ceramics

MDPI

Review

Ceramics 3D Printing: A Comprehensive Overview and Applications, with Brief Insights into Industry and Market

Mohamed Abdelkader [1,2], Stanislav Petrik [1], Daisy Nestler [3] and Mateusz Fijalkowski [1,*]

[1] Department of Advanced Materials, Institute for Nanomaterials, Advanced Technologies and Innovation (CXI), Technical University of Liberec, 461 17 Liberec, Czech Republic
[2] Department of Glass Producing Machines and Robotics, Faculty of Mechanical Engineering, Technical University of Liberec, 461 17 Liberec, Czech Republic
[3] Department of Ligthweight Structures and Polymer Technology, Faculty of Mechanical Engineering, Chemnitz University of Technology, 09111 Chemnitz, Germany
* Correspondence: mateusz.fijalkowski@tul.cz

Abstract: 3D printing enables the creation of complex and sophisticated designs, offering enhanced efficiency, customizability, and cost-effectiveness compared to traditional manufacturing methods. Ceramics, known for their heat resistance, hardness, wear resistance, and electrical insulation properties, are particularly suited for aerospace, automotive, electronics, healthcare, and energy applications. The rise of 3D printing in ceramics has opened new possibilities, allowing the fabrication of complex structures and the use of diverse raw materials, overcoming the limitations of conventional fabrication methods. This review explores the transformative impact of 3D printing, or additive manufacturing, across various sectors, explicitly focusing on ceramics and the different 3D ceramics printing technologies. Furthermore, it presents several active companies in ceramics 3D printing, proving the close relation between academic research and industrial innovation. Moreover, the 3D printed ceramics market forecast shows an annual growth rate (CAGR) of more than 4% in the ceramics 3D printing market, reaching USD 3.6 billion by 2030.

Keywords: 3D printing; additive manufacturing; ceramics; biomedical implants; aerospace; automotive; market forecast

Citation: Abdelkader, M.; Petrik, S.; Nestler, D.; Fijalkowski, M. Ceramics 3D Printing: A Comprehensive Overview and Applications, with Brief Insights into Industry and Market. *Ceramics* **2024**, *7*, 68–85. https://doi.org/10.3390/ceramics7010006

Academic Editor: Gilbert Fantozzi

Received: 10 December 2023
Revised: 11 January 2024
Accepted: 15 January 2024
Published: 18 January 2024

1. Introduction

3D printing or additive manufacturing constructs parts and products additively, layer by layer, allowing the realization of complex and sophisticated designs [1]. 3D printing offers high efficiency, customizability, and a low cost when compared to traditional manufacturing [2] and printed parts dimensions can be tiny as few micrometers, as in the case of microelectromechanical systems (MEMS) [3,4], or as large as a few meters, as in the case of printing complete houses [5,6].

3D printing is used in prototyping and product development to create physical models and functional prototypes quickly and cost-effectively. In healthcare, 3D printing enables the production of customized bone implants [7,8] and anatomical models for surgical planning [9,10]. It is also employed in the aerospace and automotive sectors for lightweight and complex component manufacturing [11–13]. Additionally, it facilitates customized manufacturing of jewelry [14] and fashion accessories [15] in the consumer market.

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 [16]. Ceramics offer high heat resistance, making them suitable for thermal insulation [17]. Their hardness, wear resistance, and chemical inertness are ideal for corrosion-resistant coatings [18] and biomedical implants [19]. Ceramics also possess excellent electrical insulation properties, making them valuable in electronic components [20,21]. Hence, these versatile properties make ceramics preferred in the aerospace, automotive, electronics, healthcare, and energy industries.

The advent of 3D printing for ceramics [22] presents numerous novel opportunities to overcome the limitations of conventional fabrication techniques like casting and machining [23]. These advantages include the capacity to create intricate and precise structures that were previously challenging or impossible to achieve using traditional methods. Additionally, this technology offers the ability to utilize a wide range of feedstock materials in powder form, allowing for the creation of both compact and porous parts and macro-porous ceramic lattice structures [24].

This review article presents the different techniques and processes to prepare 3D printed ceramics, the different materials that are being used and their properties, the design considerations, the ceramic designs optimization for 3D printing, and post-processing and surface finishing techniques. Furthermore, the article highlights the different applications and trends of 3D-printed ceramics.

2. Ceramics 3D Printing Methods

Several 3D printing techniques exist on both research [25] and industrial levels [26,27]. The different and diverse 3D printing technologies can be classified according to the nature of the raw printing materials: liquid, powder, or solid, see Figure 1 [28,29].

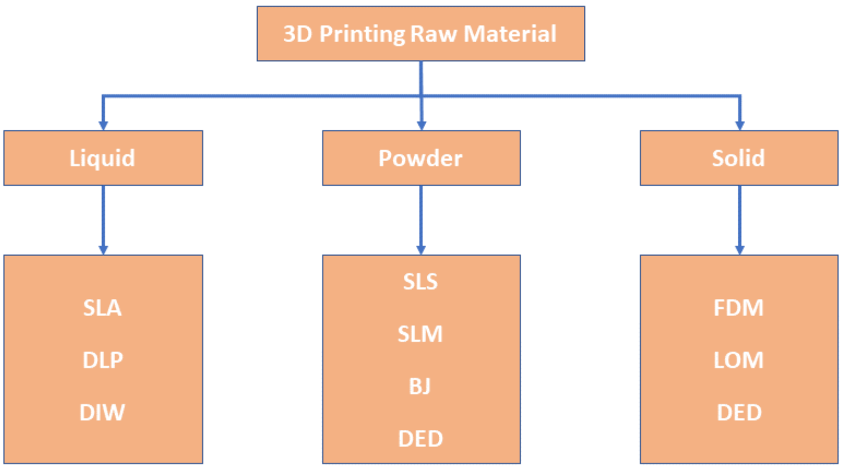

Figure 1. Classification of different 3D printing techniques according to the raw material's nature (Liquid, powder or solid): SLA: Stereolithography, DLP: Digital light processing, BJ: Binder jetting, DIW: Direct ink writing, SLS: Selective laser sintering, SLM: Selective laser melting, FDM: Fused deposition modeling, LOM: Laminated object modeling and DED: Directed energy deposition.

Figure 2 shows the different types of ceramic materials. Ceramic materials can be classified into three types: oxides, non-oxides, and composites [30–32], as shown in the figure.

Ceramics 3D printing as conventional 3D printing covers a multi-stage process, initiating with the design and CAD phase, during which a conceptual design is made using computer-aided design tools [33]. This is followed by File Conversion, where the CAD model is translated into a format that the printer understands (ex: GCODE) [34,35]. Subsequently, Machine Setup involves preparing the 3D printer and calibrating it according to the specific requirements of the ceramic material. The Printing stage then commences, where the ceramic material is meticulously layered and shaped according to the design specifications. Post-printing, the object undergoes a Drying process to eliminate any residual moisture, ensuring structural integrity. This is followed by Sintering, a critical heat treatment step that fuses the ceramic particles at a high temperature to achieve the desired density and strength. The final stage, Post-Processing, encompasses various finishing techniques, such as cleaning and surface smoothing, to enhance the aesthetic and functional qualities of the printed object [36,37]. Figure 3 from left to right shows the steps from producing the design to the finishing steps.

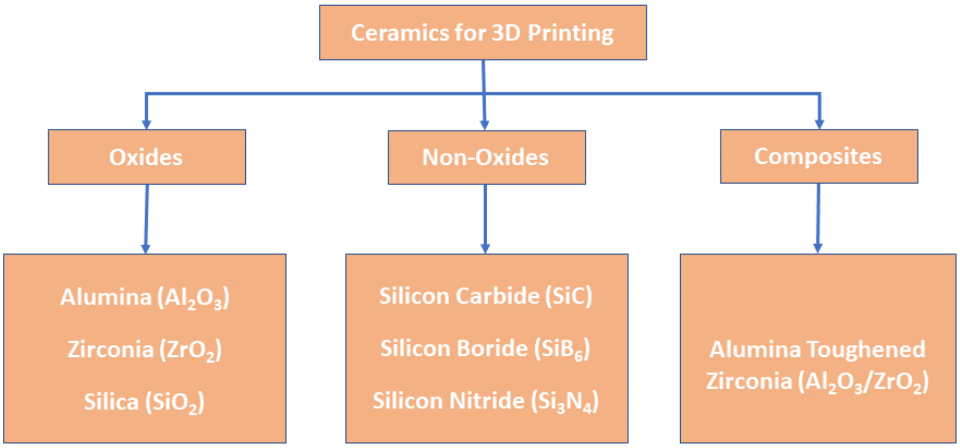

Figure 2. Different ceramic materials categories.

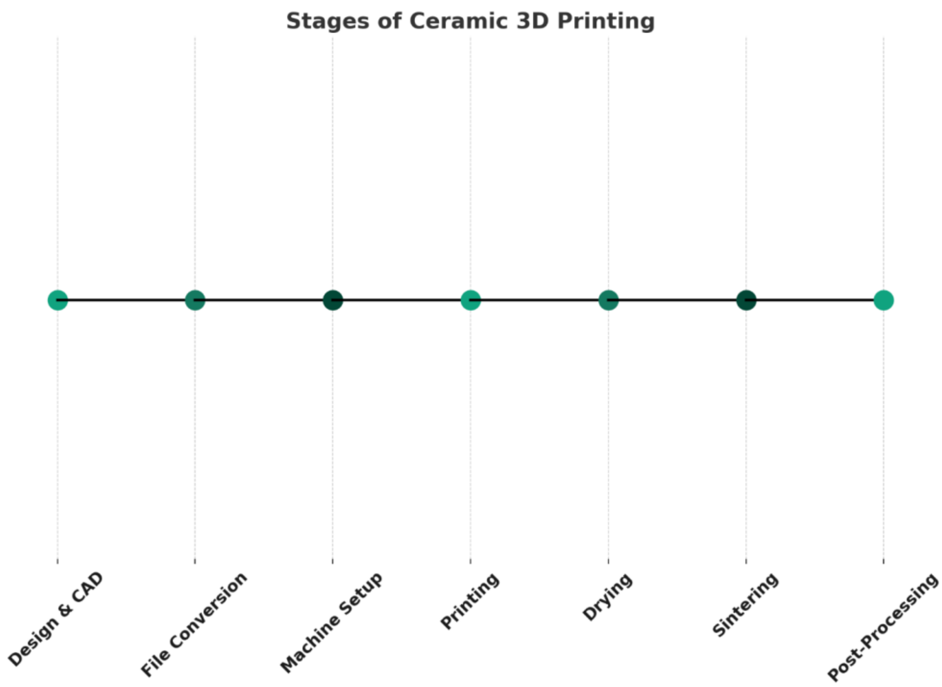

Figure 3. Ceramics 3D printing steps.

2.1. Stereolithography (SLA)

SLA employs a reservoir of liquid photopolymer resin that undergoes curing (solidification) via a UV laser. The laser precisely solidifies the resin layer by layer, fabricating intricate and high-resolution components. 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. Dong's group 3D printed Calcium Phosphate Bioceramics, as shown in Figure 4, using SLA technology. Sotov's group 3D printed barium titanate ($BaTiO_3$)-UV resin using SLA technology, as shown in Figure 5.

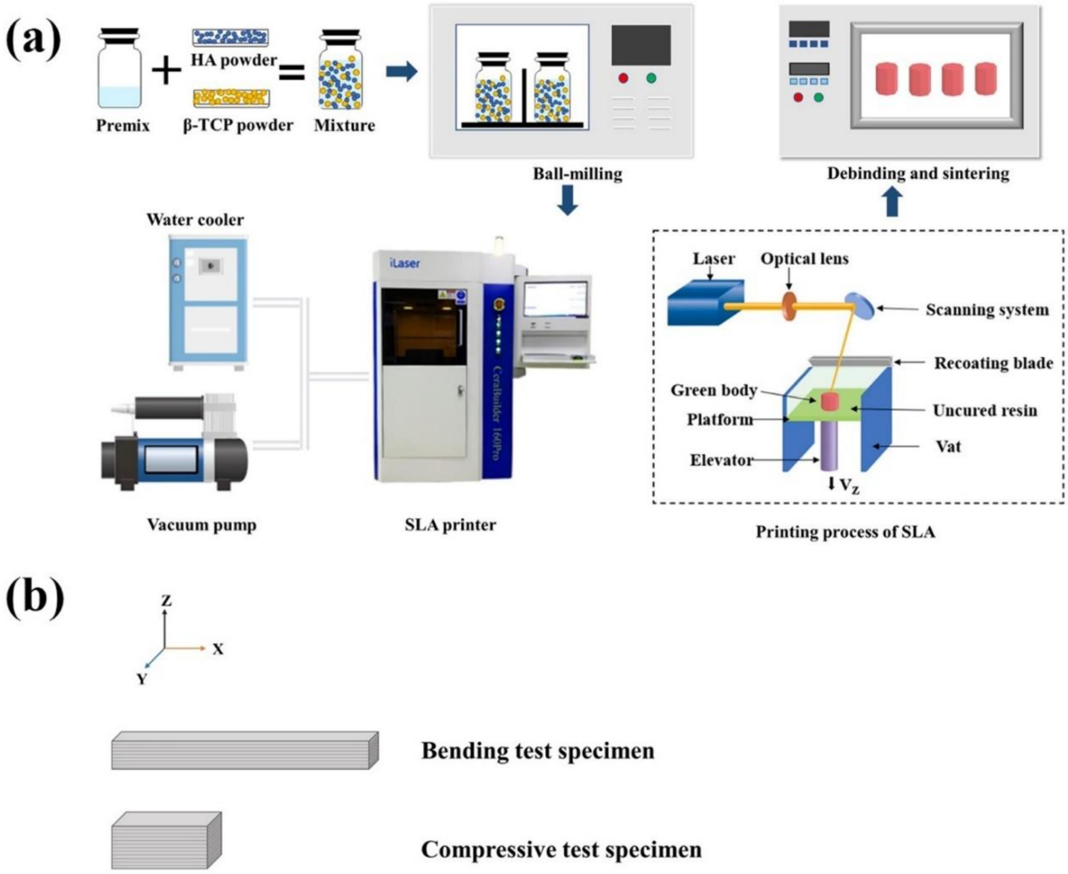

Figure 4. (**a**) The schematic diagram of the SLA 3D printing, (**b**) the printed BCP bioceramics samples [38].

Figure 5. Liquid Crystal Display (LCD)-SLA 3D printing of barium titanate ($BaTiO_3$)-UV Resin) samples [39].

2.2. Digital Light Processing (DLP)

DLP shares similarities with SLA; however, instead of a laser or UV light, it relies on a digital light projector to cure the photopolymer resin. DLP boasts quicker print times when compared to conventional SLA methods. Yao's group fabricated high-performance hydroxyapatite (HA) ceramics using digital light processing (DLP) 3D printing technology. They suggested that the improvement in densification and mechanical properties was achieved by sintering in a wet CO_2 atmosphere [40].

Figure 6 shows a lab made DLP printer that Liu's group used to 3D print a Porous β-Tricalcium Phosphate scaffold that can be used in bone regeneration.

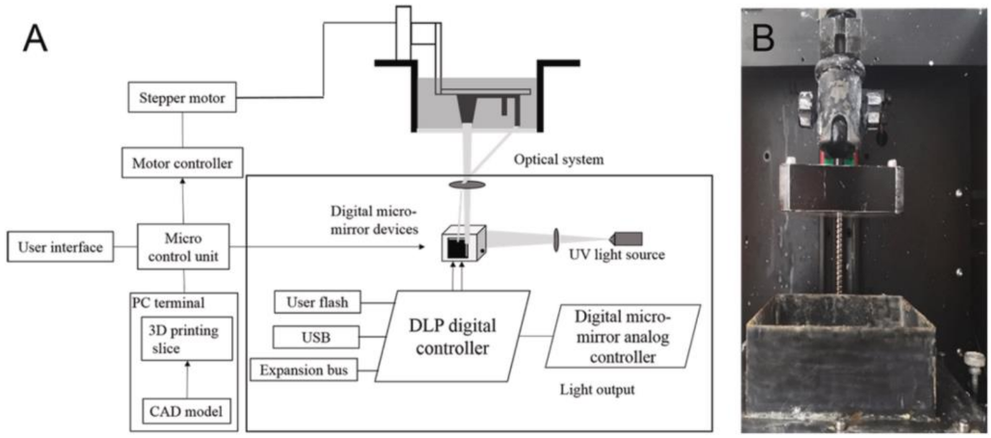

Figure 6. (**A**) DLP process schematic and (**B**) the realized DLP printer [41].

Guo's group demonstrated the potential of Digital Light Processing (DLP) 3D printing for fabricating fine lattice structures in titanium dioxide ceramics, as shown in Figure 7, achieving controllable porosity between 50% and 80%. The research detailed the process of preparing a suitable slurry, optimizing debinding and sintering parameters to prevent cracking and collapse, and achieving strut precision of 200 μm. The resulting rutile phase titanium dioxide ceramics exhibited a compressive strength that improved with decreased porosity, suggesting potential for high-strength applications. This advancement in 3D printing techniques opens new possibilities for the use of titanium dioxide ceramics in fields requiring porous structures, such as bone tissue engineering and catalytic systems [42], as shown in Figure 7.

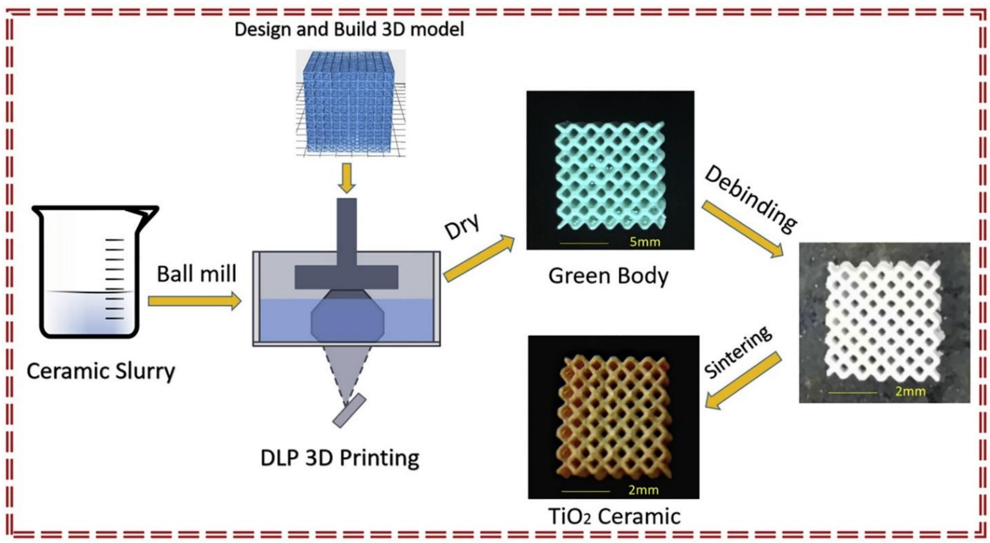

Figure 7. Schematic of the preparation of fine 3DP Lattice structural TiO_2 ceramic [42].

2.3. Direct-Ink-Writing (DIW)

DIW, or Robocasting, is an advanced 3D printing technique fabricating complex structures through precise material deposition layer-by-layer. In this additive manufacturing process, a nozzle or pen-like dispenser releases a liquid or semi-liquid substance, typically a blend of polymers and other components, onto a substrate. The material is then extruded from the nozzle and rapidly solidifies upon deposition, resulting in the desired 3D structure.

DIW finds widespread application in producing ceramic or metal components, which are subsequently consolidated through an oven process. Additionally, it is commonly used for bioprinting various materials, enabling the creation of intricate biological structures.

Jin's group prepared highly porous ceramics that possessed high mechanical and dielectric properties; such structures can have several uses, including in filters, catalyst supports, and thermal insulators, as shown in Figure 8.

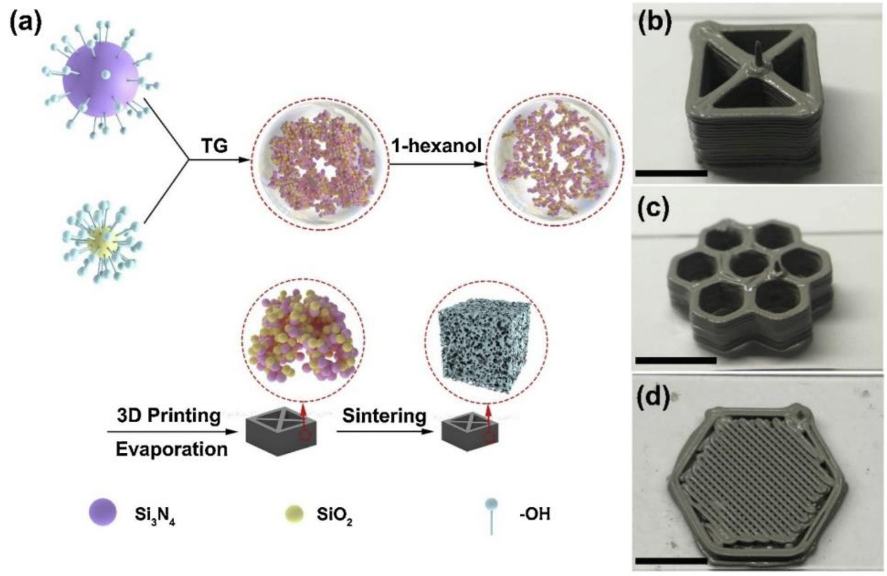

Figure 8. (**a**) Flow chart of the fabrication route for direct ink writing of porous ceramic based on strong colloidal gel ink without sedimentable organic phase. (**b**) 3D printing frame structure. (**c**) 3D printing honeycomb structure. (**d**) 3D printing cellular structure (scale bar 1 cm) [43].

2.4. Selective Laser Sintering (SLS)

SLS 3D printed ceramics can be direct or indirect. In direct SLS, the ceramic powder layers are locally heated and fused using a laser beam as the heat source. On the other hand, indirect SLS involves the laser melting of an organic binder phase within the polymer-ceramic composite powder to create preliminary "green" parts. A debinding and furnace sintering process is required to obtain the final ceramic parts.

SLS underwent extensive development and found application in the production of dense and cellular ceramic components. This technology served various industries by facilitating the creation of parts with complex designs, including integrally cored casting molds. Chen's group realized several advanced fused silica ceramic parts ranging from scaffolds to casting molds [23,44,45]. Figure 9 shows the basic setup of the SLS 3D silica ceramics printing.

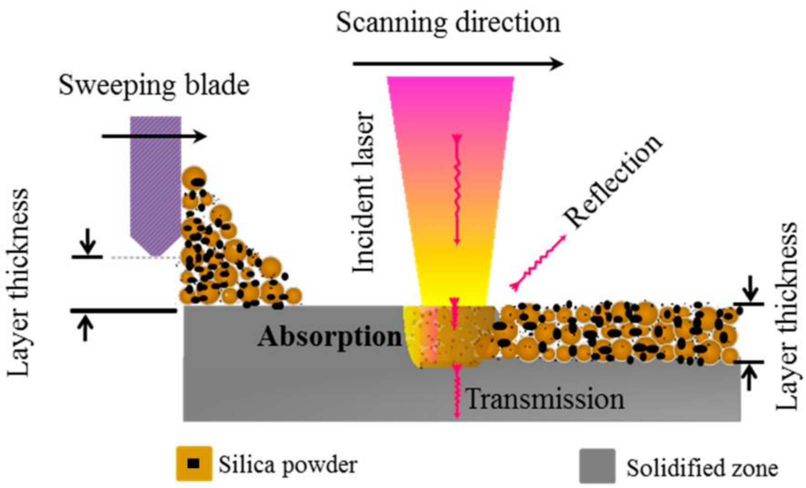

Figure 9. Basic setup of the fused silica 3D printing, adapted from [46].

2.5. Selective Laser Melting (SLM)

SLM is a relatively recent addition to 3D-printing methods, originating in 1995 through the efforts of German scientists [47]. Like SLA, which employs UV light, SLM utilizes a powerful laser beam to construct 3D components. In this process, the laser beam effectively melts and blends diverse metallic powders, selectively joining or welding the particles together as it strikes each thin material layer.

2.6. Binder Jetting (BJ)

Two materials are employed in the binder jetting process: powder-based and binder. The binder functions as an adhesive, bonding the powder layers together. Typically, the binder is a liquid, while the build material is a powder [48]. BJ ceramics 3D printing overcomes the problems of printing complex shapes and eliminates the need for sintering, which shrinks the original printed part's dimensions [49]. The BJ process has been successfully applied to large-scale production of ceramic parts with resolutions in the centimeter scale, while also providing sustainability benefits. Zocca's group demonstrated the capability of BJ by printing a large artwork piece that was 1.28 m wide, with the potential to be printed up to a diameter of 3.5 m using the same equipment [50]. Figure 10 shows the basic setup of the BJ 3D ceramics printing.

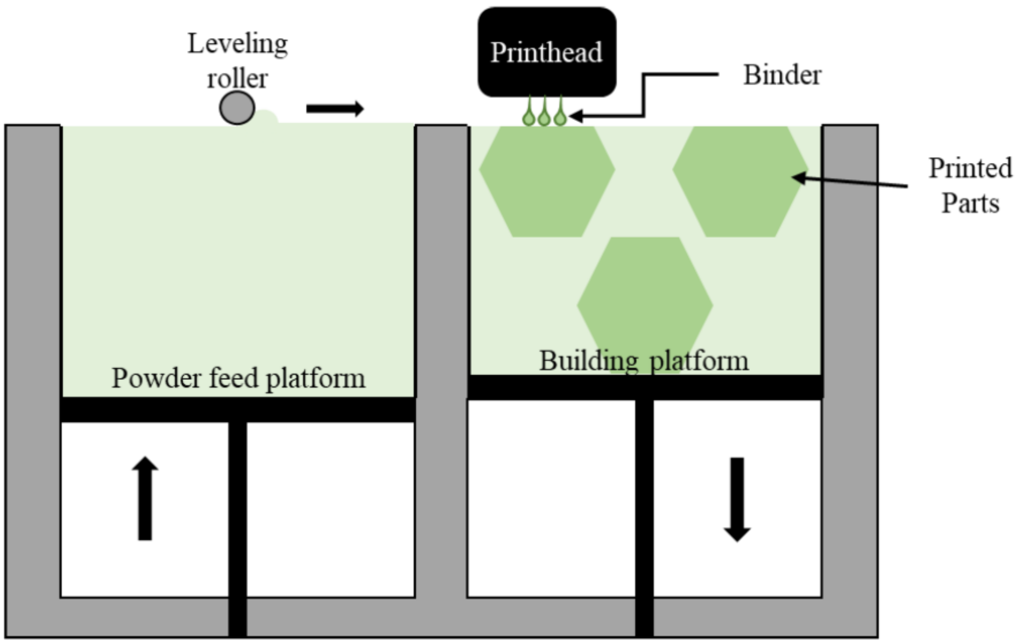

Figure 10. Basic setup of the BJ 3D printing [37].

2.7. 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. Masuda's group modified a FDM 3D printed to print SiC ceramic structures [51], as shown in Figure 11.

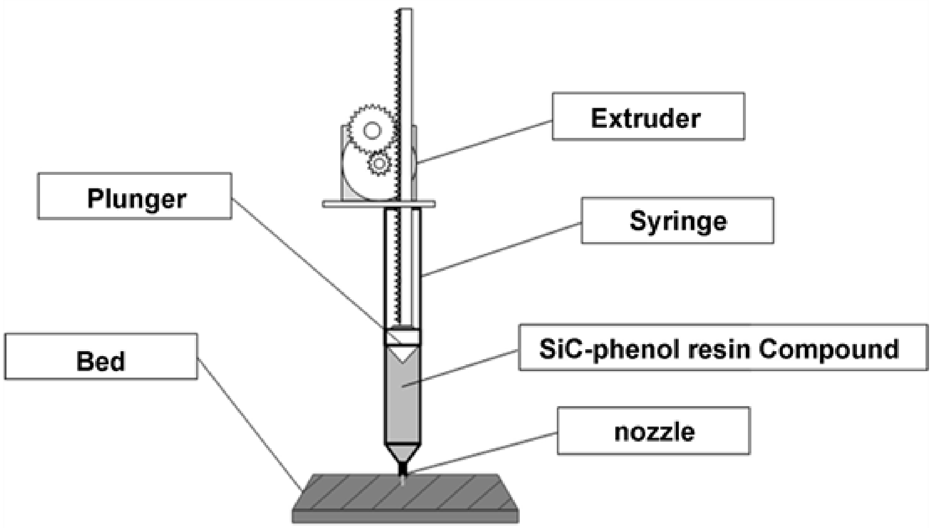

Figure 11. Modified 3D ceramics FDM printer by Masuda's group [51].

2.8. Laminated Object Manufacturing (LOM)

LOM technology is based on bonding sheets of the printed materials and then cutting the unwanted parts; this results in the formation of the desired 3D part, as shown in Figure 12. 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 micron-scaled pore network [52]. Figure 12 shows the basic setup of LOM 3D printing.

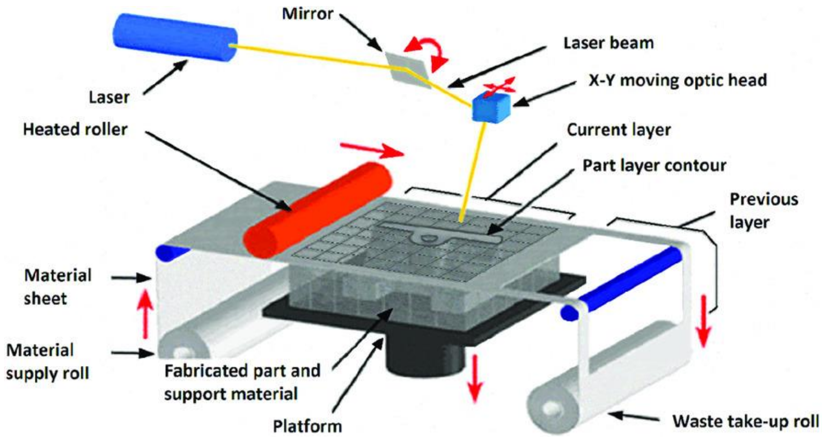

Figure 12. Basic schematic of the LOM process, to which additional processing steps may be added. The continuous flow of sheet material is marked by red arrows [53].

2.9. Directed Energy Deposition (DED)

One of the most promising techniques for 3D ceramic printing is DED. DED is an additive manufacturing process where focused thermal energy, such as a laser or electron beam, is used to fuse materials by melting them as they are deposited [54,55]. In the context of ceramics, DED allows for the creation of intricate and complex structures with high precision, layer by layer. This method not only offers rapid prototyping capabilities but also ensures enhanced mechanical properties and reduced material wastage. The integration of DED in ceramic printing holds immense promise for industries ranging from aerospace to biomedical, paving the way for innovative solutions and designs previously deemed unattainable. Figure 13 shows the basic setup of DED ceramic 3D printing.

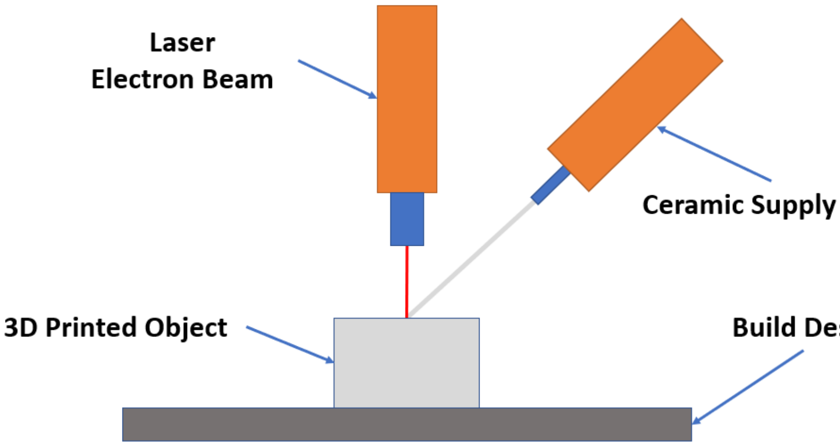

Figure 13. Basic setup of DED ceramic 3D printing.

Table 1 summarizes the different ceramics 3D printing technologies and compares them in different aspects.

Table 1. Comparison between different 3D ceramics techniques.

Raw Material	Technology	Structure Joining Method	Energy Source	Printing Resolution	The Need for Part Support	Raw Material Cost	Printing Cost	Refs.
Liquid	SLA	Polymerization	Laser	µm	Yes	High	middle	[38,39]
Liquid	DLP	Polymerization	Laser	µm	Yes	High	Middle	[41,42]
Liquid	BJ	Bond	Mechanical	mm-cm	No	Middle	Low	[48–50]
Liquid	DIW	Extrusion	Heat	µm-mm	Yes	Low	Low	[43]
Powder	SLS/DED	Powder fusion	Laser	µm-mm	No	Low	High	[23,44]
Powder	SLM	Powder fusion	Laser	µm-mm	No	Low	High	[47]
Solid	LOM	Layer bonding	Laser	µm-mm	No	Middle	Low	[52,53]
Solid	FDM	Extrusion	Heat	mm	No	Middle	Middle	[51]

3. Post-Processing and Finishing

1. Debinding

Debinding is the process of removing the organic binders used during the printing process. The goal is to eliminate these binders without causing defects or damage to the green part. Debinding can be performed using thermal, solvent, or catalytic methods depending on the binder and material system. Careful control of temperature and atmosphere is essential during debinding to avoid cracking or warping of the green part. The removal of the binders prepares the part for the subsequent sintering. The time and temperature used for debinding affect the final ceramic structures [56,57].

2. Sintering

Sintering is a critical step in ceramic 3D printing that transforms the green part into a solid ceramic object. During sintering, the ceramic particles are heated to the point where they bond together, achieving the desired density and mechanical properties. The sintering process involves various parameters, including temperature, atmosphere, and heating rate, which must be precisely controlled to avoid warping and shrinkage.

Sintering of 3D printed ceramics can be conducted using different methods, such as traditional furnace sintering [58,59], microwave sintering [60,61], or spark plasma sintering (SPS) [62,63]. The choice of sintering method depends on the specific ceramic material and the desired properties of the final part.

3. Surface finishing

Surface finishing is a critical aspect of ceramic 3D printing, as it enhances the aesthetics and performance of the final ceramic part. Depending on the application and desired characteristics, various techniques can be applied. For instance, polishing can be used to achieve a smooth and glossy surface finish, while glazing provides a protective and decorative layer [64]. Machining processes may also be employed to precisely shape and refine the part's dimensions. The choice of surface finishing method depends on the specific application and the requirements for the final ceramic part. Achieving the desired surface finish may require several iterations of post-processing.

4. Applications and Market

4.1. Biomedical Implants and Devices

The exploration of 3D printed ceramics and other materials in the field of biomedical implants and devices marks a significant advancement in medical technology. Sandeep's group evaluated the use of PEEK (Polyether ether ketone) and stainless steel, highlighting their biocompatibility and suitability for medical applications [65]. Das's group focused on integrating 2D nanomaterials with ceramics 3D printing, revealing potential advancements in drug delivery and tissue engineering [66]. Mamo et al. provided a comprehensive review of 3D printing technologies in the medical sector, including 3D printed ceramics, discussing the challenges and future perspectives of using materials like ceramics and composites [67]. Lastly, Samuel Hales et al. emphasized the integration of nanomaterials in 3D printed devices, leading to the creation of innovative biomedical and bioelectronic devices [68]. These studies showcased the significant advancements and diverse applications of 3D printing and 3D printed ceramics in the biomedical field. This innovative approach of ceramics 3D printing for biomedical applications offers several benefits:

1. Customization and Personalization: 3D printing allows for the creation of implants and devices that are custom fitted to individual patients. This personalization ensures better compatibility and comfort, leading to improved patient outcomes.
2. Complex Structures: 3D printing makes it possible to create structures with intricate geometries that mimic the natural complexity of human tissues and bones. This capability is crucial for implants that need to integrate seamlessly with the body's own systems.
3. Material Diversity: The use of various materials, including ceramics, polymers, and metals, in 3D printing provides flexibility in terms of mechanical properties and biocompatibility. Ceramics, for instance, are particularly useful for their bone-like properties and durability.
4. Rapid Prototyping: The technology enables quick production and iteration of prototypes. This rapid prototyping is essential in the medical field, where time is often a critical factor.
5. Cost-Effectiveness: Producing custom implants and devices traditionally is expensive. 3D printing can reduce these costs, making personalized medical care more accessible.
6. Improved Healing and Integration: 3D printed materials can be designed to encourage tissue growth and integration, leading to faster and more effective healing.
7. Innovation in Treatment: The ability to print complex devices opens new possibilities in treating conditions that were previously difficult to manage with standard implants.
8. Reduced Surgical Time: Customized implants that fit perfectly can reduce the duration of surgeries and the associated risks.

4.2. Aerospace and Automotive Components

3D printed ceramics are transforming the aerospace and automotive industries by offering groundbreaking solutions to intricate engineering problems. Advanced ceramics like aluminum oxide, silicon nitride, silicon carbide, and zirconia are prized for their high resistance to heat, oxidation, abrasion, and their mechanical and dimensional stability [69–71]. These properties make ceramics ideal for next-generation spacecraft construction, particularly for parts exposed to high stresses [72]. For example, the aerospike engine nozzle, made of silicon nitride, is capable of withstanding temperatures over 1200 °C and exemplifies the durability and heat resistance of these materials [73]. The integration of 3D printed ceramics in the aerospace and automotive industries showcases the material's potential in creating lighter, stronger, and more efficient components. This technology stands out due to several factors:

1. Enhanced Material Properties: Ceramics are known for their high strength, thermal resistance, and durability, making them ideal for aerospace and automotive applications. 3D printing allows for the production of ceramic parts that are lighter yet stronger, significantly improving the performance and efficiency of vehicles and aircraft.
2. Complex Geometries: Traditional manufacturing methods often fall short in creating complex shapes required in aerospace and automotive engineering. 3D printing excels at this, allowing for the creation of components with intricate designs and internal structures that were previously impossible or too costly to produce.
3. Reduced Weight and Increased Efficiency: In both aerospace and automotive sectors, weight is a critical factor. 3D printed ceramic parts contribute to significant weight reduction, leading to improved fuel efficiency and lower emissions, crucial in an era where environmental impact is a major concern.
4. Customization and Rapid Prototyping: 3D printing enables the quick production of customized parts tailored to specific requirements. This flexibility is invaluable for prototyping and testing new designs, speeding up the development process and allowing for more innovation and experimentation.
5. Cost Reduction: Manufacturing complex parts often involves high costs, especially in small volumes. 3D printing reduces these costs by simplifying the production process and minimizing material waste, making it a cost-effective solution for both small-scale prototypes and larger production runs.
6. Improved Performance: The unique properties of ceramics, combined with the precision of 3D printing, result in parts that perform better under extreme conditions. This is particularly important in aerospace applications where components need to withstand high temperatures and pressures.
7. Sustainability: The additive manufacturing process of 3D printing is more sustainable compared to traditional subtractive methods. It produces less waste and consumes less energy, aligning with the growing trend towards more environmentally friendly manufacturing practices in these industries.

4.3. Consumer Electrical Goods and Electronics

The emergence of 3D-printed ceramics in the manufacturing of Printed Circuit Boards (PCBs) represents a significant leap in the field of consumer electronics. Traditional PCB fabrication is a time-consuming process involving repetitive milling and etching, using hazardous chemicals, and generating significant waste. In consumer electronics, rapid prototyping is essential for product development. The ceramics 3D printing can be crucial in electronics for high-temperature environments [74]. This innovative approach stands out for several key reasons:

1. In-House Manufacturing: With 3D printing technology, companies can produce PCBs in-house. This capability is crucial in circumventing supply chain issues, a common challenge in traditional manufacturing. It ensures a more stable and reliable production flow, thereby reducing the dependency on external suppliers and mitigating risks related to delays or disruptions.

2. Complex Circuit Design: 3D printing allows for the creation of more intricate and complex circuit designs than traditional methods. This flexibility enables the development of advanced electronic devices with enhanced capabilities, as 3D printing can accurately produce fine details and accommodate unique geometric configurations.
3. Speed and Cost-Effectiveness: The process of 3D printing PCBs is generally faster compared to traditional manufacturing techniques. This efficiency is due to the direct-from-design-to-production approach, which eliminates several steps involved in conventional manufacturing. Moreover, 3D printing can be more cost-effective, especially for small batch production and prototyping, as it requires less material waste and reduces the need for multiple tools and molds.
4. Customization and Prototyping: 3D printing offers unparalleled customization options. Designers can quickly alter designs and produce prototypes without the need for extensive retooling, facilitating rapid prototyping and testing. This agility accelerates the development cycle, allowing for faster iteration and innovation.
5. Environmental Impact: The additive nature of 3D printing, where material is added rather than removed, leads to less waste compared to subtractive manufacturing processes. This aspect contributes to more sustainable manufacturing practices, aligning with the growing emphasis on environmental responsibility in the electronics industry.

A new insight is relating the type of ceramics, their properties, and the possible applications sectors. Table 2 shows this relationship.

Table 2. Ceramics, their properties, and possible applications.

Type of Ceramic	Properties	Application Sector	Ref.
Oxides	High thermal stability, electrical insulation	Electronics, aerospace	[23]
Non-Oxides	Enhanced mechanical strength, chemical resistance	Biomedical implants, chemical processing	[75]
Composites	Improved toughness, multi-functional characteristics	Automotive, aerospace components	[76]
Hybrids	Synergistic properties, customizable	Electronics, biomedical devices	[77]
Dense	High density, uniform microstructure	Optical components, energy storage	[23]
Cellular	Lightweight, porous structure	Filtration systems, scaffolds in tissue engineering	[75]

The realm of 3D printing ceramics is a vibrant intersection where innovative academic research meets cutting-edge industrial application. Various companies have become pivotal in this field, each contributing unique technologies and insights that have expanded the boundaries of what is possible with ceramic materials. Companies like 3D Systems [78], Voxeljet AG [79], Admatec BV [80], Lithoz [81], Wasp S.r.l. [82], Tethon 3D [83], 3Dceram [84], Prodways [85], 3D potters [86], Nanoe [87], and more are at the forefront of this revolution. They are not only implementing and refining existing 3D printing techniques, but also pioneering new methods and materials, thereby transforming the way ceramics are used in industries ranging from biomedical to aerospace. The synergy between academic research and these industrial companies is crucial. It facilitates the translation of theoretical innovations into practical, market-ready solutions, ensuring that the advancements in ceramic 3D printing continue to evolve at a pace that matches the rapid growth of both technological capabilities and market demands. This collaborative approach is key to unlocking the full potential of 3D printed ceramics, paving the way for new applications and more efficient manufacturing processes. Table 3 shows several companies that are active in the ceramics 3D printing industry and market, alongside their unique aspects and technology.

Table 3. Examples of active companies in the area of ceramics 3D printing and their leading technologies and business focus.

Company	Technologies Used	Products/Contributions	General Insights	Ref.
3D Systems (Rock Hill, SC, USA)	Various 3D printing technologies	A wide range of 3D printers and materials, including ceramics	Known for pioneering in 3D printing, with a focus on innovation and versatility.	[78]
Voxeljet AG (Friedberg, Germany)	Powder Bed Fusion (PBF), Binder Jetting	Large-format industrial 3D printing systems, especially for complex ceramic components	Specializes in high-speed, large-scale 3D printing solutions.	[79]
Admatec BV (Goirle, The Neitherlands)	Lithography-based Ceramic Manufacturing (LCM)	Advanced ceramic 3D printers for high-quality ceramic parts	Focuses on precision and quality in ceramic 3D printing.	[80]
Lithoz (Wien, Austria)	LCM technology	Ceramic 3D printers and materials, including the recent LithaGlass	Renowned for high-precision ceramic printing and innovative material development.	[81]
Wasp S.r.l. (Massa Lombarda, Italy)	Delta 3D printing technology	3D printers capable of handling ceramic materials	Known for sustainable and cost-effective 3D printing solutions.	[82]
Tethon 3D (Omaha, NE, USA)	Various 3D printing technologies	Ceramic powders, 3D printing services, and proprietary 3D printing technologies including their own Tethonite® ceramic powders and Bison 1000 DLP printer	Tethon 3D stands out for its focus on proprietary materials and printers tailored for ceramic 3D printing, bridging the gap between art and industry with a comprehensive approach	[83]
3Dceram (Bonnac-la-Côte, France)	Stereolithography (SLA)	Customized ceramic components and 3D printers	Offers a unique blend of 3D printing services and ceramic expertise.	[84]
Prodways (Montigny-le-Bretonneux, France)	Moving Light technology	Industrial 3D printers for ceramics and other materials	Known for its high-resolution printers and innovative technologies.	[85]
3D Potter (Stuart, FL, USA)	Custom 3D printing solutions- Clay printing	Specializes in large format 3D printers for ceramics	Focuses on versatility and custom solutions in 3D printing.	[86]
Nanoe (Ballainvilliers, France)	Zetamix technology	Ceramic filaments and 3D printers for accessible ceramic printing	Innovates in making ceramic 3D printing more accessible and versatile.	[87]

The global forecast of the 3D printed ceramics shows a promising growth in the market. Figure 14 shows the growth in the global 3D printed ceramics market, with a projected growth of the global ceramic 3D printing market from 2021 to 2030. In 2021, the market was valued at approximately USD 2.5 billion and is expected to grow to around USD 3.55 billion by 2030. This trend represents a significant increase, reflecting the expanding role and adoption of ceramic 3D printing technologies in various industries. The significant rise reflects the growing adoption of ceramics 3D printing technology in different applications, including aerospace, defense, and healthcare sectors.

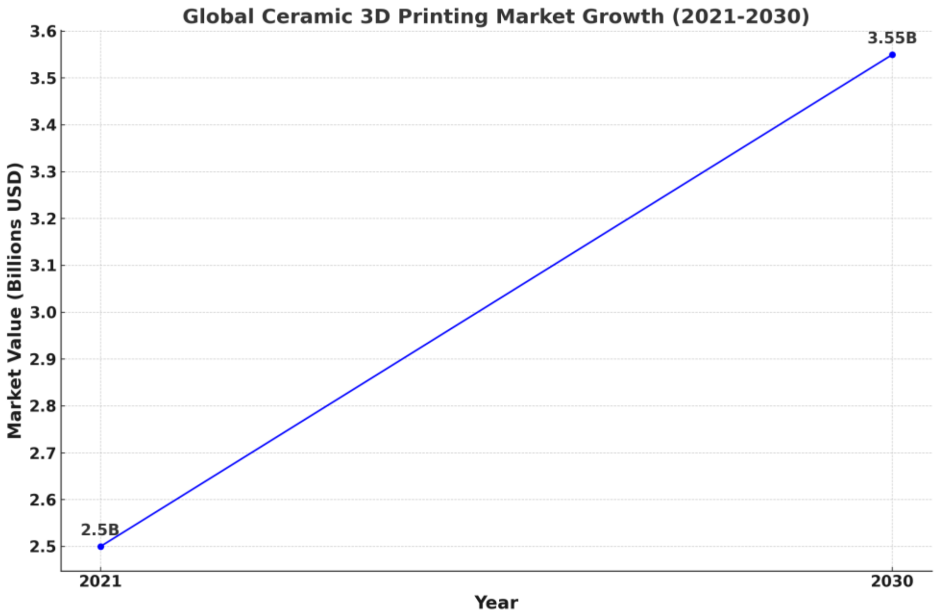

Figure 14. 3D printed ceramics forecast according to spherical insights market's forecast data for the years 2021 and 2030 [88].

5. Conclusions

In conclusion, ceramics exhibit exceptional material properties, encompassing elevated thermal resistance, electrical insulating characteristics, high hardness, and notable wear resistance. The incorporation of additive manufacturing, specifically 3D printing, into the realm of ceramics manufacturing represents a seminal advancement in the field of materials science and engineering. This study underscores how this technology transcends the confines of traditional ceramics manufacturing methodologies, extending design boundaries and augmenting the functional attributes of ceramic components. The capacity to fabricate intricate geometries and microstructures hitherto unattainable via conventional means heralds a new era of possibilities across various industries, notably within the aerospace, healthcare, electronics, and automotive sectors.

Furthermore, this investigation highlights the ongoing progress in optimizing raw material compositions and refining printing techniques specific to 3D printed ceramics. These advancements signify the immense potential of 3D printed ceramics in addressing distinctive industrial challenges, thereby establishing a fertile ground for pioneering applications and continued research endeavors in the realm of advanced materials.

In essence, the confluence of ceramics and 3D printing technology signifies a harmonious unification of established material excellence and innovative additive manufacturing capabilities, particularly in the industrial and consumer market. This fusion holds significant promise, and as research and development efforts persist, it is poised to engender a transformative paradigm shift across diverse industries. Ultimately, this synergy promises to reshape the trajectory of materials science and engineering, with far-reaching implications and pioneering contributions to scholarly and industrial domains alike.

Author Contributions: Conceptualization, M.F. and S.P.; writing—original draft, M.A.; writing—review and editing, D.N. and S.P.; funding acquisition, M.F. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the project no. TH71020002 "Ceramics with sensing capabilities for high temperature applications" (CENTAUR) provided by the Technology Agency of the Czech Republic within the Programme of applied research and experimental development EPSILON (M-ERA.NET 2 Call 2019).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Yang, J.; Li, N.; Shi, J.; Tang, W.; Zhang, G.; Zhang, F. Foundation of 3D Printing and CAD File Formats Used in the Industry. In *Multimaterial 3D Printing Techology*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 17–42. ISBN 978-0-08-102991-6.
2. Zhang, L.; Zhou, L.; Xiao, L. 3D Printing with Cloud Manufacturing. In *Customized Production through 3D Printing in Cloud Manufacturing*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 27–38. ISBN 978-0-12-823501-0.
3. Blachowicz, T.; Ehrmann, A. 3D Printed MEMS Technology—Recent Developments and Applications. *Micromachines* **2020**, *11*, 434. [CrossRef] [PubMed]
4. Pagliano, S.; Marschner, D.E.; Maillard, D.; Ehrmann, N.; Stemme, G.; Braun, S.; Villanueva, L.G.; Niklaus, F. Micro 3D Printing of a Functional MEMS Accelerometer. *Microsyst. Nanoeng.* **2022**, *8*, 105. [CrossRef] [PubMed]
5. Sakin, M.; Kiroglu, Y.C. 3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM. *Energy Procedia* **2017**, *134*, 702–711. [CrossRef]
6. Wu, P.; Wang, J.; Wang, X. A Critical Review of the Use of 3-D Printing in the Construction Industry. *Autom. Constr.* **2016**, *68*, 21–31. [CrossRef]
7. Habibovic, P.; Gbureck, U.; Doillon, C.; Bassett, D.; Vanblitterswijk, C.; Barralet, J. Osteoconduction and Osteoinduction of Low-Temperature 3D Printed Bioceramic Implants. *Biomaterials* **2008**, *29*, 944–953. [CrossRef]
8. Li, Z.; Wang, Q.; Liu, G. A Review of 3D Printed Bone Implants. *Micromachines* **2022**, *13*, 528. [CrossRef]
9. Ballard, D.H.; Mills, P.; Duszak, R.; Weisman, J.A.; Rybicki, F.J.; Woodard, P.K. Medical 3D Printing Cost-Savings in Orthopedic and Maxillofacial Surgery: Cost Analysis of Operating Room Time Saved with 3D Printed Anatomic Models and Surgical Guides. *Acad. Radiol.* **2020**, *27*, 1103–1113. [CrossRef]
10. Formisano, M.; Iuppariello, L.; Mirone, G.; Cinalli, G.; Casaburi, A.; Guida, P.; Clemente, F. 3D Printed Anatomical Model for Surgical Planning: A Pediatric Hospital Experience. In Proceedings of the 2021 International Conference on e-Health and Bioengineering (EHB), Iasi, Romania, 18 November 2021; IEEE, Piscataway, NJ, USA, 2021; pp. 1–4.
11. Garmabi, M.M.; Shahi, P.; Tjong, J.; Sain, M. 3D Printing of Polyphenylene Sulfide for Functional Lightweight Automotive Component Manufacturing through Enhancing Interlayer Bonding. *Addit. Manuf.* **2022**, *56*, 102780. [CrossRef]
12. Teniente, J.; Iriarte, J.C.; Caballero, R.; Valcazar, D.; Goni, M.; Martinez, A. 3-D Printed Horn Antennas and Components Performance for Space and Telecommunications. *Antennas Wirel. Propag. Lett.* **2018**, *17*, 2070–2074. [CrossRef]
13. Tuazon, B.J.; Custodio, N.A.V.; Basuel, R.B.; Delos Reyes, L.A.; Dizon, J.R.C. 3D Printing Technology and Materials for Automotive Application: A Mini-Review. *KEM* **2022**, *913*, 3–16. [CrossRef]
14. Yap, Y.L.; Yeong, W.Y. Additive Manufacture of Fashion and Jewellery Products: A Mini Review: This Paper Provides an Insight into the Future of 3D Printing Industries for Fashion and Jewellery Products. *Virtual Phys. Prototyp.* **2014**, *9*, 195–201. [CrossRef]
15. Chakraborty, S.; Biswas, M.C. 3D Printing Technology of Polymer-Fiber Composites in Textile and Fashion Industry: A Potential Roadmap of Concept to Consumer. *Compos. Struct.* **2020**, *248*, 112562. [CrossRef]
16. Boccaccini, A.R. Ceramics. In *Biomaterials, Artificial Organs and Tissue Engineering*; Elsevier: Amsterdam, The Netherlands, 2005; pp. 26–36. ISBN 978-1-85573-737-2.
17. Kichkailo, O.V.; Levitskii, I.A. Lithium-Bearing Heat-Resistant Ceramics (A Review). *Glass Ceram.* **2005**, *62*, 178–183. [CrossRef]
18. Hu, H.; Mao, L.; Yin, S.; Liao, H.; Zhang, C. Wear-Resistant Ceramic Coatings Deposited by Liquid Thermal Spraying. *Ceram. Int.* **2022**, *48*, 33245–33255. [CrossRef]
19. Alizadeh-Osgouei, M.; Li, Y.; Wen, C. A Comprehensive Review of Biodegradable Synthetic Polymer-Ceramic Composites and Their Manufacture for Biomedical Applications. *Bioact. Mater.* **2019**, *4*, 22–36. [CrossRef]
20. Hong, K.; Lee, T.H.; Suh, J.M.; Yoon, S.-H.; Jang, H.W. Perspectives and Challenges in Multilayer Ceramic Capacitors for next Generation Electronics. *J. Mater. Chem. C* **2019**, *7*, 9782–9802. [CrossRef]
21. Zeb, A.; Milne, S.J. High Temperature Dielectric Ceramics: A Review of Temperature-Stable High-Permittivity Perovskites. *J. Mater. Sci. Mater. Electron.* **2015**, *26*, 9243–9255. [CrossRef]
22. Wang, T.; Lu, X.; Wang, A. A Review: 3D Printing of Microwave Absorption Ceramics. *Int. J. Appl. Ceram. Technol.* **2020**, *17*, 2477–2491. [CrossRef]
23. Chen, Z.; Li, Z.; Li, J.; Liu, C.; Lao, C.; Fu, Y.; Liu, C.; Li, Y.; Wang, P.; He, Y. 3D Printing of Ceramics: A Review. *J. Eur. Ceram. Soc.* **2019**, *39*, 661–687. [CrossRef]
24. Filippov, Y.Y.; Murashko, A.M.; Evdokimov, P.V.; Safronova, T.V.; Putlayev, V.I. Stereolithography 3D Printed Calcium Pyrophosphate Macroporous Ceramics for Bone Grafting. *Open Ceram.* **2021**, *8*, 100185. [CrossRef]
25. Zhao, Y.; Zhu, J.; He, W.; Liu, Y.; Sang, X.; Liu, R. 3D Printing of Unsupported Multi-Scale and Large-Span Ceramic via near-Infrared Assisted Direct Ink Writing. *Nat. Commun.* **2023**, *14*, 2381. [CrossRef] [PubMed]
26. 3D Printing | Advanced Ceramics. Available online: https://www.bosch-advanced-ceramics.com/implementations/processes/3d-printing/ (accessed on 20 November 2023).

27. 3D Printed Ceramics. Available online: https://www.sme.org/technologies/articles/2022/june/3d-printed-ceramics/ (accessed on 20 November 2023).
28. Ranjan, R.; Kumar, D.; Kundu, M.; Chandra Moi, S. A Critical Review on Classification of Materials Used in 3D Printing Process. *Mater. Today Proc.* **2022**, *61*, 43–49. [CrossRef]
29. Izdebska-Podsiadły, J. Classification of 3D Printing Methods. In *Polymers for 3D Printing*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 23–34. ISBN 978-0-12-818311-3.
30. Different Types of Ceramics (Oxides, Non-Oxides and Composites). Available online: https://www.thomasnet.com/articles/custom-manufacturing-fabricating/types-of-ceramics/ (accessed on 20 November 2023).
31. Kurian, M.; Thankachan, S. Introduction: Ceramics Classification and Applications. In *Ceramic Catalysts*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 1–17. ISBN 978-0-323-85746-8.
32. Ceramics: Properties, Application and Classification of Ceramics. Available online: https://www.sciencedoze.com/2021/02/ceramics-properties-application-classification.html (accessed on 20 November 2023).
33. Regassa Hunde, B.; Debebe Woldeyohannes, A. Future Prospects of Computer-Aided Design (CAD)—A Review from the Perspective of Artificial Intelligence (AI), Extended Reality, and 3D Printing. *Results Eng.* **2022**, *14*, 100478. [CrossRef]
34. Baumann, W.; Schuermann, F.; Odefey, M.; Pfeil, U.M. From GCode to STL: Reconstruct Models from 3D Printing as a Service. *IOP Conf. Ser. Mater. Sci. Eng.* **2017**, *280*, 012033. [CrossRef]
35. Duong, T.H.; Jaksic, N.I.; DePalma, J.L.; Ansaf, B.; Daniel, D.M.; Armijo, J.; Galaviz, M. G-Code Visualization and Editing Program for Inexpensive Metal 3D Printing. *Procedia Manuf.* **2018**, *17*, 22–28. [CrossRef]
36. Karakurt, I.; Lin, L. 3D Printing Technologies: Techniques, Materials, and Post-Processing. *Curr. Opin. Chem. Eng.* **2020**, *28*, 134–143. [CrossRef]
37. Chavez, L.A.; Ibave, P.; Wilburn, B.; Alexander, D.; Stewart, C.; Wicker, R.; Lin, Y. The Influence of Printing Parameters, Post-Processing, and Testing Conditions on the Properties of Binder Jetting Additive Manufactured Functional Ceramics. *Ceramics* **2020**, *3*, 65–77. [CrossRef]
38. Dong, D.; Su, H.; Li, X.; Fan, G.; Zhao, D.; Shen, Z.; Liu, Y.; Guo, Y.; Yang, C.; Liu, L.; et al. Microstructures and Mechanical Properties of Biphasic Calcium Phosphate Bioceramics Fabricated by SLA 3D Printing. *J. Manuf. Process.* **2022**, *81*, 433–443. [CrossRef]
39. Sotov, A.; Kantyukov, A.; Popovich, A.; Sufiiarov, V. LCD-SLA 3D Printing of $BaTiO_3$ Piezoelectric Ceramics. *Ceram. Int.* **2021**, *47*, 30358–30366. [CrossRef]
40. Yao, Y.; Qin, W.; Xing, B.; Sha, N.; Jiao, T.; Zhao, Z. High Performance Hydroxyapatite Ceramics and a Triply Periodic Minimum Surface Structure Fabricated by Digital Light Processing 3D Printing. *J. Adv. Ceram.* **2021**, *10*, 39–48. [CrossRef]
41. Liu, S.; Mo, L.; Bi, G.; Chen, S.; Yan, D.; Yang, J.; Jia, Y.-G.; Ren, L. DLP 3D Printing Porous β-Tricalcium Phosphate Scaffold by the Use of Acrylate/Ceramic Composite Slurry. *Ceram. Int.* **2021**, *47*, 21108–21116. [CrossRef]
42. Guo, J.; Zeng, Y.; Li, P.; Chen, J. Fine Lattice Structural Titanium Dioxide Ceramic Produced by DLP 3D Printing. *Ceram. Int.* **2019**, *45*, 23007–23012. [CrossRef]
43. Jin, H.; Yang, Z.; Zhong, J.; Cai, D.; Li, H.; Jia, D.; Zhou, Y. Mechanical and Dielectric Properties of 3D Printed Highly Porous Ceramics Fabricated via Stable and Durable Gel Ink. *J. Eur. Ceram. Soc.* **2019**, *39*, 4680–4687. [CrossRef]
44. Chen, Z.; Li, D.; Zhou, W.; Wang, L. Curing Characteristics of Ceramic Stereolithography for an Aqueous-Based Silica Suspension. *Proc. Inst. Mech. Eng. Part. B J. Eng. Manuf.* **2010**, *224*, 641–651. [CrossRef]
45. Gao, B.; Zhao, H.; Peng, L.; Sun, Z. A Review of Research Progress in Selective Laser Melting (SLM). *Micromachines* **2022**, *14*, 57. [CrossRef]
46. Chang, S.; Li, L.; Lu, L.; Fuh, J. Selective Laser Sintering of Porous Silica Enabled by Carbon Additive. *Materials* **2017**, *10*, 1313. [CrossRef] [PubMed]
47. Ratna, D. Properties and Processing of Thermoset Resin. In *Recent Advances and Applications of Thermoset Resins*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 173–292. ISBN 978-0-323-85664-5.
48. Gibson, I.; Rosen, D.; Stucker, B.; Khorasani, M. Binder Jetting. In *Additive Manufacturing Technologies*; Springer International Publishing: Cham, Switzerland, 2021; pp. 237–252. ISBN 978-3-030-56126-0.
49. Lv, X.; Ye, F.; Cheng, L.; Fan, S.; Liu, Y. Binder Jetting of Ceramics: Powders, Binders, Printing Parameters, Equipment, and Post-Treatment. *Ceram. Int.* **2019**, *45*, 12609–12624. [CrossRef]
50. Zocca, A.; Colombo, P.; Gomes, C.M.; Günster, J. Additive Manufacturing of Ceramics: Issues, Potentialities, and Opportunities. *J. Am. Ceram. Soc.* **2015**, *98*, 1983–2001. [CrossRef]
51. Masuda, H.; Ohta, Y.; Kitayama, M. Additive Manufacturing of SiC Ceramics with Complicated Shapes Using the FDM Type 3D-Printer. *J. Mater. Sci. Chem. Eng.* **2019**, *7*, 1–12. [CrossRef]
52. Zhang, G.; Guo, J.; Chen, H.; Cao, Y. Organic Mesh Template-Based Laminated Object Manufacturing to Fabricate Ceramics with Regular Micron Scaled Pore Structures. *J. Eur. Ceram. Soc.* **2021**, *41*, 2790–2795. [CrossRef]
53. Dermeik, B.; Travitzky, N. Laminated Object Manufacturing of Ceramic-Based Materials. *Adv. Eng. Mater.* **2020**, *22*, 2000256. [CrossRef]
54. Svetlizky, D.; Das, M.; Zheng, B.; Vyatskikh, A.L.; Bose, S.; Bandyopadhyay, A.; Schoenung, J.M.; Lavernia, E.J.; Eliaz, N. Directed Energy Deposition (DED) Additive Manufacturing: Physical Characteristics, Defects, Challenges and Applications. *Mater. Today* **2021**, *49*, 271–295. [CrossRef]

55. Lalegani Dezaki, M.; Serjouei, A.; Zolfagharian, A.; Fotouhi, M.; Moradi, M.; Ariffin, M.K.A.; Bodaghi, M. A Review on Additive/Subtractive Hybrid Manufacturing of Directed Energy Deposition (DED) Process. *Adv. Powder Mater.* **2022**, *1*, 100054. [CrossRef]
56. Li, H.; Liu, Y.; Liu, Y.; Zeng, Q.; Hu, K.; Lu, Z.; Liang, J. Effect of Debinding Temperature under an Argon Atmosphere on the Microstructure and Properties of 3D-Printed Alumina Ceramics. *Mater. Charact.* **2020**, *168*, 110548. [CrossRef]
57. Li, H.; Liu, Y.; Liu, Y.; Hu, K.; Lu, Z.; Liang, J. Effects of Solvent Debinding on the Microstructure and Properties of 3D-Printed Alumina Ceramics. *ACS Omega* **2020**, *5*, 27455–27462. [CrossRef] [PubMed]
58. Liu, K.; Hu, J.; Du, Y.; Shi, Y.; Sun, Y.; Zhang, S.; Tu, R.; Zhang, Q.; Huang, S.; Sun, H. Influence of Particle Size on 3D-printed Piezoelectric Ceramics via Digital Light Processing with Furnace Sintering. *Int. J. Appl. Ceram. Tech.* **2022**, *19*, 2461–2471. [CrossRef]
59. Li, H.; Hu, K.; Liu, Y.; Lu, Z.; Liang, J. Improved Mechanical Properties of Silica Ceramic Cores Prepared by 3D Printing and Sintering Processes. *Scr. Mater.* **2021**, *194*, 113665. [CrossRef]
60. Curto, H.; Thuault, A.; Jean, F.; Violier, M.; Dupont, V.; Hornez, J.-C.; Leriche, A. Coupling Additive Manufacturing and Microwave Sintering: A Fast Processing Route of Alumina Ceramics. *J. Eur. Ceram. Soc.* **2020**, *40*, 2548–2554. [CrossRef]
61. Tarafder, S.; Balla, V.K.; Davies, N.M.; Bandyopadhyay, A.; Bose, S. Microwave-Sintered 3D Printed Tricalcium Phosphate Scaffolds for Bone Tissue Engineering: 3D Printed TCP Scaffolds for Bone Tissue Engineering. *J. Tissue Eng. Regen. Med.* **2013**, *7*, 631–641. [CrossRef]
62. Torresani, E.; Carrillo, M.; Haines, C.; Martin, D.; Olevsky, E. Fabrication of Powder Components with Internal Channels by Spark Plasma Sintering and Additive Manufacturing. *J. Eur. Ceram. Soc.* **2023**, *43*, 1117–1126. [CrossRef]
63. Brucculeri, R.; Airoldi, L.; Baldini, P.; Vigani, B.; Rossi, S.; Morganti, S.; Auricchio, F.; Anselmi-Tamburini, U. Spark Plasma Sintering of Complex Metal and Ceramic Structures Produced by Material Extrusion. *3d Print. Addit. Manuf.* **2023**, 3dp.2022.0279. [CrossRef]
64. Xing, H.; Zou, B.; Li, S.; Fu, X. Study on Surface Quality, Precision and Mechanical Properties of 3D Printed ZrO2 Ceramic Components by Laser Scanning Stereolithography. *Ceram. Int.* **2017**, *43*, 16340–16347. [CrossRef]
65. Shetty, S.; Nandish, B.T.; Amin, V.; Jayaprakash, K.; Shahira; Stanly Selva Kumar, G.S.; Khan, F.; Harish, P. 3D Printed Polyether Ether Ketone (PEEK), Polyamide (PA) and Its Evaluation of Mechanical Properties and Its Uses in Healthcare Applications. *IOP Conf. Ser. Mater. Sci. Eng.* **2022**, *1224*, 012005. [CrossRef]
66. Das, M.; Ambekar, R.S.; Panda, S.K.; Chakraborty, S.; Tiwary, C.S. 2D Nanomaterials in 3D/4D-Printed Biomedical Devices. *J. Mater. Res.* **2021**, *36*, 4024–4050. [CrossRef]
67. Mamo, H.B.; Adamiak, M.; Kunwar, A. 3D Printed Biomedical Devices and Their Applications: A Review on State-of-the-Art Technologies, Existing Challenges, and Future Perspectives. *J. Mech. Behav. Biomed. Mater.* **2023**, *143*, 105930. [CrossRef]
68. Hales, S.; Tokita, E.; Neupane, R.; Ghosh, U.; Elder, B.; Wirthlin, D.; Kong, Y.L. 3D Printed Nanomaterial-Based Electronic, Biomedical, and Bioelectronic Devices. *Nanotechnology* **2020**, *31*, 172001. [CrossRef]
69. Ceramics, Refractories, and Glasses. In *Materials Handbook*; Springer: London, UK, 2008; pp. 593–689. ISBN 978-1-84628-668-1.
70. Mantripragada, V.P.; Lecka-Czernik, B.; Ebraheim, N.A.; Jayasuriya, A.C. An Overview of Recent Advances in Designing Orthopedic and Craniofacial Implants. *J. Biomed. Mater. Res.* **2013**, *101*, 3349–3364. [CrossRef]
71. Dahotre, N.B.; Kadolkar, P.; Shah, S. Refractory Ceramic Coatings: Processes, Systems and Wettability/Adhesion. *Surf. Interface Anal.* **2001**, *31*, 659–672. [CrossRef]
72. Using Ceramic 3D Printing to Achieve Complex Aerospace Structures—3Dnatives. Available online: https://www.3dnatives.com/en/using-ceramic-3d-printing-to-achieve-complex-aerospace-structures-150520234/ (accessed on 16 November 2023).
73. How Are Lithoz Ceramic Materials Revolutionizing Aerospace?—3Dnatives. Available online: https://www.3dnatives.com/en/how-are-lithoz-ceramic-materials-revolutionizing-aerospace-070320225/ (accessed on 16 November 2023).
74. Alhendi, M.; Alshatnawi, F.; Abbara, E.M.; Sivasubramony, R.; Khinda, G.; Umar, A.I.; Borgesen, P.; Poliks, M.D.; Shaddock, D.; Hoel, C.; et al. Printed Electronics for Extreme High Temperature Environments. *Addit. Manuf.* **2022**, *54*, 102709. [CrossRef]
75. Lakhdar, Y.; Tuck, C.; Binner, J.; Terry, A.; Goodridge, R. Additive Manufacturing of Advanced Ceramic Materials. *Prog. Mater. Sci.* **2021**, *116*, 100736. [CrossRef]
76. Pelz, J.S.; Ku, N.; Meyers, M.A.; Vargas-Gonzalez, L.R. Additive Manufacturing of Structural Ceramics: A Historical Perspective. *J. Mater. Res. Technol.* **2021**, *15*, 670–695. [CrossRef]
77. Dadkhah, M.; Tulliani, J.-M.; Saboori, A.; Iuliano, L. Additive Manufacturing of Ceramics: Advances, Challenges, and Outlook. *J. Eur. Ceram. Soc.* **2023**, *43*, 6635–6664. [CrossRef]
78. 3D Systems. Available online: https://www.3dsystems.com/ (accessed on 4 December 2023).
79. Industrial 3D Printing & 3D Printer Manufacturer | Voxeljet. Available online: https://www.voxeljet.com/ (accessed on 4 December 2023).
80. ADMATEC—Advanced Ceramic and Metal 3D Printing on One System Using Digital Light Processing or Stereo Lithography Based Additive Manufacturing Technology. Available online: https://admateceurope.com/ (accessed on 4 December 2023).
81. Lithoz: 3D-Druck Für Keramik—Eine Weitere WordPress-Website. Available online: https://lithoz.com/en/ (accessed on 4 December 2023).
82. 3D Printers | WASP. Available online: https://www.3dwasp.com/en/ (accessed on 4 December 2023).
83. Tethon 3D. Available online: https://tethon3d.com/ (accessed on 4 December 2023).

84. 3DCeram l Ceramic 3D Printer: The Process Turnkey Provider. Available online: https://3dceram.com/ (accessed on 4 December 2023).
85. Prodways | MOVINGLight®and SLS®3D Printers for Industrial and Dental Applications. Available online: https://www.prodways.com/en/ (accessed on 4 December 2023).
86. 3D Potter—Real Clay 3D Ceramic Printers. Available online: https://3dpotter.com/ (accessed on 4 December 2023).
87. Nanoe—Development of Ceramic Materials for the Industries. Available online: https://nanoe.com/en/ (accessed on 10 January 2024).
88. Ceramic 3D Printing Market Size, Share and Forecast to 2030. Available online: https://www.sphericalinsights.com/reports/ceramic-3d-printing-market (accessed on 20 November 2023).