells, offering flexible control over how porous the structure is and the size of its holes [51].

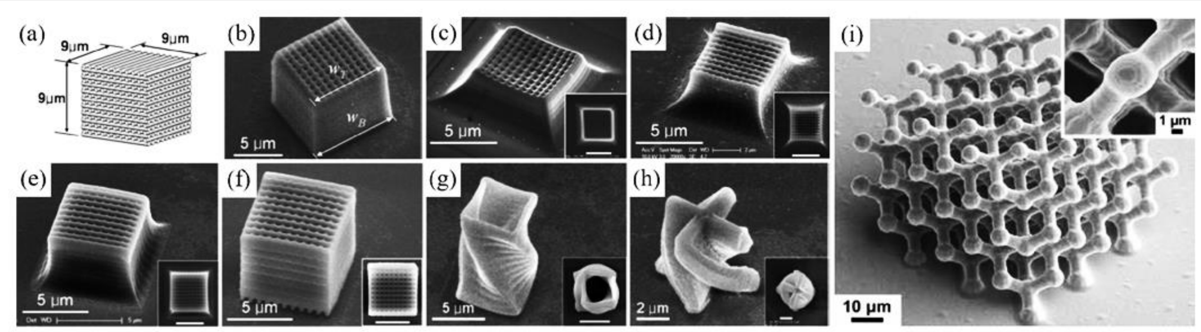

Fig. 16: Diverse SiCN and SiOC Ceramic Microstructures Created by Two-Photon Polymerization (TPP): (a) SiCN woodpile design. (b) Polymeric and (c) ceramic woodpile (no filler). (d-f) Ceramic woodpiles with 20wt%, 30wt%, and 40wt% silica filler for shrinkage control. (g) Micro-tube and (h) micro-cruciform SiCN spirals (90° twist, 40% silica; (insets show top views). (i) Unhydrolyzed SiOC diamond structure [50]

5.2 Powder-Based Technologies / Powder Bed Fusion (PBF)

The term PBF encompasses AM processes where particles in a powder bed are selectively fused together under the application of a concentrated heat source. Three common AM technologies fall into the general PBF category: Selective laser melting (SLM), Selective laser sintering (SLS) and Electron Beam Melting (EBM). Whilst the first two technologies can be used to shape ceramics, the latter is generally not applicable as most ceramic materials are not electrically conductive. Several variants of the original SLS and SLM processes, which were initially created to process polymers and metals respectively, have been developed throughout the years to adapt these technologies to the specific requirements of ceramic materials. Local densification of the powder bed can be obtained either by direct laser sintering (dLS) of the advanced ceramic powder itself, or by indirect laser sintering (iLS) of a sacrificial polymeric or inorganic binder phase that acts as a temporary matrix for the ceramic powder until its removal or conversion by heat treatment. Furthermore, the use of ceramic slurries as feedstock instead of dry powders was introduced to enable the use of submicron particles and to reach higher green/sintered densities [13-52].

In summary Powder Bed Fusion (PBF) refers to a group of additive manufacturing processes that use a thermal energy source to selectively fuse regions of a powder bed. Among these, Laser Powder Bed Fusion (LPBF) is the most widely used for ceramics and metals. LPBF employs a high-power laser to fully melt the powder particles layer by layer, enabling the production of dense, complex parts. It is often used interchangeably with terms like Selective Laser Melting (SLM) or Direct Metal Laser Sintering (DMLS). While PBF encompasses both laser and electron beam-based methods, LPBF specifically denotes laser-based fusion under an inert gas atmosphere, offering high resolution and material performance.

Table 5: Binding and powder deposition mechanisms of single and multiple-step PBF

PBF	Binding mechanism	Powder deposition mechanism
Single-step	Full melting	Conventional, slurry coater, aerosol-assisted spray deposition
	Partial melting	Conventional, slurry coater, slurry sprayer, ring blade, electrophoretic deposition
	Solid-state sintering	Conventional
	Chemically induced binding	Conventional, slurry coater, ring blade
Multiple-step	Partial melting	Conventional, slurry coater
	Gelling	Slurry coater

5.2.1 Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS) is a powder bed fusion (PBF) technique developed in the 1980s. This method creates near-net shaped polymer parts by melting or fusing layers of powdered material using a carbon dioxide (CO2) laser. During the process, loose powder particles are spread evenly across a build chamber by a roller. Before sintering, the particles are heated to just below their melting point. A laser then traces cross-sections based on a digital design (CAD model). After each layer is processed and bonds to the previous one, the build platform moves down by one layer's thickness.

These steps repeat until the part is finished. Following fabrication, a post-processing step, often involving sanding or cleaning with pressurized air, is required. SLS is known for its ability to process a variety of affordable and environmentally friendly materials, producing fully dense parts with high accuracy. Fig.17 illustrates schematic diagram for Selective Laser Sintering [54]. It is reported that the SLS process can also be used for building crack-free dense ceramic components with extremely high melting points, low or no plasticity and poor thermal shock resistance compared to polymers and metals [53]. Fig.18 demonstrates various stages in the SLS processing of ceramic parts, from the feedstock mate rial to the final dense part [88].

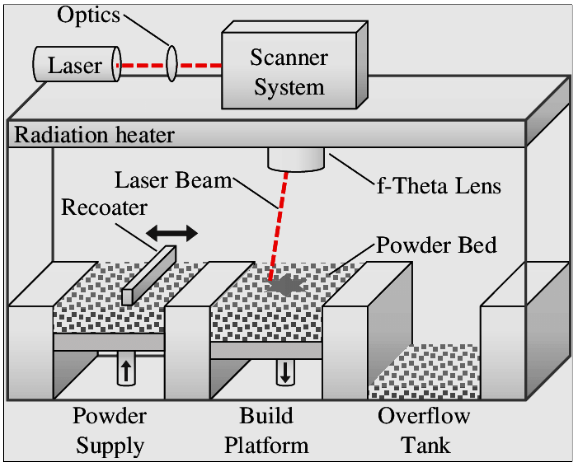

Fig. 17: Schematic diagram for Selective Laser Sintering [54].

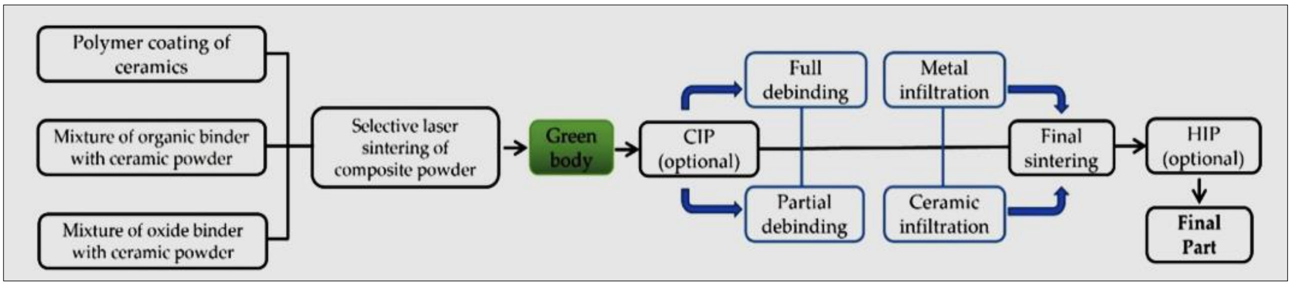

Fig. 18: SLS processing of ceramic parts, CIP: Cold isostatic pressing; HIP: Hot isostatic pressing [88].

Selective Laser Sintering (SLS) was originally developed to produce wax models for investment casting of metal prototypes such as aluminum. Its scope has since expanded to accommodate a wide range of powdered materials. Early research focused on low-melting-point polymers, including acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), polyether ether ketone (PEEK), polycarbonate (PC), and polyamide (PA), before transitioning to metallic and composite powders with higher melting points [55-61].

The feasibility of Selective Laser Sintering (SLS) for ceramics was first demonstrated by Lakshminarayan *et al.*, (1990) at the University of Texas using alumina-based powders with low-melting binders such as ammonium phosphate and boron oxide [62, 63]. Due to the high melting temperatures of ceramics (e.g., 2045 °C for Al_2O_3), direct laser densification is impractical, necessitating the use of organic or inorganic binders that temporarily bond particles during processing [63–71].

Processing under inert atmospheres (N_2 or Ar) prevents binder oxidation, while the main challenge remains high porosity and shrinkage in final parts [70]. To enhance densification, post-processing methods such as quasi-isostatic pressing (QIP), warm isostatic pressing (WIP), and pressure infiltration have achieved densities up to 94% of theoretical values [73–78]. Further improvements have been reported in aluminum oxide (Al_2O_3) composites with polypropylene and zirconium oxide (ZrO_2) composites stabilized with 3 mol% yttrium oxide (Y_2O_3) (3YSZ), demonstrating significant progress in microstructural optimization [74, Figure 19(b)]. Overall, these advancements highlight the continued progress toward optimizing microstructural integrity and densification in SLS-processed ceramic systems.

Note:

Yttria-Stabilized Zirconia (3YSZ) is a high-performance ceramic where Y_2O_3 stabilizes the cubic/tetragonal phases of ZrO_2, preventing cracking and improving thermal stability and strength. It offers excellent toughness, wear and corrosion resistance, making it ideal for demanding applications such as dental implants, oxygen sensors, and SOFCs.

Fig. 19: Complex ceramic parts produced by SLS: (a) Al_2O_3 parts with the assistance of quasi-isostatic pressing and final firing [73]; (b) 3YSZ parts after SLS and after combination with pressure infiltration (PI)/warm isostatic pressing (WIP) and final firing [74].

Selective Laser Sintering (SLS) has been increasingly applied in biomedical engineering, particularly for the fabrication of biocompatible ceramic scaffolds for tissue regeneration. These scaffolds commonly employ ceramic–polymer or ceramic–glass composites with high binder contents (up to 60 vol%) to support macro-porous structures suitable for biological function [66-85]. The performance of SLS-fabricated ceramic scaffolds is strongly influenced by feedstock characteristics and laser–material interaction, which determine mechanical integrity. Specifically, spherical, micrometer-scale powders improve flowability, while binder type and content critically affect the strength of both green and sintered parts [86, 87].

5.2.2 Selective Laser Melting (SLM)

SLM is a powder bed fusion additive manufacturing technique that uses a high-energy laser to completely melt and fuse powder particles into a dense, solid part. It enables single-step fabrication without binders or post-processing and is widely used for producing high-performance, complex components. Selective Laser Melting (SLM), developed at the Fraunhofer Institute for Laser Technology (ILT) in 1996 [90], represents an advanced evolution of Selective Laser Sintering (SLS), achieving complete powder melting via a high-energy laser to form nearly fully dense, homogeneous parts. Initially applied to metal powders such as aluminum, copper, and stainless steel, SLM has since extended to advanced alloys for lightweight aerospace applications [91]. The process is valued for producing strong, low-porosity components with controlled microstructures, establishing it as a leading metal additive manufacturing technique. When adapted for ceramic powders, SLM enables binder-free full melting, yielding dense, high-purity, and geometrically complex components.

However, the final part quality is influenced by powder characteristics, laser–material interaction, and particularly layer thickness, which balances surface quality and build time.Fig.21 illustrates Schematic diagram of the SLM process [92].

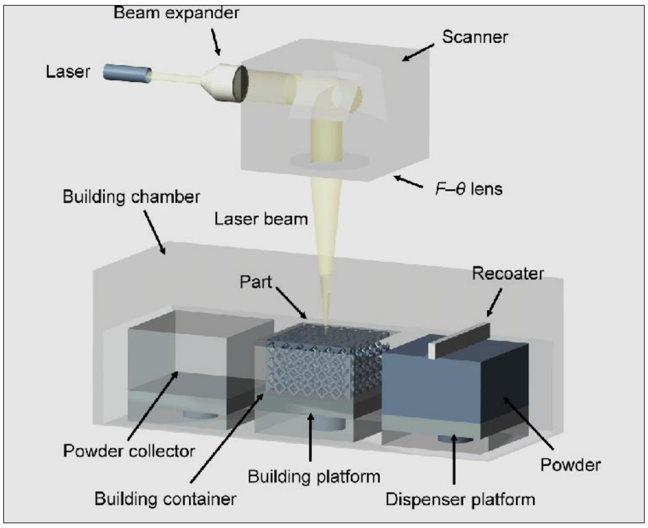

Fig. 21: Schematic diagram of the SLM process [89]

Studies highlight the difficulty of achieving high density in SLM-fabricated ceramics. Although fully dense microstructures have not yet been realized, these methods have enabled the fabrication of various structural porcelain parts with improved surface quality and packing [94, 95].

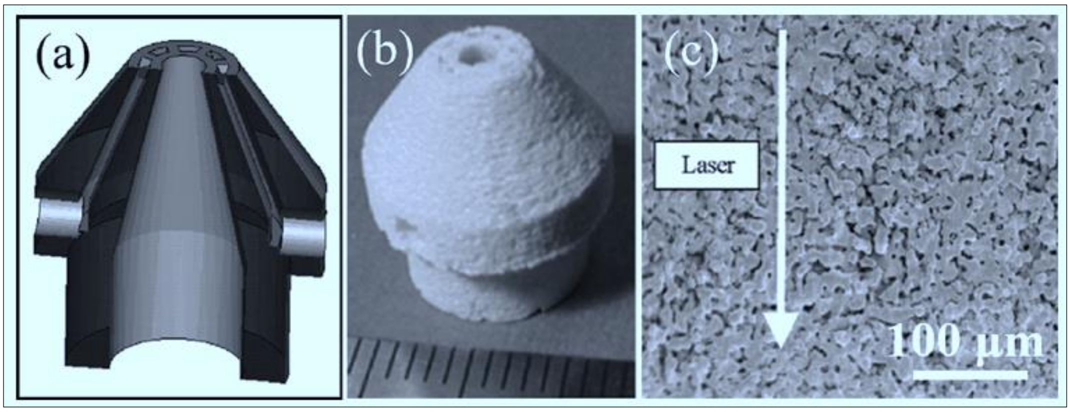

Fig. 22: (a) 3D CAD model of a nozzle, (b) fabricated zirconia part and (c) SEM image of a cross section showing the high porosity [93].

5.3 Bulk Solid-Based Technology

Bulk solid-based additive manufacturing (AM) technologies are increasingly being explored to produce ceramic components due to their cost-efficiency, ability to form complex geometries, and compatibility with a range of ceramic feedstocks. These technologies rely on the controlled layer-by-layer deposition of solid or semi-solid ceramic-loaded materials to construct near-net-shape parts, followed by post-processing steps such as drying, debinding, and sintering to achieve final ceramic properties.

One widely adopted method in this category is Material Extrusion Additive Manufacturing (MEAM). In ceramic MEAM, ceramic powders are mixed with a polymeric binder to form a printable feedstock, which is extruded through a nozzle and deposited in layers to build the desired geometry. This approach is simple, cost-effective, and flexible in material formulation. While most MEAM machines are equipped with a single extrusion head, dual-head configurations can enable multi-material or functionally graded ceramic parts [1]. Figure 23 illustrates different types and methods of material extrusion techniques in additive manufacturing.

A better variant for clay- and slurry-based ceramics is Liquid Deposition Modeling (LDM), which is used by companies like WASP. LDM involves the extrusion of a viscous ceramic paste (such as clay or porcelain) through a syringe-like system at ambient temperatures. The technique enables the construction of intricate ceramic structures, including large-scale architectural elements and art pieces, without the need for melting. After shaping, the printed parts undergo drying and sintering to consolidate the material.

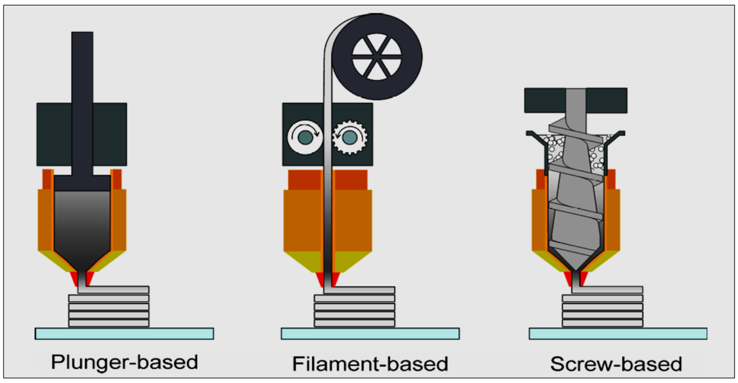

Figure 23: Different types and approaches for extrusion-based additive manufacturing [1]

5.3.1 Fused Deposition Modeling (FDM)

FDM ranks among the most extensively employed 3D printing methods. This technique involves the gradual extrusion of a heated thermoplastic filament through a nozzle, which subsequently deposits the material layer by layer, thereby constructing the desired 3D object. Due to their affordability, FDM printers have gained popularity among makers and small-scale applications [100]. Also known as fused deposition of ceramics (FDC), FDM was first patented by Crump *et al*., in 1989 [101], and later commercialized by Stratasys Inc. in 1990 [102]. Commonly used thermoplastics include ABS, PLA, PC, and PA, which are melted and extruded through a heated nozzle [103]. Figure 24 illustrates the schematic diagram of FDM [107].

For ceramic applications, FDM requires composite filaments made by mixing ceramic particles (up to 60 vol%) with thermoplastic binders. An example is a filament composed of 35 vol% barium titanates (BT) in an ABS matrix [104]. After printing, the parts undergo binder removal and sintering to densify the ceramic material. The first use of FDM for ceramics was reported by Danforth in 1995, using Al_2O_3 and Si_3N_4 -filled systems [105], though the resulting parts showed relatively low sintered densities (75–90%) due to porosity. More recently, FDM has been used to produce functional components such as piezoelectric ceramic transducers, fabricated using composites like PZT and PMN [106]. In some cases, glazing is applied after sintering to improve surface quality or chemical resistance, depending on the final application.

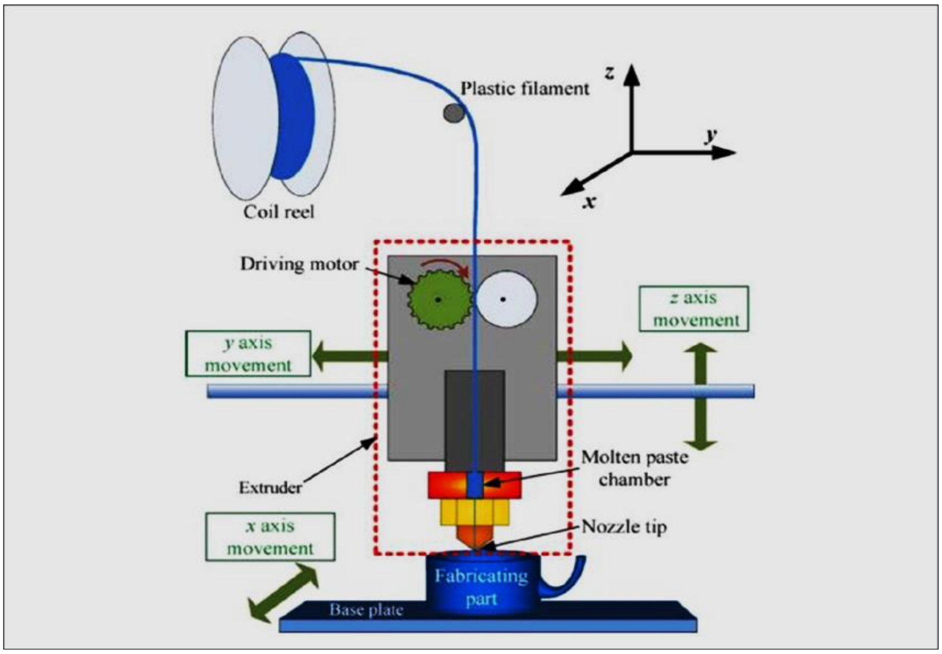

Fig. 24: schematic diagram of FDM [107]

5.3.2 Laminated Object Manufacturing (LOM)

LOM technology is based on bonding sheets of the printed materials and then cutting the unwanted parts resulting in the desired 3D part, as shown in Figure 25. In ceramics, LOM involves bonding layers of ceramic-based sheets or films using heat or an adhesive to create intricate ceramic parts with improved mechanical properties and high temperature resistance. It finds applications in the aerospace, electronics, and engineering industries due to its ability to produce complex and robust ceramic objects. Zhang's group yielded alumina 3D printed parts with porosities of 51.5% and round hole diameters of 80 ± 5 µm. The use of an organic mesh as a framework and template reduced the risk of damage to the green body while ensuring regularity, uniformity, and connectivity of the micro-scaled pore network [108]. Figure 25 illustrates Basic schematic of the LOM process [109].

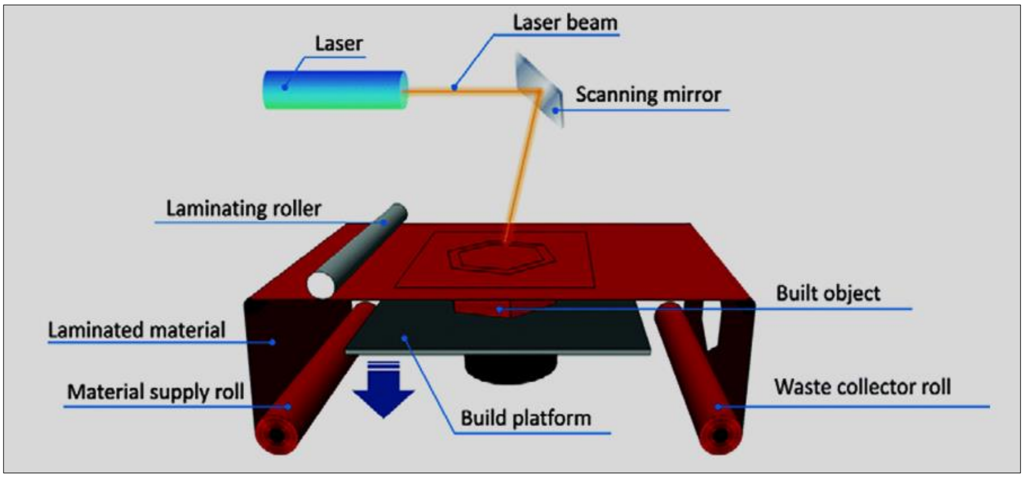

Figure 25: Basic schematic of the LOM process [109]

SUMMARY

This investigation underscores the transformative potential of 3D printing technologies in ceramic manufacturing, enabling unprecedented design flexibility, high precision, and the fabrication of highly intricate geometries that traditional methods often cannot achieve. Additive manufacturing (AM) introduces a range of opportunities, including increased design freedom, functional and material grading, mold-free fabrication processes, and cost-effective solutions for low-volume, complex-shaped ceramic components. Consequently, AM is particularly well-suited to replace traditional injection molding for producing small batches of intricate ceramic parts.

Despite these advantages, the AM of advanced ceramics remains challenging due to their high melting points, inherent brittleness, and low tolerance for processing defects. Achieving high density, optimal surface finish, and dimensional accuracy continues to require significant research and development. Over the past two decades, notable progress has been made—initial efforts focused on adapting existing AM machines to ceramic feedstocks. However, more effective strategies now emphasize integrating the optimization of ceramic material formulations with the development of purpose-built AM equipment specifically designed for ceramics. The choice of AM process is highly dependent on application-specific parameters, including material properties, part size, final density, surface finish, and complexity. Each process offers distinct advantages and limitations, requiring careful selection based on the targeted performance criteria.

As technological advancements improve the consistency, reliability, and scalability of ceramic AM, industry interest and adoption are rapidly increasing. These innovations are poised to improve manufacturing efficiency, reduce costs, and enable the creation of novel, complex ceramic geometries. Ultimately, the continued development and integration of 3D printing in ceramic fabrication will play a crucial role in advancing next-generation ceramic materials and engineering solutions, fostering innovative applications across various industries.

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