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# The Applications of Ceramics In 3D Printing and Additive Manufacturing

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Abstract: Ceramic-based additive manufacturing (AM) and 3D printing technologies have emerged as transformative methods enabling the production of complex, high-performance ceramic components for a broad range of applications including biomedical implants, aerospace parts, and chemical engineering systems. Despite their promising potential, the processing of ceramic materials via AM remains highly challenging due to intrinsic material limitations such as low flowability, brittleness, and sensitivity to processing conditions. Most ceramic powders, typically in sub-micron size, suffer from electrostatic interactions and poor powder spreading behavior, which impede the formation of uniform layers essential for layer-by-layer fabrication. This review presents a comprehensive overview of recent advancements in ceramic additive manufacturing, covering both single-step and multi-step techniques such as stereolithography, binder jetting, selective laser sintering, direct ink writing, and fused deposition modeling. In addition, novel approaches including bioinspired designs, negative ceramic AM using sacrificial molds, and the fabrication of hierarchical porous structures are discussed in detail. Emphasis is placed on the relationship between ceramic material properties, printing parameters, and post-processing steps that govern the structural integrity and functionality of the final product. The review also highlights the current challenges—such as achieving high densification, controlling microstructure, and scaling up production—as well as emerging opportunities in the development of next-generation ceramic systems through additive manufacturing.

**Keywords:** Additive manufacturing, ceramics, 3D printing, bioceramics, processing techniques, porous ceramics.

# Seramiklerin 3D Baskı ve Eklemeli İmalat Uygulamaları

Özet: Seramik tabanlı eklemeli imalat ve 3D baskı teknolojileri; biyomedikal implantlar, uzay-havacılık parçaları ve kimya mühendisliği sistemleri gibi geniş bir uygulama yelpazesinde karmaşık ve yüksek performanslı seramik bileşenlerin üretimini mümkün kılan dönüştürücü yöntemler olarak ortaya çıkmıştır. Bu umut verici potansiyele rağmen, seramik malzemelerin eklemeli imalat ile işlenmesi, düşük akışkanlık, kırılganlık ve işlem koşullarına duyarlılık gibi içsel malzeme sınırlamaları nedeniyle oldukça zorludur. Genellikle mikron altı boyutlarda olan seramik tozları, elektrostatik etkileşimler ve zayıf yayılma davranışları nedeniyle homojen katmanların oluşumunu zorlaştırmakta, bu da katman-katman üretim sürecini engellemektedir. Bu derleme, seramik tabanlı eklemeli imalat alanındaki son gelişmeleri kapsamlı bir şekilde ele almakta; stereolitografi, bağlayıcı püskürtme, seçici lazer sinterleme, doğrudan mürekkep yazımı ve ergiterek yığma modelleme gibi tek ve çok adımlı yöntemleri içermektedir. Ayrıca, biyomimetik tasarımlar, kurban kalıplar kullanılarak yapılan negatif seramik eklemeli imalat ve hiyerarşik gözenekli yapıların üretimi gibi yenilikçi yaklaşımlar ayrıntılı olarak tartışılmaktadır. Seramik malzeme özellikleri, baskı parametreleri ve son işlem adımları arasındaki ilişkiye odaklanılarak, nihai ürünün yapısal bütünlüğü ve işlevselliği üzerinde belirleyici olan faktörler vurgulanmaktadır. Derleme ayrıca, yüksek yoğunluk elde etme, mikroyapı kontrolü ve üretimin ölçeklenmesi gibi mevcut zorluklara ve seramik sistemlerin eklemeli imalat yoluyla geliştirilmesine yönelik yeni fırsatlara da dikkat çekmektedir.

**Anahtar Kelimeler:** Eklemeli imalat, seramikler, 3D baskı, biyoseramikler, işleme teknikleri, gözenekli seramikler.

Review

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## 1.Introduction

The introduction should briefly place the study in a broad context and highlight why it is important. It should define the purpose of the work and its significance. The current state of the research field should be carefully reviewed and key publications cited (Trenberth et al., 2003). Additive manufacturing (AM), commonly known as 3D printing, refers to a transformative production technology that enables the fabrication of three-dimensional objects through the sequential deposition of material layers. In this method, each newly formed layer adheres to the previous one, ultimately forming a unified and complex structure. The manufacturing process typically begins with a computer-aided design (CAD) model, which is digitally sliced into individual layers to guide the production system accordingly [1].

One of the most significant advantages of AM is its ability to fabricate geometrically complex components with reduced material waste and cost, making it ideal for prototyping, custom parts, and low-volume production. Depending on the state of the raw material used, AM techniques are broadly categorized into liquid-based, solid-based, and powder-based systems [2].

- Liquid-based systems, such as photopolymerization, material jetting, and extrusion-based methods, utilize fluid precursors that solidify during the printing process.
- Solid-based techniques, including fused deposition modelling (FDM) and sheet lamination (SL), rely on solid filament or sheet material feedstocks.
- Powder-based AM methods—such as selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), and laser metal deposition—employ powdered materials that are selectively fused or melted to create the desired geometry [3, 4].

Surface defects often serve as the initiation points for structural damage in conventional manufacturing methods. In contrast, additive manufacturing technologies allow the fabrication of components with highly controlled surface morphologies and complex geometries, constructed precisely on a layer-by-layer basis. This level of control facilitates the production of functional and high-resolution parts with minimal post-processing. As a result, AM enables the creation of innovative, customized designs that are particularly advantageous in technical and biomedical fields—where accuracy, complexity, and material performance are critical [1].

Although additive manufacturing technologies have shown rapid progress in recent years, the development of ceramic-based AM remains relatively immature compared to their polymeric and metallic counterparts. This technological gap highlights a vast, yet underexplored, potential for ceramics within the AM landscape [2].

Ceramics are inorganic, non-metallic materials broadly classified based on their structural characteristics and industrial applications. A distinction is made between traditional ceramics—derived from naturally occurring raw materials and advanced ceramics (also known as engineering ceramics), which are typically polycrystalline and synthesized with high-purity constituents. Unlike traditional ceramics, advanced ceramics exhibit enhanced physical, chemical, and mechanical properties, making them suitable for high-performance applications across sectors such as biomedicine, aerospace, automotive, electronics, energy, and defense [4].

Additive manufacturing offers a promising route for the precise fabrication of advanced ceramic components, allowing for greater design flexibility, reduced material waste, and the potential for customized functionalities.

Ceramic components fabricated through additive manufacturing are processed using workflows that differ substantially from conventional ceramic production techniques, represented in Figure 2. The typical process involves the digital design of the object using CAD software, followed by slicing the model into printable layers, material deposition, post-processing, and sintering or heat treatment steps. The duration and complexity of the production process are influenced by various parameters, including layer thickness, printing speed, and the specific post-treatment requirements. This approach enables the fabrication of ceramic parts with tailored properties and opens up a wide range of applications across multiple industries [1].

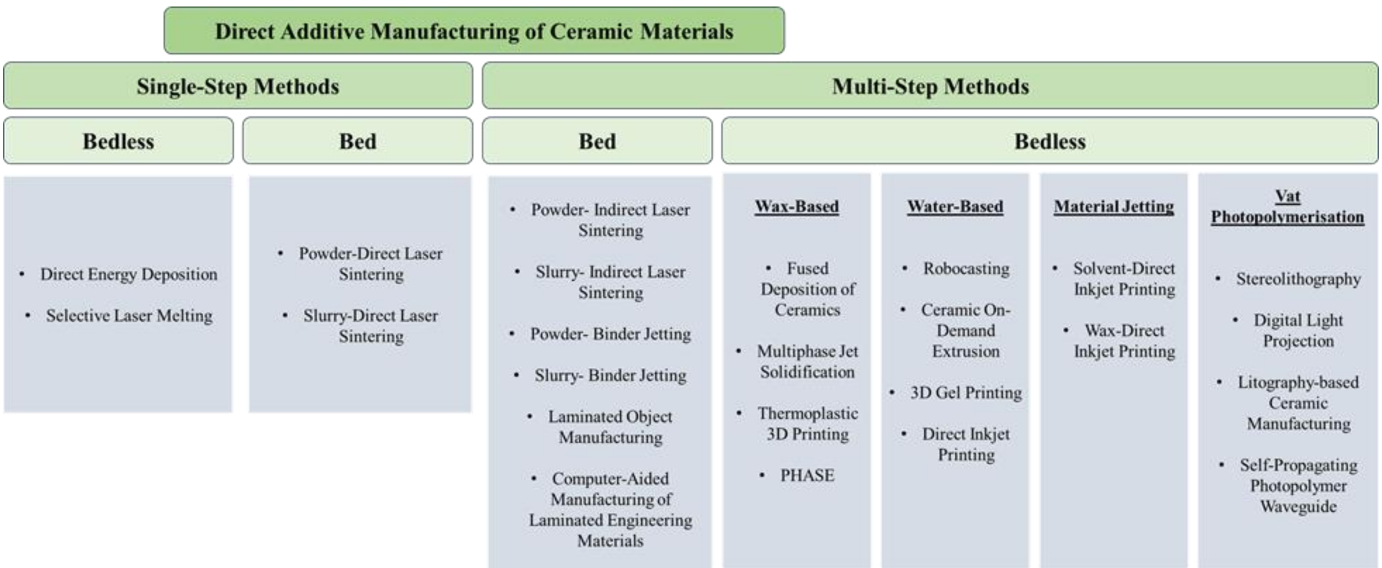


Figure 1. Additive Manufacturing methods used for ceramic-based materials fabrication.
*Şekil 1. Seramik esaslı malzemelerin üretiminde kullanılan eklemeli imalat yöntemleri.*

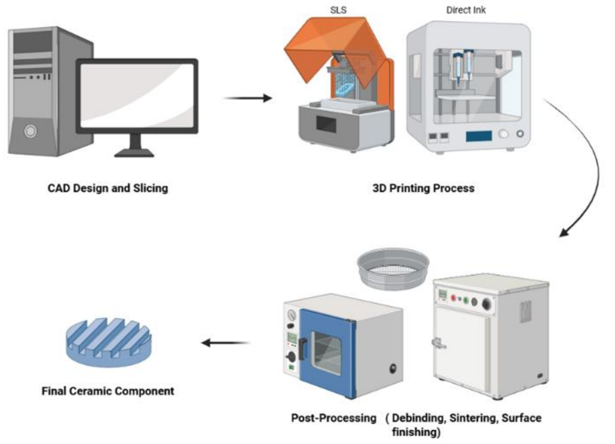


Figure 2. General workflow for ceramic 3D printing: from CAD design and slicing to additive manufacturing, post-processing, and final part fabrication.
*Şekil 2. Seramik 3D baskıya yönelik genel iş akışı: CAD tasarımı ve modelin dilimlenmesinden başlayarak, eklemeli imalat, son işlemler ve nihai parçanın üretilmesine kadar uzanan süreç.*

## 2. Breaking the Mold: Innovations in Ceramic Manufacturing Through Additive Manufacturing and 3D Printing

The manufacturing process of ceramic-based structures can be performed using different technologies/methods. These include casting/solidification, deformation, machining/material removal, joining, and solid free-forming processes. Among these, "solid free-forming" is considered an additive manufacturing approach. In other production methods, it is possible to encounter defects in the fabricated ceramic materials, such as cracks, voids, or loss of geometrical shape. Moreover, mold-based production methods limit design flexibility. The solid free-forming process introduces new approaches for handling ceramics in additive manufacturing, utilizing the advantages of 3D printing for both direct and indirect ceramic structure fabrication [5,6,7].

The additive manufacturing (AM) of ceramics can be performed through either single-step or multi-step processes. Most AM methods involve multi-step production, such as sheet lamination, extrusion-based fused deposition of ceramics (FDC), freeze-form extrusion fabrication (FEF), robocasting (RC), direct inkjet printing (DIP), binder jetting, and indirect laser sintering (LS). On the other hand, single-step methods are capable of shaping and sintering ceramic materials simultaneously. Two recorded techniques that allow such a process are selective laser melting (SLM) and direct energy deposition (DED) [5,6,7]. These differences are summarized in Table 1.

Another emerging approach in ceramic material production is the negative ceramic AM method, which involves the use of polymer molds to shape ceramic slurries via investment casting or gel casting. Once the slurry stabilizes, the mold is removed either by dissolution or thermal burn-out. The advantage of this method lies in the use of AM-produced polymer-based molds that preserve the detailed and specific geometry of the design. These polymer molds are considered easier to fabricate and more cost-effective than direct ceramic AM processes, and they can be utilized in AM technologies such as fused deposition modeling (FDM), material jetting, laser sintering, and stereolithography methods [5].

Single-step AM processes for ceramic material fabrication offer great potential due to their near-net-shape capabilities, which reduce or even eliminate the need for post-process machining. Currently, methods such as laser sintering (dLS), selective laser melting (SLM), and direct energy deposition (DED) face certain limitations, primarily due to the complex and not fully understood interactions between the laser and ceramic materials. However, with careful material selection and optimization of printing parameters, it is possible to produce fully dense ceramics—for example, the $Al_2O_3$–$ZrO_2$ composite fabricated by Niu et al. using the LENS technique [8].

In multi-step AM processes, specially designed fusible or sand molds are often employed in combination with SLS 3D printing technologies. For effective implementation, the sand mold must be specifically designed with key fabrication parameters in mind, such as refractoriness, heat storage capacity, and cooling rate. Today, molds produced via SLS and 3DP methods are typically composed of a single sand material [5,6]. The purposed method for sand mold fabrication and ceramic/metallic based material is described in Figure 3.

Table 1. Comparison of single-step and multi-step additive manufacturing methods for ceramic materials in terms of process stages, material requirements, performance, and application readiness.
*Tablo 1. Seramik malzemeler için tek adımlı ve çok adımlı eklemeli imalat yöntemlerinin; süreç aşamaları, malzeme gereksinimleri, performans ve uygulamaya hazır olma düzeyi açısından karşılaştırılması.*

| Criteria | Single-Step AM (e.g., SLM, DED) | Multi-Step AM (e.g., DIW, SLA, BJ) | Reference |
|---|---|---|---|
| **Process Description** | Shaping and sintering occur simultaneously | Involves shaping, drying, debinding, and sintering in stages | [5], [6], [7] |
| **Examples** | SLM, DED | DIW, Binder Jetting, SLA, FDC, RC | [5], [6], [8] |
| **Production Time** | Shorter overall | Longer due to post-processing | [7], [8] |
| **Process Control Complexity** | High — laser-material interaction must be precisely controlled | Moderate — multiple steps allow more flexibility | [8], [12] |
| **Material Requirements** | Limited to highly pure, laser-fusible powders | Allows slurries, pastes, or composite suspensions | [6], [12], [30] |
| **Energy Consumption** | Higher during printing due to laser melting | Spread across stages, can be optimized | [12], [16] |
| **Defect Risk** | Prone to thermal stress, warping | Risks in drying/debinding but better geometry control | [8], [33], [36] |
| **Design Flexibility** | Lower due to path/plasma constraints | Higher due to flexible feedstock and support structures | [7], [12] |
| **Cost** | Higher equipment cost, lower labor | Moderate machine cost, higher labor and processing time | [7], [20] |
| **Current Readiness for Ceramics** | Experimental, still evolving | Widely used and validated in lab/clinical-scale studies | [6], [7], [20] |

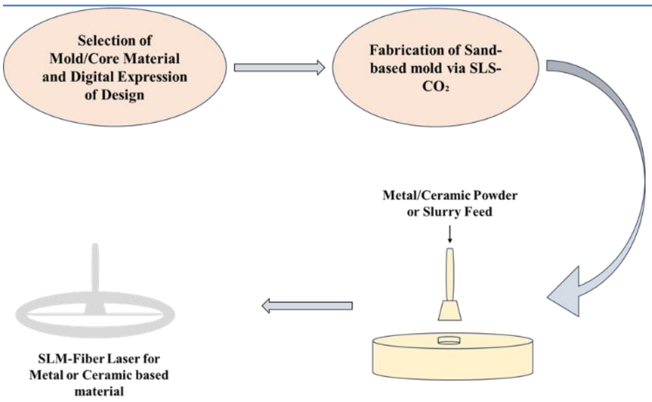


Figure 3. A sand-based mold fabrication for ceramic or metallic material fabrication via SLS and 3DP technologies.
*Şekil 3. Seramik veya metalik malzeme üretimi amacıyla, SLS ve 3DP teknolojileri kullanılarak kum esaslı kalıp imalatı.*

## 3.From Design to Reality: Transforming Ceramic Production with Additive Manufacturing and 3D Printing

Ceramic printing is a branch of additive manufacturing (AM) that allows the creation of intricate ceramic objects with complex geometries and customized shapes. AM overcomes the drawbacks of ceramics by utilizing printable materials that can be tailored to meet specific requirements. In recent years, there have been several advancements and novel techniques in ceramic production. The diverse range of techniques used to describe ceramic AM processes can be a source of considerable confusion for those attempting to navigate this field. The terminology surrounding ceramic material extrusion can be convoluted, with terms such as extrusion free-forming (EFF) [9] and filament-based direct ink writing (DIW) [10] being used interchangeably to describe a broad range of processes. However, it is worth noting that the EFF acronym originally referred to a process similar to fused deposition modeling (FDM) [11], whereas DIW is now predominantly used as an alternative term for robocasting.

AM as a 3D printing technology has emerged as a powerful tool for transforming the way ceramics are produced. Unlike traditional ceramic production methods, which rely on subtractive processes such as cutting and shaping, 3D printing the deposition of material layer by layer to create a three-dimensional object [12, 13]. Prior to ceramic production with 3D printing, the process typically involved the use of a mixture of powders, along with binders and other additives, which were transformed into the desired form using a range of conventional manufacturing techniques. These techniques include injection molding, die pressing, tape casting, and gel casting, among others [14]. Despite their widespread use, conventional ceramic forming techniques are characterized by extended processing times and high costs, leading to certain limitations. For instance, it is often impossible to fabricate structures with intricate geometries or interconnected holes due to the dependence of these methods on molding processes. Incorporating 3D printing technology in the fabrication of ceramic components provides novel opportunities to address the difficulties and hurdles previously mentioned. The benefits of this approach include the ability to produce complex geometries and customized shapes that are difficult or impossible to achieve using traditional methods, as well as the potential to reduce material waste and enhance the mechanical properties of ceramics. Additionally, energy consumption is minimized since there is no excess material to discard [15, 16].

There are various approaches to the 3D printing of ceramic materials, which can be broadly classified into three categories: slurry-based, powder-based, and bulk solid-based methods, present in Figure 4. Slurry-based methods typically use liquid or semi-liquid systems that are mixed with finely dispersed ceramic particles, often in the form of inks or pastes. The formulation of these systems depends on the solid loading and viscosity required. In contrast, powder-based technologies primarily rely on the use of loose ceramic particles as feedstock, which are consolidated either by spreading liquid binders or through the application of thermal energy via a laser beam. Finally, bulk solid-based methods involve the direct consolidation of bulk ceramic materials through techniques such as FDM [12].

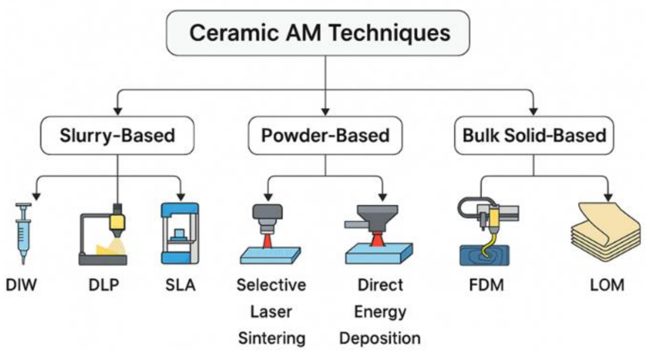


Figure 4. Classification of ceramic additive manufacturing techniques into slurry-based, powder-based, and bulk solid-based processes, along with their commonly used methods; SLS–Selective Laser Sintering; BJ–Binder Jetting; SLM–Selective Laser Melting; SLA–Stereolithography; DLP–Digital Light Processing; DIW–Direct Ink Writing; FDM–Fused Deposition Modeling; and LOM–Laminated Object Manufacturing.
*Şekil 4. Seramik katkı üretim tekniklerinin, bulamaç (slurry) bazlı, toz bazlı ve kütle katı (bulk solid) bazlı süreçler olarak sınıflandırılması ve yaygın olarak kullanılan yöntemleri: SLS–Seçici Lazer Sinterleme, BJ–Bağlayıcı Püskürtme, SLM–Seçici Lazer Eritme, SLA–Stereolitografi, DLP–Dijital Işık İşleme, DIW–Doğrudan Mürekkep Yazımı, FDM–Eriyerek Yığma Modelleme ve LOM–Lamine Nesne Üretimi.*

In addition to enhancing mechanical properties, 3D printing has the potential to produce ceramic parts with improved functionality. 3D printing technology also has the ability to create porous ceramics with both periodic and hierarchical porous structures, such presented in Figure 5. This unique capability allows for the production of functional porous ceramics with precisely designed mechanical properties. By tailoring the pore size, shape, and distribution, it is possible to control the mechanical behavior of the material [17]. This opens up new possibilities for the design and manufacture of advanced ceramics with improved functionality and performance, such as biomedical implants, catalytic supports, and energy storage devices. Recent studies have demonstrated the potential of 3D-printed porous ceramics for a wide range of applications, including bone tissue engineering, drug delivery, and thermal insulation. This underscores the transformative potential of additive manufacturing/3D printing in ceramic production and its ability to push the boundaries of what is possible with traditional ceramic processing techniques.

One of the most novel techniques in ceramic 3D printing is the use of bioinspired design principles [18]. By mimicking the structures found in nature, researchers have been able to create ceramic objects with unique properties, such as enhanced mechanical strength and self-healing capabilities. This approach has potential applications in various fields, including medicine, where ceramic objects with bioinspired designs can be used to create implants and prosthetics [19].

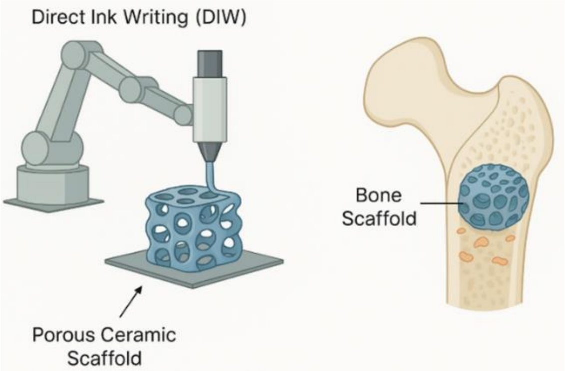


Figure 5. Fabrication of a porous ceramic scaffold using direct ink writing (DIW) and its biomedical application as a bone implant. The highly porous structure enables tissue ingrowth and promotes osteointegration.
*Şekil 5. Doğrudan Mürekkep Yazımı (DIW) yöntemiyle gözenekli bir seramik iskeletin üretilmesi ve bunun kemik implantı olarak biyomedikal uygulaması. Yüksek gözeneklilik yapısı, doku büyümesini destekler ve osteointegrasyonu teşvik eder.*

Ceramic production with 3D printing is a promising technology that offers significant advantages over traditional manufacturing methods. The recent advancements and novel techniques in ceramic printing have expanded its potential applications and made it more accessible to various industries. As this technology continues to evolve, it will undoubtedly revolutionize the way we create ceramic objects and open up new possibilities for innovation and design. Although significant advancements have been made in the selection of suitable ceramic materials, optimization of processing parameters, and post-processing techniques, several barriers still hinder the broader application of 3D printing in ceramic manufacturing. Achieving industrial-scale production can be a daunting task, and 3D printing larger ceramic components remains rare and challenging, mainly due to the intrinsic brittleness and low coefficient of thermal expansion of these materials. Despite these challenges, the potential advantages of 3D printing technology in ceramic fabrication—such as reduced material waste, enhanced design flexibility, and the ability to produce customized components—make it an attractive avenue for research and development. To explore the materials, processes, and applicability of 3D printing in the advancement of ceramics, these aspects will be discussed in the following thread.

## 4. Advancements in Ceramic Printing: Exploring Materials, Processes, and Applications Additive Manufacturing/3D Printing of Ceramics: A Comprehensive Overview of Techniques and Technologies

Alumina, zirconia, silicon carbide, silicon nitride, and hydroxyapatite are among the most commonly used ceramics in additive manufacturing [20]. Zirconia is particularly preferred due to its favorable chemical composition and high mechanical strength [21]. Similarly, alumina is notable for engineering applications, owing to its high hardness, and superior thermal and electrical insulation properties [22]. Both alumina and zirconia are frequently used in body implants because of their excellent mechanical strength, corrosion resistance, and their biocompatible and bioinert nature [23].

Silicon nitride exhibits excellent mechanical properties, including fracture toughness and high strength [24]. The osteogenic/antibacterial dualism makes silicon nitride a highly favorable bioceramic for use as an implant material. Its surface can simultaneously inhibit bacterial growth, support the physiological functions of eukaryotic cells, and aid in bone tissue regeneration [25].

Hydroxyapatite is a calcium phosphate ceramic that is the primary mineral component of bone, teeth, and hard tissues such as enamel and calcified structures [26]. Due to its ability to repair damaged cells and bond with neighboring tissues, it has applications in various areas such as fillers and coating materials for bone defects [27, 28]. Because of their exceptional qualities, such as low density, high melting point and hardness, excellent chemical resistance, and high wear resistance, boron carbide ceramics and silicon carbide ceramics are also among the preferred ceramics [29].

Faster and more precise technologies for making ceramics are needed to meet the growing demand for bioceramic devices and components. Although subtractive manufacturing technologies are common, they are not without limitations. Most traditional techniques for making ceramic scaffolds—whether through the use of polymer molds or foaming agents—are based on subtractive approaches, which often result in random pore structures. These limitations have been addressed by the development of cost-effective AM, which enables 3D printers to produce complex shapes with fewer parts and less material waste. While subtractive methods remain widely used, newer AM techniques offer improved dimensional accuracy and efficiency, particularly for bioceramic synthesis [30].

3D printing techniques that facilitate the production of delicate and complex ceramic structures which are difficult to fabricate using conventional manufacturing methods can be divided into three categories: slurry-based, powder-based, and bulk solid-based methods [12].

The major feedstock used in powder-based ceramic 3D printing technology is a powder bed, typically composed of loose ceramic particles. A laser beam's thermal energy is used either to fuse the powder or to deposit liquid binders, which then bind the ceramic particles together. Types of powder-based deposition techniques include binder jetting, selective laser sintering (SLS), laser powder bed fusion (LPBF), and directed energy deposition (DED) [31].

Selective laser sintering (SLS) is a 3D printing technology that uses a laser to selectively fuse powdered materials—such as polymers, metals, or ceramics—into a solid object. The laser scans the surface of a bed of powdered material, melting and fusing the particles together to create a thin layer of the object. This process is repeated layer by layer until the final object is complete. SLS is known for its ability to produce complex geometries and functional parts with high accuracy and resolution [32].

In the process, by moving the piston inside the powder feed chamber, a predetermined amount of powder is fed into the platform. The feed powder is then uniformly distributed throughout the platform. Using heating systems, the powder particles over the platform are preheated to a temperature slightly below their melting point. A high-power laser beam is then scanned over the cross-sectional region defined by the sliced data from the computer-aided design (CAD) model. The powder particles are heated by the focused laser beam and either fully or partially melt, leading to the fusion of particles. As a result, a solid layer is formed. After completion of each layer, the piston in the build chamber descends by a height equal to the layer thickness. The spreading mechanism then evenly distributes a new layer of powder, and the process continues until the full object is built [33].

In the Laser-Powder Bed Fusion (LPBF) method of additive manufacturing, layers of powdered material are selectively melted and fused together to form three-dimensional objects. In this method, a build platform is covered with a thin coating of powder, which is then selectively melted using a laser in accordance with a 3D model. The process is repeated layer by layer until the desired product is produced. LPBF is capable of fabricating complex geometries with exceptional accuracy and precision [34].

The DED process allows for the formation of a coating layer with a nominal composition by melting a thin layer of the substrate during fabrication. This newly applied coating can enhance the surface characteristics of high-value components, extending their lifespan by improving resistance to wear, corrosion, or oxidation [35].

In slurry-based 3D ceramic printing technology, liquid or semi-liquid systems containing fine ceramic particles are used as raw materials. Stereolithography (SLA) techniques such as photopolymerization-based digital light processing (DLP) and two-photon polymerization (TPP) can be used to print slurry-based ceramics. In addition, inkjet printing (IJP) and extrusion-based direct ink writing (DIW) techniques can also be applied [30].

Stereolithography is a technique in which each layer is modeled by laser scanning to convert it from a liquid monomer into a solid resin. In this process, photopolymerizable ceramic slurries are used instead of conventional liquid monomers [36]. The DLP printing technique consists of three components: a light source, a printing platform, and a resin tray. After the CAD model is sliced using dedicated software, the data is projected as cross-sectional images from the device's light source at a specific wavelength. Each layer is projected, causing the resin to harden due to a photochemical reaction. After the platform moves upward, the next image is projected, and printing continues layer by layer until complete. Digital micromirror devices (DMDs) enable instant curing of the entire layer by projecting the geometric data of each layer. This technique offers advantages such as higher resolution and faster printing [37].

Two-photon polymerization (2PP) is a technique that uses the simultaneous absorption of two photons of near-infrared radiation for additive manufacturing with sub-diffraction-limit resolution inside a photosensitive material [38]. It is important to meet specific requirements such as maintaining high ceramic content and low viscosity in light-curable ceramic resins prepared for the 2PP technique [39].

In the IJP technique, thin layer deposition is achieved by spraying the material in liquid form from the inkjet device onto the substrate surface. IJP is divided into two categories: continuous inkjet (CIJ) and drop-on-demand (DOD) inkjet systems [40]. In the CIJ method, a controllable stream of droplets is generated through a micronozzle. In the DOD method, droplets are produced via the piezoelectric effect, pyro-electric effect, or thermal stimulation within the nozzle head [41].

In the direct ink writing (DIW) technique, a viscous slurry consisting of liquid and solid phases is extruded. The slurry contains a high content of ceramic and binder particles. This technique allows for the fabrication of complex parts with interconnected holes and varied configurations. During printing, the robotic arm moves according to the CAD model. After printing, debinding and sintering processes are applied to remove the binder materials and solidify the structure [42].

Bulk solid-based processes include techniques that use material sheets, semi-molten or semi-liquid systems, and feedstock composed of uniformly dispersed small ceramic particles. Types of bulk solid-based processes are Laminated Object Manufacturing (LOM) and Fused Deposition Modelling (FDM). The LOM technique typically involves the layer-wise adhesion of one cut sheet on top of another, which is pre-coated with adhesive agents, to create 3D parts, followed by computer-controlled laser cutting of thin sheets of materials into cross sections in accordance with sliced digital CAD models. Real-time heating and mechanical compression can be used to bond and laminate adjacent layers [43]. LOM has several advantages, including the flexibility to obtain parts made of various materials and compositions, a high volumetric build rate, minimal material requirements, excellent surface finish, and inexpensive process and equipment costs.

Table 2. Ceramic and composite structures fabricated using 3D printing techniques.
*Tablo 2. 3D baskı teknikleri kullanılarak üretilmiş seramik ve kompozit yapılar.*

| Ceramics compositon | 3D printing method | Reference |
|---|---|---|
| Biphasic calcium phosphate (BCP), poly(l-lactic acid) (PLLA), Poly(l-lactic-co-glycolic acid) (PLGA) | SLS | [47] |
| Hydroxyapatite (HA), aliphatic-polycarbonate(a-PC) | SLS | [48] |
| Nano-hydroxyapatite, poly-ε-caprolactone (PCL) | SLS | [49] |
| Silica (SiO2), Nylon-11 | SLS | [50] |
| Zirconia (ZrO2), polypropylene (PP) | SLS | [51] |
| acrylonitrile butadiene styrene (ABS)-Barium Titanate | FDM | [52] |
| Poly-ε-caprolactone (PCL), hydroxyapatite (HA) | FDM | [53] |
| Biphasic calcium phosphate (BCP), Zirconia (ZrO2) | FDM | [54] |
| γ-alumina (γ- Al2O3), ethylene vinyl acetate (EVA) | FDM | [55] |
| Alumina ( Al2O3 ), Zirconia ( ZrO2 ) | DED | [56] |
| Zirconate titanate (PZT) | DED | [57] |
| Alumina ( Al2O3 ), Gadolinium aluminate (Gd2O3 ), Zirconia( ZrO2 ) | DED | [58] |
| hydroxyapatite (HA), poly (propylene fumarate) (PPF), diethyl fumarate (DEF) | SLA | [59] |
| Alumina ( Al2O3 ), Zirconia ( ZrO2 ) | SLA | [60] |
| Alumina (Al2O3 ), Silicon nitride(LPS-Si3N4) | SLA | [61] |
| Hydroxyapatite (HA) and tricalcium phosphate (TCP) | SLA | [62] |
| Silicon carbide (SiC) | DIW | [63] |
| Hardystonite ($Ca_2ZnSi_2O_7$) | DIW | [64] |
| Silicon nitride (LPS-$Si_3N_4$) | IJP | [65] |
| Silica ($SiO_2$), Bismuth Borate($H_3BO_3$) | IJP | [66] |

A layer-by-layer 3D printing technique known as fused deposition modeling (FDM) includes a build platform, print bed, liquefier head, and a spool of build material [44]. In the process, the produced material is heated to approximately 0.5°C above its melting point, which causes it to solidify within one second of post-extrusion. After the first layer is produced, the build platform is lowered, and the nozzle head deposits the next layers fused to the previous ones. Up until the final object is manufactured, this process continues. During the FDM process, the state of materials transitions from solid to viscous paste and back to solid. Using heating, the solid ingredients dissolve into a thick paste. The nozzle, which is moved in both vertical (z-axis) and horizontal (x/y-axis) directions by a numerically controlled mechanism, is then used to extrude the material. The extruded paste immediately solidifies after cooling down due to its surroundings [45]. Due to its capability to produce geometrically complex parts, production speed, variety of build styles, selection of engineering polymers, simplicity in support removal, and cost-effectiveness, FDM technology is extremely adaptable for polymeric materials [46].

## 5. Building a Better Future with Additive Manufacturing and 3D Printing of Ceramics: Opportunities and Challenges

Ceramic additive manufacturing (3D printing) enables better control over the microstructure and composition of components, which is not possible with conventional techniques. Additionally, it offers the opportunity to make robust and adaptable ceramic scaffolds with intricate shapes for tissue engineering. The demand for materials with high strength-to-weight ratios has facilitated the development of complex ceramic lattices for a variety of uses, including ceramic scaffolds used in tissue engineering. A successful implementation of additive manufacturing (AM) for the production of ceramics could significantly affect the production of ceramic components and result in completely new production and business models [67].

Various difficulties are encountered in the processing of ceramic materials using AM technologies. These materials are difficult to machine because of their high melting temperature and hardness, which complicate traditional melting and casting methods. Obtaining a compact with the desired microstructure, which is essential for realizing the superior physicochemical properties of advanced ceramics, is another of the major challenges. To achieve this structure, it is important to combine a specific AM technology with a suitable raw material formulation that will enable the production of dense ceramic parts with optimum properties [68]. The low density and limited mechanical strength of the available well-developed raw materials result in processing flaws and material composition restrictions. A lack of standardization, slow process improvement, and insufficient defect measurement and identification are additional issues [69]. Promoting additive manufacturing (AM) of ceramics as more than a niche technology is still the most crucial problem to be solved [68].

The potential for ceramic additive manufacturing (3D printing) is promising. Opportunities for research and development in the enhancement of AM technologies and the expansion of material options for ceramic 3D printing still exist. The creation of new materials and techniques will make it possible to overcome some of the drawbacks of 3D printing and open up additive manufacturing to a wider range of uses and sectors. Moreover, the use of 3D printing in the medical industry is anticipated to increase as it enables the creation of personalized implants and prosthetics [67,70,71,72,73].

## 6. Future Perspectives on Ceramic Additive Manufacturing

In recent decades, additive manufacturing (AM) has become a widely used technology, including polymeric and/or metallic materials in its production capabilities. However, manufacturing ceramic materials in this new technology is somewhat difficult due to the nature of ceramic materials and the prerequisites of the process. Ceramics are widely used for many purposes, from semiconductors to biomedical applications. Due to this wide usage, there are many conventional processes to prepare ceramic materials, but these processes cause a loss of time and excessive cost. In this chapter, we have discussed the opportunities and challenges of ceramic materials as AM/3D printing materials. Additive manufacturing of ceramics is challenging due to the nature of ceramics' microstructure. The ceramic materials possess a critical dependency on their molecular microstructure and the packaging of the powder compact. Fabrication and/or mimicking a sustainable microstructure for AM/3D printed ceramics requires precise 3D mimicking, rendering, and understanding of ceramics. Another limitation of ceramic materials in terms of AM/3D printing is their flowability. Because of their general production procedure, most obtained ceramic materials are in the form of fine powders, which exhibit substandard flowability for AM. AM is based on layer-by-layer fabrication of the complete structure, but in terms of ceramics, the sub-micrometer powders will not be able to spread a fine line and form a layer due to electrostatic disturbances and/or aggregation of powders. Although AM/3D printing of ceramics is a challenge, creating ceramic-based materials/structures with AM has a huge impact on medical sciences, chemistry, aerospace, etc. Nowadays, the usage of the powder bed technique for powder-based production is well-received and improved. It is low-cost, easy to scale up, flexible in terms of design, and can fabricate ceramic structures with very low organic additives. Another method is using ceramic slurries for AM/3D printing; this slurry contains ceramic powders in varying sizes and can be used for layer-by-layer manufacturing. In the future, it can be expected that AM/3D printing technologies will become more precise and sophisticated, in order to create a complex ceramic surface/material with a dense lattice and a stable microstructure.

## 7. Conflicts of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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