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A Comprehensive Review on 3D Printing Technology: Current Applications and Challenges

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Abstract

The key advantages of 3D printing technology include design freedom, customization, pollution prevention, the capacity to construct advanced systems, and rapid prototyping. In this paper, a concise overview of the fundamental 3D printing techniques, materials, and their advancement in emerging fields is presented. Besides, the significant potential of additive manufacturing in medical, aeronautical, architecture, and defensive structures are discussed in detail. The latest developments in materials, comprising alloys, polymer composites, ceramics, and concrete are also discussed. Finally, the key processing issues and computer design limitations of 3D printing technology is described. In short, this study presents a survey of the advantages and disadvantages of 3D printing as a baseline for possible future research work.

Keywords: Additive manufacturing; 3D printing applications; Materials; Key challenges.

Nomenclature

3DP	3D printing
AM	Additive manufacturing
CAD	Computer-aided design
SLA	Stereolithography
FDM	Fused deposition modeling
PBF	Powder bed fusion
SLS	Selective laser sintering
SLM	Selective laser melting
IJP	Inkjet printing
LOM	Laminated object manufacturing
DED	Direct energy deposition
CC	Contour crafting
QD	Quantum Dot

1. Introduction

3D printing (3DP) is a technology for creating a variety of shapes and intricate patterns using three-dimensional data modelling [1], [2].The process entails printing several layers of material on top of one another. Charles Hull invented this technique in 1986 through a procedure called stereolithography followed by further advancements, for instance, fused deposition modelling, powder bed fusion, contour crafting, and inkjet printing, etc.[3].Over the decades, 3DP has progressed, using diverse procedures, equipment and materials and can handle production and logistical activities. Additive manufacturing (AM)is extensively being used nowadays in various areas, especially construction, prototype manufacturing, and biomechanics. The implementation of 3DP in architectural projects is restricted, despite the benefits of decreased waste, increased design freedom, and mechanization. [4], [5].

As AM technology advances, its application in a variety of fields expands as well. One of the primary reasons for this technology's increased accessibility is the expiration of existing inventions that enabled engineers to create modern 3D printing machines. Latest advancements have lowered the expense of 3D printers, enabling them to be used in more areas including institutions, residences, hospitals, and laboratories. Previously, design engineers utilized 3DP widely to create decorative and practical models because of its quick and cost-effective prototyping capabilities. Thus, the usage of 3DP has resulted in a significant reduction in the expenses associated with product development[6].

However, in recent times 3DP has been widely implemented in a variety of companies, from prototype to finished items. Owing to the increased expenses associated with developing a specially designed product for individual customers, manufacturers have struggled with product customization. Conversely, AM enables low-cost 3D printing of limited numbers of customized products. It is particularly advantageous in the medical sector, where customized items for each individual are frequently required[7]. Wohlers Associates predicted that by 2020, around 50% of the commercial product will be manufactured by 3DP[1]. However, to further enhance the

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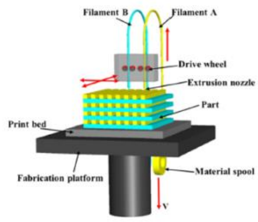
benefits of 3DP for the public, much research is needed on this technology[5].

The emerging agreement in favour of implementing 3DP is that it will improve system efficiencies, design flexibility, and customization. Metals, polymers, ceramics, and concrete are some of the materials that are commonly utilized in 3DP.Usually, modern 3DP metals and alloys are used in the aircraft industry since conventional procedures are extremely time-consuming, complicated, and expensive. Ceramics are mostly utilized in the additive manufacture of scaffolds, while concrete is the primary material applied in the additive manufacturing of structures. Nevertheless, the poor mechanical characteristics and anisotropic behaviour of 3D printed objects continue to constrain the possibility of mass printing. As a result, an optimized 3D printing design is vital in protecting defect susceptibility and anisotropic performance. Additionally, variations in the printed conditions affect the final product's appearance[8].AM is proficient in creating components in a wide range of dimensions, from microscopic to massive. Yet, the quality of printed items is reliant on the technique's precision and the scale of the print. For example, micro-scale additive manufacturing has difficulties with resolutions, surface integrity, and multilayer adhesion, necessitating the use of comment procedures like sintering. Besides, the scarcity of materials accessible for 3DP creates barriers to the widespread use of this technology in a variety of sectors. As a result, there is a necessity for the development of appropriate material for 3DP.Moreover, additional study is required to improve the mechanical characteristics of 3D printed components[9].

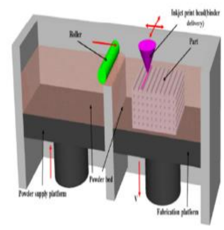
The benefits of the 3DP technique will continue to manifest as a result of ongoing scientific research which should be carried out to comprehend and eradicate the limits that prevent this technology from being used. AM-oriented Computer-aided design (CAD) systems are only a few of the critical characteristics that must be implemented[10].A distinct feature of 3DP is its capacity for mass customization, which means manufacturing a number of individualized products in a way that every item is unique. 3DP eliminates the additional cost associated with mold creation and tooling for a customized component. Consequently, bulk fabrication of a large number of similar components can be as economically efficient as producing a similar number of unique individualized products. The transition between alternative designs is simple, incurring minimal additional costs and requiring no particular planning. Additionally, AM offers the possibility of mass-producing complicated shapes including lattice structures, where the implementation of conventional manufacturing technologies like casting is complicated and requires additional time for processing[11]. However, advances in production rate and cost savings must be accomplished using machine design advancements. Furthermore, the high price and lengthy processing time associated with the AM method continue to be significant impediments to large-scale production[12]. This article will offer an in-depth examination of 3DP techniques, including the major processes used, the materials utilized, their present predicament, and applicability in a variety of sectors. Additionally, this report also presents knowledge gaps and problems in deploying this technology.

2. Different basic methods of 3DP

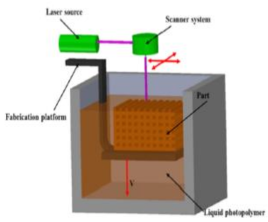
To fulfill the need for printing complicated objects at high resolutions, AM methods have been created. Fused deposition modeling is still the most popular technique of 3DP that primarily utilizes polymer filaments. Also, AM of powders in 3DP via selective laser sintering, selective laser melting, or liquid binding, as well as inkjet printing, contour crafting, stereolithography, direct energy deposition, and laminated object manufacturing, are the primary methods of AM[13], [14].These procedures are concisely described in the subsequent sub-sections, along with respective benefits and the materials needed for each approach. **Figure 1** depicts a schematic diagram of the primary techniques of AM.



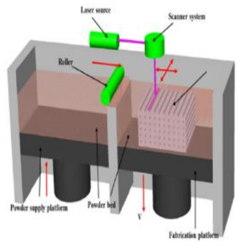
(a) Fused deposition modelling



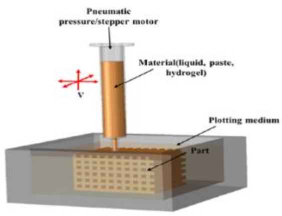
(b) Inkjet printing



(c) Stereolithography



(d) Powder bed fusion



(e) 3D Plotting

Figure 1. Schematic diagram of the various 3DP methods[15]

2.1. *Stereolithography (SLA)*

SLA is one of the oldest techniques used in AM. It initiates a chain reaction on a film of resin by ultraviolet light or an electron beam. Once activated, the monomers immediately change to polymer chains. Following polymerization, a design is established within the resin layer to serve as a support for the subsequent layers. After the printing is completed, the unreacted resin is retrieved. Several printed parts may require a post-processing intervention, like heating or photocuring, to produce the necessary mechanical characteristics. Ceramic-polymer composites (silicon oxycarbide) can be printed using the diffusion of ceramic particles in monomers.SLA produces high-quality components at a resolution of as little as 10 µm. Moreover, it is a somewhat slower and costly technique, with a fairly restricted selection of printing materials[16].

2.2. Fused deposition modeling (FDM)

A filament of a thermoplastic is utilized in the FDM technique to print3D layers of different materials. The filament is warmed up to a quasi-condition at the nozzle before being dispensed onto the base or over formerly produced layers. The thermoplasticity of the filament is critical for this process because it enables the filament to merge together throughout the printing and then harden at ambient conditions. The layer's depth, the filament's breadth, and alignment, and the air gaps are the primary operating factors that influence the structural qualities of printed components. The primary source of structural fragility is observed to be inter-layer misalignment. However, the primary advantages of FDM are cost-effectiveness, high efficiency, and flexibility. whereas, the primary disadvantages of this process are poor mechanical qualities, layer-by-layer appearances, poor surface integrity, and a restrictive choice of thermoplastics[17].

2.3. Powder bed fusion (PBF)

PBF methods involve the application of fine layers of ultrafine particles that are distributed and packed firmly together on a platform. Particles of layers are fused collectively using a laser beam or a binder. Successive layers of particles are started rolling over the preceding layers and cemented permanently till the finished three-dimensional item is constructed. The excessive powder is subsequently vacuumed away and, when required, additional treatment including coating, sintering, or infiltration is accomplished. The dispersion of powder type and packaging, which define the densities of the printed item, is the primary critical aspects affecting the technique's performance.The laser must be utilized with particles that have a minimal melting temperature, while liquid binders must be employed in all other cases. Selective laser sintering (SLS) is being utilized to process a wide range of polymers, metals, and alloy powders. However, selective laser melting (SLM) can be employed on a limited number of metals, including steel and aluminium[18].

2.4. Inkjet printing (IJP)

IJP is a widely used technique for the AM of ceramics. It is utilized to print sophisticated and expensive ceramic objects for purposes like tissue engineering. The injecting nozzle is used to infuse and inject a persistent ceramic solution, such as zirconium oxide powder, into the substrate in the form of bubbles, where it solidifies into a pattern strong enough to support future layers of printed materials. This process is quick and reliable, which gives designers and printers greater choice when developing and printing complicated shapes. Ceramic inks are classified into two categories: wax-based inks and liquid suspensions. To settle wax-based inks, they are melted and applied onto a cold substrate. By contrast, liquid suspensions are stabilized through the process of liquid evaporation[19].

2.5. Laminated object manufacturing (LOM)

LOM is among the earliest industrially accessible AM processes, which is based upon layer-by-layer cutting.Using a mechanized cutter or a laser, consecutive layers are accurately sliced and then fused firmly, or vice versa. This procedure is especially advantageous for the thermal joining of ceramic or metallic materials because it simplifies the design of internal features by eliminating excess material prior to bonding. After cutting, the extra materials can be retrieved and reused.LOM is compatible with a wide range of materials, including polymer composites, ceramics, paper, and metal-filled tapes[20].

2.6. Direct energy deposition (DED)

DED has been employed in the production of super alloys with exceptional performance. This technique is also referred to as laser engineered net shaping, laser solid forming, directed light fabrication, direct metal deposition, electron-beam AM, and wire-arc AM.DED utilizes an electron beam that is targeted specifically on the little part of the substrate while concurrently melting a feedstock material. After the electron beam has moved, the molten material is placed and bonded to the melted substrates and hardened. This technology is frequently utilized in aeronautical applications utilizing titanium, Inconel, stainless steel, and aluminum, and related alloys[21].

2.7. 3D Plotting

3D plotting is a technique that involves extruding a viscous liquid from a pressurized injector (syringe) in order to construct three-dimensional shapes of materials. The syringe head may revolve in three dimensions whereas the substrate remains stable. This allows for the layer-by-layer assembly of discharged materials. Curing processes can be triggered mainly by UV light or by distributing two reactive chemicals utilizing a blending nozzle. Materials can be transported to a plotting surface to complete the curing reaction in some instances. The fluidity of the material and the rates of deposition are related to the accuracy of the ultimate printed items. The primary benefit of this approach is that it allows for materials flexibility.3D plotting printers allow solutions, pastes, and hydrogels. A short-term, fatal material may be required to maintain the printed component, as raw viscous materials have poor rigidity, which can cause complicated structures to crash[22].**Table 1** presents a comparative analysis of various 3DP technologies.

2.8. Direct write technique

Direct Writing (DW), sometimes called Robo-casting, is a layer-by-layer production technology focused on extrusion and is appropriate for complicated structures. Composites, ceramics, biomaterials, and shape memory alloys are among the materials that can be utilized for DW. DW is useful for a variety of applications, from biological to optics, because of its simplicity and cost-effectiveness.

Recent DW research has revealed a trend toward developing novel materials. This method is divided into three main categories: (a) extrusion-based DW, (b) continuous droplet-based DW, and (c) energy-assisted DW, which allow for the production of functional and industrial parts complex shapes, and scales [21].

Table 1: A summary of the primary 3DP methods[10], [15], [23]

Method	Materials	Applications
SLA	Resin and its monomers	Prototyping, and biomedical
FDM	Thermoplastic and fibre-reinforced polymers	toys, advanced composite parts and rapid prototyping,
PBF	Powders of metals, alloys, and polymers	Electronics, biomedical, lightweight structures, aerospace and heat exchangers
IJP	Dispersed particles in a liquid Ceramic	Large structures, buildings, and biomedical
LOM	Ceramics, paper, polymer composites, and metal rolls	Electronics, and foundry industries
DED	Powders of metals and alloys	Retrofitting, aerospace, repair, biomedical, and cladding
DW	Composites, ceramics, biomaterials, and shape memory alloys	Industrial complex parts

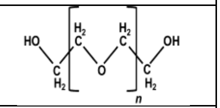
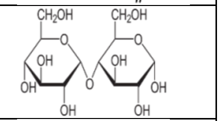
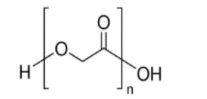
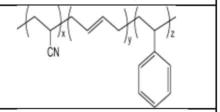
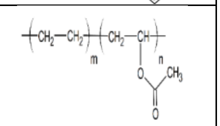
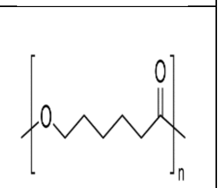
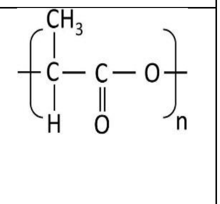
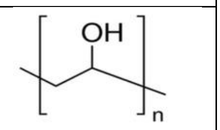
3. Applications of 3DP in various fields

3.1. Biomaterials and bio-fabrications

Today, the medical sector accounts for 11% of the entire AM industry and is expected to be a major driver of AM innovation and expansion[24].Bio-fabrication is the process of fabricating tissues and organs via bio-printing, bio-assembly, and maturation. The primary distinction amongst bio fabrication and traditional AM is the incorporation of cells into the created biomaterials to make bio-inks. The integration of bio-ink printing with laser-induced forward transfer, inkjet printing, and robotic dispensing enables the production of bio-inks[25].The biomaterials are developed into the appropriate pattern and tissues using bimolecular and cells. Biomaterials serve as scaffolds and physiological clues for the formation of the tissue matrix, whereas biomolecules direct the tissue rejuvenation processes[26].Numerous bio-inks and cells will be merged with increasingly sophisticated organs and tissues. Also, improved imaging will enable the accurate determination of the size, shape, and structure of faulty components. Additionally, by utilizing homologous cells from the client, the chance of refusal of the created implant is decreased. In vitro fabrication of cartilage, bone, aortic valves, branched vascular trees, and microbial tracheal splints are already accomplished[3].In situ tissues creation, to heal tissues and organs immediately inside the body is yet another critical objective of biofabrication, that has also been accomplished to a certain degree with skin, bone, and cartilage[27].

Likewise, bio-fabricated components will be employed as prototypes for toxicity studies, and cancer simulations[28].Commercially accessible materials for 3DP of biomedical applications are illustrated in **Table 2**.

Table 2: Commercially accessible materials for 3DP of biomedical applications[29]–[33]

Material	Uses	Chemical structure
Polyethylene oxide	Tablets	
Cellulose polymer	Oral dosage in the form of tablets	
Polyglycolic acid	Custom implants for antibiotic delivery	
Acrylonitrile butadiene styrene	Osteoid medical cast	
Ethylene-vinyl acetate	Intrauterine and subcutaneous devices	
Polycaprolactone	Scaffolding for bone tissue engineering, tablets loaded with nano-capsules, and vaginal rings,	
Polylactic acid	Vaginal rings, implants, microneedles, multi-compartment capsular device, beads, catheters, and discs	
Polyvinyl alcohol	Tablets, orodispersable films, and multi-compartment capsular device	

The production of vascularized organs is a significant problem in biofabrication. Due to the fact that huge organs require blood arteries to function metabolically, technologies for creating complicated vascular systems and neuropathy needs to be developed[23].Zhang et al. discussed current advancements in three-dimensional bioprinting of blood veins and functionally vascularized tissues. Due to the existing limitations of printing at high resolutions on a microscopic level, and also due to the absence of mechanical qualities for vasculature cells, additional investigation, and improvement in this field is necessary to manufacture 3DP tissues[34]. Nevertheless, recent advancements in adaptable bio-ink demonstrate AM's promise for tissue creation of sensitive human body organs. Bioreactors have been investigated in conjunction with elements that stimulate angiogenesis and neuropathy in order to develop bioprinted components with the required qualities. The combination of various bioinks and AM processes demonstrates optimistic possibilities in the fabrication of human cell structures[35].Moreover, in situ printing technology for tissue rejuvenation is a cutting-edge concept that will revolutionize the medical business.

The pharmaceutical companies will also gain significant benefits from AM.As a result, drug production and delivery methods will undergo dramatic changes. In 2015, the Food and Drug Administration(FDA)certified the first AM medication[26].There are several novel AM drug delivery technologies being investigated, including oral, prosthetic, and topical drug delivery methods.AM may be used to manipulate the release profile of pharmaceuticals by altering the three-dimensional shape, morphology, and location of the active participants in drug delivery methods.AM is used to develop novel pharmaceutical products, including hydrogels, antimicrobial micropatterns, artificial extrinsic scaffolds, micropores bioactive glass structures, nanocapsules, and multi-layered pharmaceuticals[36].AM is also transforming the implantation market, as it enables the development of patient-specific prosthetics[37].

For instance, **Figure 2** illustrates a custom-made Jig used to enhance cryoablation needle positioning. Currently, the production of pipelines incorporates image analysis of the person's body, its refinement, implant designing, and production, all of which are accomplished through the use of CAD programs[3].A dependable and premium AM technology can rapidly build biologically complicated shapes. Although patient-specific AM prosthetics are now accessible, the majority of those have been utilized solely in clinical studies with the client's explicit consent[38].Reliability of procedures and components will also be valuable in the long run for permanent legislative certification. Implants can also incorporate intricate geometrical characteristics. For instance, low-stiffness, high-strength lattice architectures have been investigated in order to reduce stress shields among the implants and the bones[39]. Biomimetics can be used to influence certain lattice patterns. AM's free-form capabilities enable the combination of this physical function with many other aspects like tissue implantation, restoration, nutrition, wastes, and antimicrobial delivery, biodegradability, and bio-resorbability. Additionally, lattices with graded architectures may alter the local characteristics, optimizing the implant's behavior. For instance, the lattice may be stiffer on the inside to withstand greater weights and porous on the outside to aid in bones in growth[40], [41].

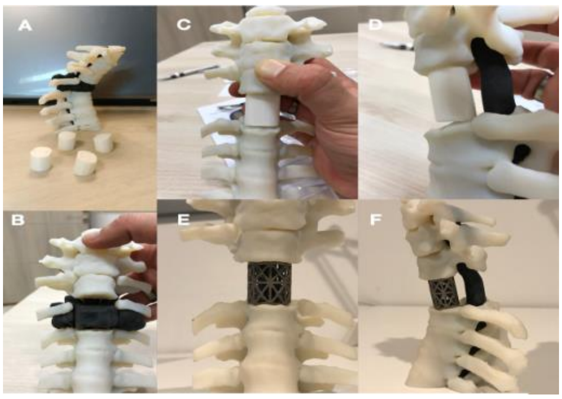


Figure 2. Jig optimized for cryoablation needle positioning using 3DP[42]

3.2. Aviation and aerospace

Aeronautical equipment including aircraft components, gas turbines, and heat exchangers could be made or replaced via AM[43].Non-metal AM techniques like SLA, multijet modelling, and FDM are used to rapidly prototype components and fabricate fittings as well as interior design comprised of plastic, ceramic, and composites[44].DED methodology is utilized to fabricate big structural elements because it is less precise but faster than PBF technology. Because of the accuracy of PBF technologies, system development and integration with various functions can be optimized. This approach is mostly utilized for smaller; more complicated components.GE Aviation is utilizing PBF machines to make its latest series of jet engine parts that have complicated designs for improved cooling channels and supports. The life span has been increased fivefold. The needed number of items was decreased from 18 to 1, and the overall weight was decreased by 25%[45].Non-metallic components also play a significant role in the aircraft sector.SLA, MJP, and FDM methods can be used to make plastics, ceramics, and composites. Stratasysbegan using FDM in conjunction with numerous aviation industries, including Piper Aircraft, Bell Helicopter, and NASA, for rapid prototyping, tooling, and part production[46].For example, **Figure 3** depicts a 3DP multi-stable architectural structure and a protecting structure for Mars artifacts.AM of high-temperature ceramics is a promising topic of research at the moment. Modern and sophisticated production methods are used to create high-performance aircraft parts. These components are exposed to corrosion, impact stress, and repetitive temperature cycles, all of which can result in flaws or fractures.Due to the high cost of these components, replacement is preferable over maintenance[47].

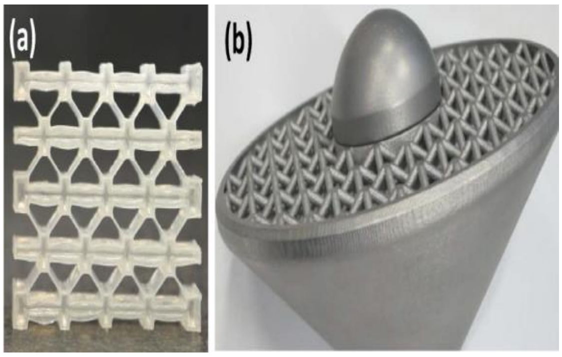


Figure 3. (a) Multi-stable crafted object created by 3DP (b) Protecting structure for Mars created 3DP[48]

In comparison to traditional welding procedures, AM technology can fix metal parts with exceptional accuracy and minimum energy consumption. A laser beam forms metallurgical connections among the component and the repairing metal that is added. This technology produces little deformation and is suitable for complicated and thin-walled aircraft structures[47].Additionally, AM can be used to replace materials that are not weldable or parts that are prone to deformation.DED machines disseminate and melt metal powder over the wounded region, whereas computer numerical control(CNC)machinery enhances the repairing quality. This approach enables better construction capacity, improved precision, and superior surface quality[49].The additional material exhibits superior fatigue qualities to the existing wrought material while keeping dimensional tolerances. Further, this technology minimizes the decaying of mechanical characteristics induced by thermal loads and can easily heal damages of any substances. Maintenance costs have been estimated at 50% of the cost of remanufacturing the component[50].Automated solutions are now being designed to identify damages, match the initial computer-aided design(CAD) model with the actual equipment, and replace defective parts using AM and CNC machinery.AM also can impact the supply networks for spares. Dispersed manufacturing of spares will minimize operational costs and delays, while also reducing the burden on supply chain management and logistical informatics. Simultaneously, AM will enhance consumer satisfaction, adaptability, efficiency, and resilience against supply chain interruptions. Such improvements, although, would occur if the pricing of AM machines and materials decreases[51].Further, AM can make antique components without relying on outdated equipment, molds, and die.For instance, maintaining and modernizing F-15 aircraft utilizing AM has resulted in significant cost reductions.3DP technologies have already exhibited impressive capabilities, ranging from quick prototyping to finished part manufacture and semi-automatic maintenance[23].

3.3. Buildings and structures

About 3% of the whole AM business is devoted to architectural projects[52].Nevertheless, this domain is still in its adolescence, having been employed in household structures for the first time in 2014 and demonstrating tremendous promise ever since. Recent years have seen an increase in interest in mechanized building construction using 3DP technologies. It can transform the building sector and enable astronauts to erect structures on the moon more easily[53].It enables substantial time and resources savings during construction. Casting, molding, and extrusion are all conventional procedures utilized in the construction process.3DP can be used where there will be limitations, such as geometric complexity in the construction sector. As a result, its effectiveness is based on its capacity to construct precisely, which opens up several design options. Khoshnevis invented the contour crafting (CC) technique for mechanized design and constructions, as well as for aerospace uses. Owing to its capability to utilize in-situ resources, it is well suited for low-income accommodation and the fabrication of lunar shelters[54].In 2014, the first 3DP residential construction was created in Amsterdam using the FDM process. Dus Architects carried the proposal forward to display the printer's mobility while minimizing material waste and logistic expenses, thus clearing the way for its adoption in the construction sector. Also in 2014WinSun, a Chinese architecture business, bulk printed apartment dwellings in less than 24 hours in Shanghai. However, WinSun experienced a number of hurdles over the project's length, including issues related to fragility, architecture service compatibility, and indirect printing[55].

Companies which utilise 3D printing technology in the fabrication of automobile structures gain significant market competitive advantages over their contenders. Furthermore, using 3DP, vehicle manufacturing companies can adapt to complex geometry and accomplish distinct customising capability when creating unique vehicle parts for the world market. Moreover, the prolonged utilisation of 3D printing technologies has allowed automobile producers to create prototypes and one-of-a-kind concept cars that also perform an important role in characterising the prospect of vehicles technologies. As a result, comprehensive investigation is required to determine the effect of this technology in revolutionising the world - wide car production industry[56].

Few years ago, Lim et al. suggested three large-scale 3DP procedures suited for the construction sector, each with its own set of advantages and disadvantages depending on the materials used and the applying processes. D-shape and concrete printing both are frame-mounted and gantry-mounted processes that are normally completed off-site. Besides, the CC process can be employed for on-site operations when installed on a robot and crane[57].Additionally, Nadal described the approaches for scaling up ordinary desktop 3DP.Nevertheless, other issues arise, like material waste and inaccuracy, which are typically more labour-intensive[58].

Hager et al. developed a potential process comparable to CC that utilizes cementations materials, thermoplastics, and ceramic products and has the potential to revolutionize the architectural sector in the long run. The initial onsite contour crafts structure was constructed using a sand-cement mixture.CC method is frequently referred to as the first practical AM technology for structure construction. By contrast, the D-shape approach employs the powder deposition procedure, which involves the employment of a chemical substance, including a chlorine-based liquid, to fuse the powder. The technique yields structural components with excellent mechanical qualities. Nonetheless, the regulatory directions and increased service requirements continue to be the primary drawbacks of this strategy[59].Cesaretti et al. also explored the feasibility of employing the D-shape printing process in hostile spatial situations and utilizing the available materials[60].**Figure 4** illustrates a construction utilizing 3DP technology.

Figure 4. Construction using 3DP technology[61]

4. Materials used for 3D printing

4.1. Polymers and composites

Polymers are the foremost used materials in the 3DP industries because of their versatility and flexibility of incorporation into various 3DP processes[62]. Thermoset filaments, reactive monomers, resins, and powders are all examples of polymers used in AM. Wohlers Associates' yearly business analysis indicates that photopolymer-generated prototypes accounted for over 50% of the 3DP market in industrial sectors. Yet, photopolymers' thermo - mechanical characteristics should be enhanced further[63].For example, depending on the difference in Ultraviolet radiation and intensities, the microstructure and alignments of 3DP polymers are dependent upon layer thickness. Conversely, it's also believed that plastics for SLS are the second most essential type of 3DP[63].Polystyrene, polyamides, and thermoplastic elastomers are all examples of SLS polymers. Photopolymer-based technologies provide consistency, thin layers, and high accuracy. Additional advancements utilizing novel resins have resulted in increased rigidity and thermal tolerance. Numerous 3DP techniques can be used to treat thermoplastic polymers. While sustaining an optimal resin viscosity at low temperatures is a significant hurdle to overcome when utilizing polylactic acid[64].At the moment, polylactic acid-based composites are being utilized to fabricate 3DP tissue engineering scaffolds.FDM is frequently utilized to fabricate low-melting-point thermoplastics and polymer composites. However, environmentally acceptable polymeric materials with good physical qualities are critical for FDM since commonly used commercialized polymers for 3DP, such as acrylonitrile-butadiene-styrene copolymers and polylactic acid, do not fulfil the necessary requirements[65].According to Song et al., polylactic acid produced by 3DP exhibits excellent mechanical qualities when compared to injection-moldedpolylactic acid. Additionally, post-tensioning organic fiber reinforcement inserted in the polylactic acid matrix enhanced mechanical characteristics, which is a promising advancement in 3DP[66], [67]. The polymer composite parts produced by 3DP technology are shown in **Figure 5.**

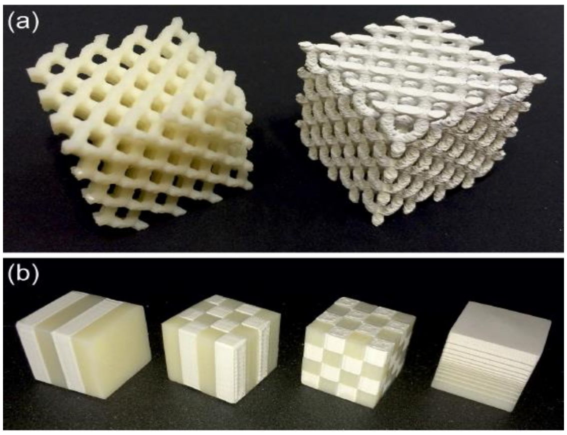


Figure 5. Polymer composite parts produced by 3DP technology (a) rod connected diamond photonic crystals, (b) 1D, 2D, and 3D periodic structure[68]

Nanoparticles can be incorporated into a 3DP item individually, mechanically, with occasional stoppages, or by mixing them in the matrix material[69], [70].While the use of nanoparticles and AM has various benefits, one of the most important advantages is that the products' uniformity can be enhanced. Nanocomposites have gained interest from a variety of organizations owing to their desirable qualities, which include high thermal conductivity, enhanced fire resistance, superior strength, and low weight. When nanoparticles are incorporated and mixed into parent materials via 3DP, significant potential for nanocomposite synthesis occurs. Thus, improving the durability of nanocomposites, as well as their pricing and thermal instability, may provide benefits and potential prospects[71], [72].Elliott et al. explored the influence of adding Quantum Dot (QD) nanoparticles onto a photopolymer resin using the polyjet 3DP method.QD is a form of nanoparticles with a dimension of 2–20 nm and the ability to absorb UV rays. It was discovered that introducing nanoparticles alters the rheology of the substance. By combining this material with 3DP technology, a final object with distinctive optical qualities is developed[73].3DP of polymeric materials has evolved over the decades, allowing for the investigation and exploration of unique materials. The combination of 3DP and a polymer matrix composite enables commercial manufacturing with superior features and physical characteristics. Even so, the lack of printed materials that enable the process of 3DP to be used to a wider range of commercial uses for high-performance composites is still a significant barrier[74].The inclusion of fibre reinforcement could perhaps improve the physical qualities of polymeric materials, which is an enticing breakthrough in 3D printing. Recent times, researchers noted that continuous fibre reinforcement for enhancing the physical characteristics of 3D-printed polymeric materials has proven difficult [106], [107]. Tekinalp et al. investigated the difficulties attributed to 3D printing fiber - reinforced polymer composites and assessed the load bearing capacity of carbon fibre composite parts. The specimens made with FDM had a substantial increment in strength and stiffness[75], [108].

4.2. Metals and alloys

Metal AM has tremendous growth potential. This technique has been primarily employed in the aviation sector for testing, development, and smart functions. Additionally, it is employed in the biomedical, defense, and automobile sectors[24]. In comparison to traditional fabrication techniques, metal AM enables the creation of complicated shapes with unique interfaces. Titanium and its alloys, steel alloys, a few aluminium alloys, nickel alloys, and a few cobalt and magnesium-based metals are all optimized for AM applications. Particularly, titanium and its alloys are high-performance materials that are widely utilized in a variety of sectors. They are characterized by significant machining expenses and a long lead time when manufactured using traditional techniques. Thus, AM can provide major financial gains by allowing for the production of extremely complicated structures at a reduced cost and with fewer wastages[76].Ti-6Al-4V has undergone extensive research and is now being utilized commercially in the aeronautical and healthcare areas.AM frequently employs steels including austenitic stainless steels, maraging steels, precipitation hardenable stainless steels, and tool steels. These alloys are suitable for common purpose usage as well as those requiring great hardness and strength, including tools or molding[77].Austenitic steels and precipitation-hardenable stainless steels are especially susceptible to the effects of AM parameters. Currently, only a few aluminium alloys are employed in AM for a variety of purposes[78]. In comparison to titanium alloys, they are easier to machine and less expensive. As a result, commercial demand for titanium alloys for AM has been diminished. Additionally, some high-performance aluminium alloys are difficult to weld and have a high reflectivity for the laser wavelengths usually employed in AM[79].Furthermore, the low viscosity of molten aluminium precludes the formation of a wide melting pool. Superior thermal conductivity of aluminium minimizes inner thermal stresses and enables rapid AM procedures[80].With reference to the metallurgy of SLM Al-Si alloys, a typical microstructure with overlapped melt pools is illustrated in **Figure 6.**

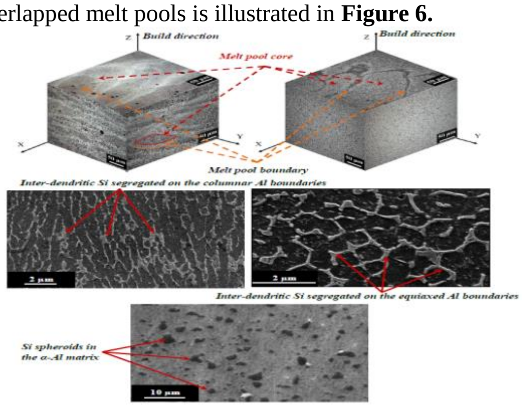


Figure 6. A typical microstructure of SLM Al-Si alloys[81]

For high-temperature usage, nickel-based superalloys like Inconel 625 and Inconel 718 have been produced, whereas, CoCr alloys are being investigated for medicinal and dermatological applications. Additional materials, including magnesium, and copper alloys, are being studied for medical purposes[82].In general, densely packed components generated via AM are of equivalent, if not superior quality to traditionally manufactured components. To achieve such results, it is vital to control porosity and morphology. The primary imperfection that results in fracture propagation is porosity that may be regulated by adjusting the imparted volume energy as well as the feedstock quality[83].Low levels of imposed energy cause the material to produce abnormally shaped cavities. However, an abundance of energy results in the formation of circular pores. The feedstock's performance can be enhanced by employing denser powder beds and smaller particles to enhance flowability and uniformity[84]. Also, the existence of impurities and the alloy's purity should be maintained.AM metal parts have fine microstructures than conventionally made metallic parts, resulting in greater yield and final strengths. Conversely, their microstructure is anisotropic and is assessed by the direction of construction.As a result, anisotropy of material characteristics is quite prevalent, with greater strength and strain in the directions of printing. Additionally, surface roughness and material imperfections influence the fractured behaviour and fatigue strength of AM parts. Higher surface roughness leads to enhanced stress concentration and a more rapid failure rate when subjected to fatigue loading. Furthermore, intrinsic material flaws and poor layer binding reduce the fatigue resistance of AM components. Post-manufacturing operations minimize residue porosity, alter the morphology, and minimize surface imperfections[85].

4.3. Concrete

The architectural industry has benefited from the expansion of AM technology. A comparable technique to IJP, termed CC, has been invented as the primary technique for the AM of structural components. To extrude the concrete mixture, this technology employs bigger nozzles and higher pressures[86].To provide a flawless finishing rather than a layer-by-layer impression, trowel-like equipment is coupled to the printer. At the moment, 3DP technology for construction is in adolescence. As a result, the technology's life-cycle efficiency has not been confirmed[86].Contemporary scientific work on 3DP concrete structures has resulted in the development of novel technologies and materials that are briefly reviewed below. The foremost critical feature of effective CC is the concrete's fresh attributes. Extrusion of complicated structures demands a high level of workability.Gosselin et al. invented a printing technique that separates the accelerator and the premixed mortar and then blends them at the printhead prior to extrusion. The properties of the premixed mortar can be managed for a prolonged duration of time using this technology without compromising the initial strength of the printed layers necessary for successful layer construction.By employing a six-axis robotic system and managing the behaviour of materials before and after the extrusion process, this technology might be capable of fabricating complicated units and without the use of transitory support[87].Paul et al. studied various concrete combinations and discovered that tribological features of the mixture, particularly its thixotropic behaviour, affect the printing and pumping of these mixtures[88].Perrot et al. proposed a mathematical model focused on the rheological behaviour of cement mixtures to optimize the construction rate while avoiding fracture and deformation of the bottom layers[89]. Zhong et al. examined a 3DP nanocomposite geopolymer, for example, a non-portland cement concrete treated with alkali.To achieve a higher resolution, a mixture of quick-setting cement and polyvinyl alcohol composite has been used. However, layer deformation and the creation of voids in between layers were detected and are found to be less apparent when the specimens are post-cured in water[90].Xia and Sanjayan examined the 3DP powder-based structure in a geopolymer matrix. The powder bed is composed of powdered blast furnace slag, sand, and anhydrous sodium silicate, which acts as an alkali activator. The fluid-binder is composed of water and a trace of 2-Pyrrolidone.With geometrical inflation; the 3DP blocks have a low tensile strength of 0.9 MPa. The specimens were post-treated in alkaline solutions at 60°C to improve their strength to 16.5 MPa. Nevertheless, treatments with an alkaline and subjected to elevated temperatures are thought unlikely in full-scale 3DP objects. It is also necessary to evaluate the endurance of 3DP constructions[91].For instance, when compared to traditional concrete, a 3DP construction may experience increased water evaporation due to the absence of formwork to guard from air exposure. As a result, contraction and the danger of fracturing can be increased. Thus, powder-bed AM requires more development in order to produce high-strength constructions[23].

4.4. Ceramic

AM has established itself as a critical technology for manufacturing sophisticated ceramics for biomedical and bioengineering applications. Regardless of the printing precision, the layer-by-layer structure and constrained material availability are the primary hurdles for 3DP of ceramics. Post-processing sintered ceramic components to achieve the required structure is a lengthy and expensive operation[19].As a result, 3DP of complex shapes accompanied by sintering has grown in popularity (**Figure 7**).

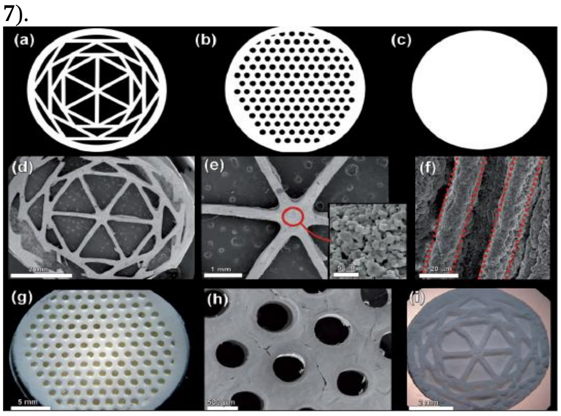


Figure 7. 3D printed ceramic structures[92]

3DP of porous ceramics or lattices resulted in several benefits through the development of new lighter materials customized for specific purposes. Ceramic scaffolds for biomedical applications have improved in terms of convenience and speed when compared to conventional casting and sintering procedures. Moreover, 3DP technology enables precise control over the porosity of lattices[93].

Numerous techniques and materials have been researched in order to improve the physical characteristics of 3DP ceramic lattices as compared to ancient techniques.IJP, PBF, and SLA are the primary technologies for 3DP of ceramics.IJP is considered to be the primary approach for producing thick ceramic specimens which do not require post-treatment.For IJP, a consistent solution with controllable rheology which flows readily, may not choke at the nozzle, and has an efficient drying procedure is necessary[94].Cracking and flattening of the printed filament is also considered to be a critical feature of IJP, with the viscoelastic behaviour of the inks playing an important role[95].SLS is another popular technique for 3DP of ceramic powders. Nevertheless, the thermal shock caused by fusion heating and cooling to room temperature might result in the production of cracks in ceramic components[96]. For ceramic-matrix composites, a technology called selective laser gelation has been developed that integrates SLS with sol-gel technology. For ceramic powders which do not readily fuse or melt at the lowered laser heating temperature, binders with lower melting temperatures are utilized. This process is referred to as indirect SLS and is most frequently employed to create ceramic-polymer and ceramic-glass composites[97].

Ceramics' particle size distribution also has an impact on their flowability, density, and shrinkage during printing. It is demonstrated that increasing the proportion of smaller particles lowered the flowability of a glass-ceramic combination, resulting in a reduced printing resolution and increased shrinkage. Furthermore, because the glass-ceramic powder has a reduced bulk density, it shrinks more during sintering[98]. **Table 3** summarizes the primary applications, advantages, and disadvantages of the 3DP materials.

Table 3: A summary of the primary uses, advantages, and disadvantages of the primary 3DP materials[23]

Materials	Uses	advantages	disadvantages
Polymers and composites	Medical, sports, architecture, biomedical aerospace, and automotive	Cost-effective, fast prototyping, mass customization, and complex structures	A limited selection of polymers and weak mechanical properties
Metals and alloys	Military, automotive, aerospace, and biomedical	Mass customization, multifunctional optimization, fewer assembly components, and reduced material waste	Dimensional inaccuracy, a limited selection of alloys, and poor surface finish
Concrete	Construction, and infrastructure	Less labor required and no need for formwork	Anisotropic mechanical properties, layer-by-layer appearance, and poor inter-layer adhesion
Ceramics	Aerospace, biomedical, chemical industries, and automotive	Reduced fabrication time, controlling porosity of lattices, and microstructure	A limited selection of printable ceramics

5. Key challenges of 3DP technology

Despite the advantages of 3DP, which include creative freedom, personalization, and the capability to build complicated shapes, there are significant limitations that would require additional research and innovation. Among these disadvantages are excessive costs, restricted uses in massive constructions, poorer and anisotropic mechanical qualities, etc. Irrespective of the time and cost of 3DP, that should be determined for each usage, four major issues inherent in AM are described[23], [99].**Figure 8** illustrates a few microstructural defects in 3DP polymer samples.

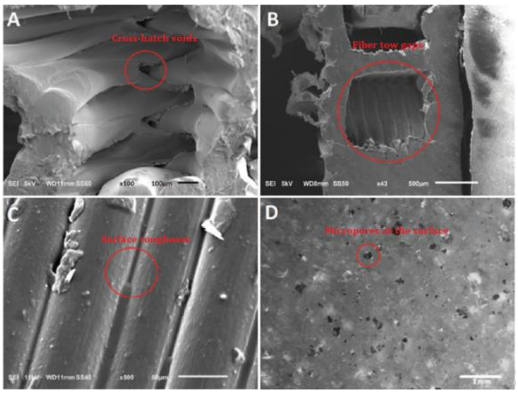


Figure 8: Microstructural defects in 3D-printed, unreinforced polymer specimens[100]

5.1. Void formation

The creation of voids between successive layers of materials is among the primary disadvantages of 3DP technology. The increased porosity caused by AM can be rather large, reducing mechanical performances owing to decreased interfacial adhesion between printed layers. The extent to which voids emerge is significantly dependent on the 3DP method and material used. The development of voids is much more prevalent in processes that utilize filament of materials, like FDM or CC, and is believed to be amongst the primary faults that lead to poorer and anisotropic mechanical characteristics. Additionally, this void creation can cause subsequent layer deformation. Increased filament thickness lowers porosity and cohesiveness in a 3DP composite utilizing the FDM process. It leadsto an enhancement in water intake and a decrease in tensile strength[101].

5.2. Microstructure and mechanical properties

One of the primary difficulties in AM technology is anisotropic behaviour. Due to the complexity of layer-by-layer printing; the structure of the material within every layer is distinct from the microstructure at the layer borders. Owing to the anisotropic nature of the material, the mechanical properties of the 3DP part are varied in the vertical plane than in the horizontal plane[102].Whenever metals and alloys are printed using SLS or SLM, succeeding layers reheat the borders of the preceding layer, resulting in a distinct grain structure and anisotropic behaviour. The laser beams heat penetration into the individual layer is critical for not only managing the sintering operation but also for reducing anisotropic characteristics. The alterations in morphological and textural behaviour in the transverse direction lead to increased strength and ductility in 3DP titanium alloy using the SLM process as contrasted to the longitudinal direction[103].

5.3. Divergent from design to execution

The primary tool for designing 3D printable parts is CAD software. Due to the constraints of AM, the printed part may contain a few faults that were not expected in the manufactured component. The CAD system utilizes both solid geometry and boundaries.It often approximates the model using tessellation principles. Transferring CAD data into a 3DP item, frequently leads to flaws and faults, especially on curvatures. While a super fine tessellation may partially fix this issue, however, the calculated processing and printing will be time-consuming and difficult. As a result, post-processing by heating to correct these flaws is often contemplated. To minimize the difference between design and execution, it would be required to prepare and determine the part's optimal alignment, split the portion into adequate layers, and produce supportive elements[104].

5.4. Layer-by-layer appearance

Due to the nature of AM technology, layer-by-layer aesthetics is another issue. Whenever the 3DP part is disguised in the final design, the aesthetic may be irrelevant– for example in bioengineered scaffolds. In some purposes, including architecture, toys, and aircraft, a uniform surface is favored over the layer-by-layer appearance. Physical or chemical post-processing techniques, including sintering, can eliminate that fault but raise production time and expense[105 - 108].

6. Summary/Conclusion

The greatest advantages of 3DP technology include design freedom, mass customization, and the capacity to build complicated shapes with minimum wastage. A detailed assessment of 3DP methods, materials, and the state of the art in popular applications across multiple industries was conducted. Additionally, the primary issues associated with the nature of 3DP were explored. FDM is among the most widely used 3DP technologies due to its cheap cost, accessibility, and fast processing speed. It was initially developed for 3DP of polymer filaments but has now been repurposed to print a variety of other materials. FDM is primarily employed for rapid prototyping, but the mechanical characteristics and precision of the printed items are lower than those produced by powder-bed technologies. Furthermore, SLA is a pioneering technology of 3DP that is mostly utilized with photopolymers to create highly precise items. Nevertheless, it is a time-consuming and intricate process that is constrained for selective materials.

Polymers are the most often used materials for rapid prototyping. By reinforcing polymers with fibers and nanomaterials, the mechanical characteristics of the 3DP composite were improved.The three primary methods of 3DP used for metals and alloys are SLS, SLM, and DED.Due to a restricted number of metals and alloys suitable for 3DP technology, modern techniques must be adapted to a greater range.Ceramics have permitted the development of sophisticated ceramic lattices for a variety of purposes, including ceramic scaffolds used for tissue engineering.Recent improvements have focused on developing a concrete mixture with superior flowability, processability, mechanical strength, and aesthetics.AM has made a significant contribution to contemporary biomaterial research and innovation for prototyping complicated and customized structures with patient-specific requirements. Yet, it faces obstacles such as resource scarcity and regulatory concerns. While the continuous scientific investigation of materials and processes has aided in overcoming a few of these obstacles, there is still scope for improvements. Considering its radical potential for developing innovative products, 3DP technology requires additional research to compete with existing technologies in the mass manufacturing of everyday goods due to its higher cost and production time. However, AM has advanced tremendously during the last few years. Increased investment, research, and advancement will result in a rapid transition from conventional production to 3DP technology.

References

[1] N. Hossain, M. A. Chowdhury, M. B. A. Shuvho, M. A. Kashem, and M. Kchaou, "3D-Printed Objects for Multipurpose Applications," *Journal of Materials Engineering and Performance 2021 30:7*, vol. 30, no. 7, pp. 4756–4767, Mar. 2021, doi: 10.1007/S11665-021-05664-W.

[2] H. Alzyod and P. Ficzere, "The Influence of the Layer Orientation on Ultimate Tensile Strength of 3D Printed Poly-lactic Acid," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 16, no. 3, 2022.

[3] A. A. Zadpoor and J. Malda, "Additive Manufacturing of Biomaterials, Tissues, and Organs," *Annals of Biomedical Engineering 2016 45:1*, vol. 45, no. 1, pp. 1–11, Sep. 2016, doi: 10.1007/S10439-016-1719-Y.

[4] P. Kumar, D. K. Rajak, M. Abubakar, S. G. M. Ali, and M. Hussain, "3D Printing Technology for Biomedical Practice: A Review," *Journal of Materials Engineering and Performance 2021 30:7*, vol. 30, no. 7, pp. 5342–5355, Apr. 2021, doi: 10.1007/S11665-021-05792-3.

[5] R. A. García-León, J. A. Gómez-Camperos, and H. Y. Jaramillo, "Scientometric Review of Trends on the Mechanical Properties of Additive Manufacturing and 3D Printing," *Journal of Materials Engineering and Performance 2021 30:7*, vol. 30, no. 7, pp. 4724–4734, Feb. 2021, doi: 10.1007/S11665-021-05524-7.

[6] B. Berman, "3-D printing: The new industrial revolution," *Business Horizons*, vol. 55, no. 2, pp. 155–162, Mar. 2012, doi: 10.1016/J.BUSHOR.2011.11.003.

[7] J. W. Stansbury and M. J. Idacavage, "3D printing with polymers: Challenges among expanding options and opportunities," *Dental Materials*, vol. 32, no. 1, pp. 54–64, Jan. 2016, doi: 10.1016/J.DENTAL.2015.09.018.

[8] O. Ivanova, C. Williams, and T. Campbell, "Additive manufacturing (AM) and nanotechnology: promises and challenges," *Rapid Prototyping Journal*, vol. 19, no. 5, pp. 353–364, 2013, doi: 10.1108/RPJ-12-2011-0127.

[9] M. Vaezi, H. Seitz, and S. Yang, "A review on 3D micro-additive manufacturing technologies," *The International Journal of Advanced Manufacturing Technology 2012 67:5*, vol. 67, no. 5, pp. 1721–1754, Nov. 2012, doi: 10.1007/S00170-012-4605-2.

[10] W. Xu *et al.*, "3D printing for polymer/particle-based processing: A review," *Composites Part B: Engineering*, vol. 223, p. 109102, Oct. 2021, doi: 10.1016/J.COMPOSITESB.2021.109102.

[11] T. Sivarupan *et al.*, "A review on the progress and challenges of binder jet 3D printing of sand moulds for advanced casting," *Additive Manufacturing*, vol. 40, p. 101889, Apr. 2021, doi: 10.1016/J.ADDMA.2021.101889.

[12] Z. Chen *et al.*, "3D printing of ceramics: A review," *Journal of the European Ceramic Society*, vol. 39, no. 4, pp. 661–687, Apr. 2019, doi: 10.1016/J.JEURCERAMSOC.2018.11.013.

[13] BhushanBharat and CaspersMatt, "An overview of additive manufacturing (3D printing) for microfabrication," *Microsystem Technologies*, vol. 23, no. 4, pp. 1117–1124, Apr. 2017, doi: 10.1007/S00542-017-3342-8.

[14] M. Mao *et al.*, "The Emerging Frontiers and Applications of High-Resolution 3D Printing," *Micromachines 2017, Vol. 8, Page 113*, vol. 8, no. 4, p. 113, Apr. 2017, doi: 10.3390/MI8040113.

[15] X. Wang, M. Jiang, Z. Zhou, J. Gou, and D. Hui, "3D printing of polymer matrix composites: A review and prospective," *Composites Part B: Engineering*, vol. 110, pp. 442–458, Feb. 2017, doi: 10.1016/J.COMPOSITESB.2016.11.034.

[16] M. FP, F. J, and G. DW, "A review on stereolithography and its applications in biomedical engineering," *Biomaterials*, vol. 31, no. 24, pp. 6121–6130, Aug. 2010, doi: 10.1016/J.BIOMATERIALS.2010.04.050.

[17] O. A. Mohamed, S. H. Masood, and J. L. Bhowmik, "Optimization of fused deposition modeling process parameters: a review of current research and future prospects," *Advances in Manufacturing 2015 3:1*, vol. 3, no. 1, pp. 42–53, Feb. 2015, doi: 10.1007/S40436-014-0097-7.

[18] C. Y. Yap *et al.*, "Review of selective laser melting: Materials and applications," *Applied Physics Reviews*, vol. 2, no. 4, p. 041101, Dec. 2015, doi: 10.1063/1.4935926.

[19] N. Travitzky *et al.*, "Additive Manufacturing of Ceramic-Based Materials," *Advanced Engineering Materials*, vol. 16, no. 6, pp. 729–754, Jun. 2014, doi: 10.1002/ADEM.201400097.

[20] J. Li, T. Monaghan, T. T. Nguyen, R. W. Kay, R. J. Friel, and R. A. Harris, "Multifunctional metal matrix composites with embedded printed electrical materials fabricated by ultrasonic additive manufacturing," *Composites Part B: Engineering*, vol. 113, pp. 342–354, Mar. 2017, doi: 10.1016/J.COMPOSITESB.2017.01.013.

[21] I. Gibson, D. Rosen, and B. Stucker, "Introduction and Basic Principles," *Additive Manufacturing Technologies*, pp. 1–18, 2015, doi: 10.1007/978-1-4939-2113-3_1.

[22] A. Gannarapu and B. A. Gozen, "Freeze-Printing of Liquid Metal Alloys for Manufacturing of 3D, Conductive, and Flexible Networks," *Advanced Materials Technologies*, vol. 1, no. 4, Jul. 2016, doi: 10.1002/ADMT.201600047/FULL.

[23] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges," *Composites Part B: Engineering*, vol. 143, pp. 172–196, Jun. 2018, doi: 10.1016/J.COMPOSITESB.2018.02.012.

[24] Wohlers Associates, "Wohlers Annual Report: Additive Manufacturing and 3D Printing State of the Industry," 2021.

[25] C. L. Ventola, "Medical Applications for 3D Printing: Current and Projected Uses," *Pharmacy and Therapeutics*, vol. 39, no. 10, p. 704, Oct. 2014, Accessed: Aug. 07, 2021. [Online]. Available: /pmc/articles/PMC4189697/.

[26] N. J, M. RD, M. CM, K. MA, and K. A, "A new chapter in pharmaceutical manufacturing: 3D-printed drug products," *Advanced drug delivery reviews*, vol. 108, pp. 39–50, Jan. 2017, doi: 10.1016/J.ADDR.2016.03.001.

[27] V. Keriquel *et al.*, "In situ printing of mesenchymal stromal cells, by laser-assisted bioprinting, for in vivo bone regeneration applications," *Scientific Reports 2017 7:1*, vol. 7, no. 1, pp. 1–10, May 2017, doi: 10.1038/s41598-017-01914-x.

[28] W. C, T. Z, Z. Y, Y. R, L. L, and S. W, "Three-dimensional in vitro cancer models: a short review," *Biofabrication*, vol. 6, no. 2, 2014, doi: 10.1088/1758-5082/6/2/022001.

[29] G. A, B. AB, H. GB, G. S, and B. AW, "3D printing of modified-release aminosalicylate (4-ASA and 5-ASA) tablets," *European journal of pharmaceutics and biopharmaceutics : official journal of Arbeitsgemeinschaft*

fur Pharmazeutische Verfahrenstechnik e.V, vol. 89, pp. 157–162, 2015, doi: 10.1016/J.EJPB.2014.12.003.

[30] F. J, Y. X, and J. Y, "3D printing of vaginal rings with personalized shapes for controlled release of progesterone," *International journal of pharmaceutics*, vol. 539, no. 1–2, pp. 75–82, Mar. 2018, doi: 10.1016/J.IJPHARM.2018.01.036.

[31] C. H *et al.*, "A comparative analysis of scaffold material modifications for load-bearing applications in bone tissue engineering," *International journal of oral and maxillofacial surgery*, vol. 35, no. 10, pp. 928–934, Oct. 2006, doi: 10.1016/J.IJOM.2006.03.024.

[32] S. G, M. W, B. AB, T. KM, and G. S, "In vitro characterisation of terbutaline sulphate particles prepared by thermal ink-jet spray freeze drying," *International journal of pharmaceutics*, vol. 447, no. 1–2, pp. 165–170, Apr. 2013, doi: 10.1016/J.IJPHARM.2013.02.045.

[33] M. A, M. A, P. F, F. A, Z. L, and G. A, "3D printed multi-compartment capsular devices for two-pulse oral drug delivery," *Journal of controlled release : official journal of the Controlled Release Society*, vol. 268, pp. 10–18, Dec. 2017, doi: 10.1016/J.JCONREL.2017.10.008.

[34] Z. Zhang, B. Wang, D. Hui, J. Qiu, and S. Wang, "3D bioprinting of soft materials-based regenerative vascular structures and tissues," *Composites Part B: Engineering*, vol. 123, pp. 279–291, Aug. 2017, doi: 10.1016/J.COMPOSITESB.2017.05.011.

[35] J. W *et al.*, "Direct 3D bioprinting of perfusable vascular constructs using a blend bioink," *Biomaterials*, vol. 106, pp. 58–68, Nov. 2016, doi: 10.1016/J.BIOMATERIALS.2016.07.038.

[36] U. ID, C. L, and P. A, "Three-dimensional drug printing: a structured review," *Journal of the American Pharmacists Association : JAPhA*, vol. 53, no. 2, pp. 136–144, 2013, doi: 10.1331/JAPHA.2013.12217.

[37] W. X *et al.*, "Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: A review," *Biomaterials*, vol. 83, pp. 127–141, Mar. 2016, doi: 10.1016/J.BIOMATERIALS.2016.01.012.

[38] I. Campbell, D. Bourell, and I. Gibson, "Additive manufacturing: rapid prototyping comes of age," *Rapid Prototyping Journal*, vol. 18, no. 4, pp. 255–258, Jun. 2012, doi: 10.1108/13552541211231563.

[39] H. P, M. L, K. C, S. RF, and M. FA, "Cellular Ti-6Al-4V structures with interconnected macro porosity for bone implants fabricated by selective electron beam melting," *Acta biomaterialia*, vol. 4, no. 5, pp. 1536–1544, Sep. 2008, doi: 10.1016/J.ACTBIO.2008.03.013.

[40] R. Sharma, R. Singh, R. Penna, and F. Fraternali, "Investigations for mechanical properties of Hap, PVC and PP based 3D porous structures obtained through biocompatible FDM filaments," 2018, doi: 10.1016/j.compositesb.2017.08.021.

[41] Z. Hu *et al.*, "Design of ultra-lightweight and high-strength cellular structural composites inspired by biomimetics," *Composites Part B: Engineering*, vol. 121, pp. 108–121, Jul. 2017, doi: 10.1016/J.COMPOSITESB.2017.03.033.

[42] L. R, R. G, S. K, K. M, and L. Z, "Use of 3-Dimensional Printing Technology in Complex Spine Surgeries," *World neurosurgery*, vol. 133, pp. e327–e341, Jan. 2020, doi: 10.1016/J.WNEU.2019.09.002.

[43] C. K. Chua, K. F. Leong, and C. S. Lim, "Rapid prototyping: Principles and applications, third edition," *Rapid Prototyping: Principles and Applications, Third Edition*, pp. 1–512, Jan. 2010, doi: 10.1142/6665.

[44] L. Yin, J. Doyhamboure-Fouquet, X. Tian, and D. Li, "Design and characterization of radar absorbing structure based on gradient-refractive-index metamaterials," *Composites Part B: Engineering*, vol. 132, pp. 178–187, Jan. 2018, doi: 10.1016/J.COMPOSITESB.2017.09.003.

[45] "Layer by Layer | MIT Technology Review." https://www.technologyreview.com/2011/12/19/20869/layer-by-layer/ (accessed Aug. 07, 2021).

[46] "Additive Manufacturing for Innovative Design and Production | MIT xPRO." https://learn-xpro.mit.edu/additive-manufacturing?utm_medium=ppc&utm_source=google&utm_campaign=amx&utm_term=industrial 3d printing&utm_content=aw-c&utm_term=industrial 3d printing&utm_campaign=Lifetime+Campaign+-+Additive+Manufacturing+-+C+(Run+11)&utm_source=adwords&utm_medium=ppc&hsa_acc=5861714288&hsa_cam=8553314852&hsa_grp=90248772881&hsa_ad=448051485815&hsa_src=g&hsa_tgt=kwd-43641086169&hsa_kw=industrial 3d printing&hsa_mt=b&hsa_net=adwords&hsa_ver=3&gclid=CjwKCAjw3riIBhAwEiwAzD3TiU46-oEYiMRAVrS4rS45k684Bq0obuqb9qR26sg3Rw1uVtJ_NYkqfxoC9acQAvD_BwE (accessed Aug. 07, 2021).

[47] B. Graf, A. Gumenyuk, and M. Rethmeier, "Laser Metal Deposition as Repair Technology for Stainless Steel and Titanium Alloys," *PhPro*, vol. 39, pp. 376–381, 2012, doi: 10.1016/J.PHPRO.2012.10.051.

[48] S. S *et al.*, "Multistable Architected Materials for Trapping Elastic Strain Energy," *Advanced materials (Deerfield Beach, Fla.)*, vol. 27, no. 29, pp. 4296–4301, Aug. 2015, doi: 10.1002/ADMA.201501708.

[49] J. Ruan, K. Eiamsa-Ard, J. Zhang, and F. W. Liou, "AUTOMATIC PROCESS PLANNING OF A MULTI-AXIS HYBRID MANUFACTURING SYSTEM," 2002, Accessed: Aug. 07, 2021. [Online]. Available: https://proceedings.asmedigitalcollection.asme.org.

[50] I. L. de Camargo, J. F. P. Lovo, R. Erbereli, R. T. Coelho, I. B. da Silva, and C. A. Fortulan, "An Overview of Laser Engineered Net Shaping of Ceramics," *Matéria (Rio de Janeiro)*, vol. 25, no. 1, Apr. 2020, doi: 10.1590/S1517-707620200001.0916.

[51] L. Chen, Y. He, Y. Yang, S. Niu, and H. Ren, "The research status and development trend of additive manufacturing technology," *The International Journal of Advanced Manufacturing Technology 2016 89:9*, vol. 89, no. 9, pp. 3651–3660, Aug. 2016, doi: 10.1007/S00170-016-9335-4.

[52] B. Kianian, "3D Printing and Additive Manufacturing State of the Industry, Annual Worldwide Progress Report: Chapters titles: The Middle East, and other countries," *Wohlers Report - 3D Printing and Additive Manufacturing State of the Industry*, vol. 22, p. 344, 2017, Accessed: Aug. 08, 2021. [Online]. Available: https://researchspace.auckland.ac.nz/handle/2292/46626.

[53] N. Labeaga-Martínez, M. Sanjurjo-Rivo, J. Díaz-Álvarez, and J. Martínez-Frías, "Additive manufacturing for a Moon village," *Procedia Manufacturing*, vol. 13, pp. 794–801, 2017, doi: 10.1016/J.PROMFG.2017.09.186.

[54] B. Khoshnevis, "AUTOMATED CONSTRUCTION BY CONTOUR CRAFTING-RELATED ROBOTICS AND INFORMATION TECHNOLOGIES," vol. 13, no. 1, pp. 5–19, 2004, Accessed: Aug. 08, 2021. [Online]. Available: www.calearth.org.

[55] P. Wu, J. Wang, and X. Wang, "A critical review of the use of 3-D printing in the construction industry," *Automation in Construction*, vol. 68, pp. 21–31, May 2016, doi: 10.1016/J.AUTCON.2016.04.005.

[56] A. S. Elakkad, "3D Technology in the Automotive Industry," *International Journal of Engineering Research and*, vol. V8, no. 11, Nov. 2019, doi: 10.17577/IJERTV8IS110122.

[57] S. Lim, R. A. Buswell, T. T. Le, S. A. Austin, A. G. F. Gibb, and T. Thorpe, "Developments in construction-scale additive manufacturing processes," *Automation in Construction*, vol. 21, no. 1, pp. 262–268, Jan. 2012, doi: 10.1016/J.AUTCON.2011.06.010.

[58] A. Nadal, J. Pavón, and O. Liébana, "3D printing for construction: A procedural and material-based approach," *Informes de la Construccion*, vol. 69, no. 546, 2017, doi: 10.3989/IC.16.066.

[59] I. Hager, A. Golonka, and R. Putanowicz, "3D Printing of Buildings and Building Components as the Future of Sustainable Construction?," *Procedia Engineering*, vol. 151, pp. 292–299, Jan. 2016, doi: 10.1016/J.PROENG.2016.07.357.

[60] G. Cesaretti, E. Dini, X. De Kestelier, V. Colla, and L. Pambaguian, "Building components for an outpost on the Lunar soil by means of a novel 3D printing technology," *Acta Astronautica*, vol. 93, pp. 430–450, 2013, doi: 10.1016/j.actaastro.2013.07.034.

[61] "3D Printing: The Future of Construction - 3Dnatives." https://www.3dnatives.com/en/3d-printing-construction-310120184/ (accessed Aug. 08, 2021).

[62] A. M. Al-Huneidei and I. S. Jalham, "Studying the Properties of Polymer blends Sheets for Decorative Purposes," *Jordan Journal of Mechanical and Industrial Engineering*, vol. 7, no. 1, 2013.

[63] L. SC, L. R, S. J, G. M, and M. R, "Polymers for 3D Printing and Customized Additive Manufacturing," *Chemical reviews*, vol. 117, no. 15, pp. 10212–10290, Aug. 2017, doi: 10.1021/ACS.CHEMREV.7B00074.

[64] Y. Zhuang *et al.*, "3D–printing of materials with anisotropic heat distribution using conductive polylactic acid composites," *Materials & Design*, vol. C, no. 126, pp. 135–140, Jul. 2017, doi: 10.1016/J.MATDES.2017.04.047.

[65] S. FS, N. KV, Z. MY, M. AV, K. SD, and E. YZ, "Mechanical properties and shape memory effect of 3D-printed PLA-based porous scaffolds," *Journal of the mechanical behavior of biomedical materials*, vol. 57, pp. 139–148, Apr. 2016, doi: 10.1016/J.JMBBM.2015.11.036.

[66] Y. Song, Y. Li, W. Song, K. Yee, K.-Y. Lee, and V. L. Tagarielli, "Measurements of the mechanical response of unidirectional 3D-printed PLA."

[67] Albarnawi, Alkhair. The effects of content and surface modification of filler on the mechanical properties of selective laser sintered polyamide12 composites. *Jordan Journal of Mechanical and Industrial Engineering*. 8. 265-274, 2014.

[68] F. Castles *et al.*, "Microwave dielectric characterisation of 3D-printed BaTiO3/ABS polymer composites," *Scientific Reports 2016 6:1*, vol. 6, no. 1, pp. 1–8, Mar. 2016, doi: 10.1038/srep22714.

[69] A. Chiappone *et al.*, "Study of graphene oxide-based 3D printable composites: Effect of the in situ reduction," *Composites Part B: Engineering*, vol. 124, pp. 9–15, Sep. 2017, doi: 10.1016/J.COMPOSITESB.2017.05.049.

[70] S. Dul, L. Fambri, and A. Pegoretti, "Fused deposition modelling with ABS–graphene nanocomposites," *Composites Part A: Applied Science and Manufacturing*, vol. C, no. 85, pp. 181–191, Jun. 2016, doi: 10.1016/J.COMPOSITESA.2016.03.013.

[71] Q. T. Nguyen, T. Ngo, P. Tran, P. Mendis, M. Zobec, and L. Aye, "Fire performance of prefabricated modular units using organoclay/glass fibre reinforced polymer composite," *Construction and Building Materials*, vol. 129, pp. 204–215, Dec. 2016, doi: 10.1016/J.CONBUILDMAT.2016.10.100.

[72] J. Song, C. Chen, and Y. Zhang, "High thermal conductivity and stretchability of layer-by-layer assembled silicone rubber/graphene nanosheets multilayered films," *Composites Part A: Applied Science and Manufacturing*, vol. 105, pp. 1–8, Feb. 2018, doi: 10.1016/J.COMPOSITESA.2017.11.001.

[73] A. M. Elliott, O. S. Ivanova, C. B. Williams, and T. A. Campbell, "AN INVESTIGATION OF THE EFFECTS OF QUANTUM DOT NANOPARTICLES ON PHOTOPOLYMER RESIN FOR USE IN POLYJET DIRECT 3D PRINTING."

[74] G. Alaimo, S. Marconi, L. Costato, and F. Auricchio, "Influence of meso-structure and chemical composition on FDM 3D-printed parts," *Composites Part B: Engineering*, vol. C, no. 113, pp. 371–380, Mar. 2017, doi: 10.1016/J.COMPOSITESB.2017.01.019.

[75] H. L. Tekinalp *et al.*, "Highly oriented carbon fiber–polymer composites via additive manufacturing," *Composites Science and Technology*, vol. 105, pp. 144–150, Dec. 2014, doi: 10.1016/J.COMPSCITECH.2014.10.009.

[76] S. Gorsse, C. Hutchinson, M. Gouné, and R. Banerjee, "Additive manufacturing of metals: a brief review of the characteristic microstructures and properties of steels, Ti-6Al-4V and high-entropy alloys," *http://www.tandfonline.com/action/journalInformation?show=aimsScope&journalCode=tsta20#.VmBmuzZFCUk*, vol. 18, no. 1, pp. 584–610, Dec. 2017, doi: 10.1080/14686996.2017.1361305.

[77] H. Attar, M. Calin, L. Zhang, S. Scudino, and J. Eckert, "Manufacture by selective laser melting and mechanical behavior of commercially pure titanium," *ECU Publications Post 2013*, vol. 593, pp. 170–177, Jan. 2014, doi: 10.1016/j.msea.2013.11.038.

[78] L. E. Murr *et al.*, "Microstructures and Properties of 17-4 PH Stainless Steel Fabricated by Selective Laser Melting," *Journal of Materials Research and Technology*, vol. 1, no. 3, pp. 167–177, Oct. 2012, doi: 10.1016/S2238-7854(12)70029-7.

[79] C. Brice, R. Shenoy, M. Kral, and K. Buchannan, "Precipitation behavior of aluminum alloy 2139 fabricated using additive manufacturing," *Materials Science and Engineering A*, vol. 648, pp. 9–14, Nov. 2015, doi: 10.1016/J.MSEA.2015.08.088.

[80] K. Bartkowiak, S. Ullrich, T. Frick, and M. Schmidt, "New Developments of Laser Processing Aluminium Alloys via Additive Manufacturing Technique," *Physics Procedia*, vol. 12, no. PART 1, pp. 393–401, Jan. 2011, doi: 10.1016/J.PHPRO.2011.03.050.

[81] N. T. Aboulkhair, M. Simonelli, L. Parry, I. Ashcroft, C. Tuck, and R. Hague, "3D printing of Aluminium alloys: Additive Manufacturing of Aluminium alloys using selective laser melting," *Progress in Materials Science*, vol. 106, p. 100578, Dec. 2019, doi: 10.1016/J.PMATSCI.2019.100578.

[82] A. G. Demir and B. Previtali, "Additive manufacturing of cardiovascular CoCr stents by selective laser melting," *Materials & Design*, vol. 119, pp. 338–350, Apr. 2017, doi: 10.1016/J.MATDES.2017.01.091.

[83] A. T. Sutton, C. S. Kriewall, M. C. Leu, and J. W. Newkirk, "Powder characterisation techniques and effects of powder characteristics on part properties in powder-bed fusion processes," *http://dx.doi.org/10.1080/17452759.2016.1250605*, vol. 12, no. 1, pp. 3–29, Jan. 2016, doi: 10.1080/17452759.2016.1250605.

[84] T. Vilaro, C. Colin, and J. D. Bartout, "As-Fabricated and Heat-Treated Microstructures of the Ti-6Al-4V Alloy Processed by Selective Laser Melting," *Metallurgical and Materials Transactions A 2011 42:10*, vol. 42, no. 10, pp. 3190–3199, May 2011, doi: 10.1007/S11661-011-0731-Y.

[85] "Additively Manufactured Inconel 718: Microstructures and Mechanical Properties - Dunyong Deng - Google Books."

[86] M. R. Khorramshahi and A. Mokhtari, "Automatic Construction by Contour Crafting Technology," *Emerging Science Journal*, vol. 1, no. 1, pp. 28–33, Jul. 2017, doi: 10.28991/ESJ-2017-01113.

[87] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, and P. Morel, "Large-scale 3D printing of ultra-high performance concrete – a new processing route for

architects and builders," *Materials & Design*, vol. 100, pp. 102–109, Jun. 2016, doi: 10.1016/J.MATDES.2016.03.097.

[88] B. Panda, N. A. N. Mohamed, S. C. Paul, G. B. Singh, M. J. Tan, and B. Šavija, "The Effect of Material Fresh Properties and Process Parameters on Buildability and Interlayer Adhesion of 3D Printed Concrete," *Materials*, vol. 12, no. 13, Jul. 2019, doi: 10.3390/MA12132149.

[89] A. Perrot, D. Rangeard, and A. Pierre, "Structural built-up of cement-based materials used for 3D-printing extrusion techniques," *Materials and Structures 2015 49:4*, vol. 49, no. 4, pp. 1213–1220, Feb. 2015, doi: 10.1617/S11527-015-0571-0.

[90] J. Zhong, G. X. Zhou, P. G. He, Z. H. Yang, and D. C. Jia, "3D printing strong and conductive geo-polymer nanocomposite structures modified by graphene oxide," *Carbon*, vol. 117, pp. 421–426, Jun. 2017, doi: 10.1016/J.CARBON.2017.02.102.

[91] M. Xia and J. Sanjayan, "Method of formulating geopolymer for 3D printing for construction applications," *Materials & Design*, vol. C, no. 110, pp. 382–390, Nov. 2016, doi: 10.1016/J.MATDES.2016.07.136.

[92] E. M. Hernández-Rodríguez *et al.*, "Prospective use of the 3D printing technology for the microstructural engineering of Solid Oxide Fuel Cell components," *Boletin de la Sociedad Espanola de Ceramica y Vidrio*, vol. 53, no. 5, pp. 213–216, Sep. 2014, doi: 10.3989/CYV.252014.

[93] Y. Wen *et al.*, "3D printed porous ceramic scaffolds for bone tissue engineering: a review," *Biomaterials Science*, vol. 5, no. 9, pp. 1690–1698, Aug. 2017, doi: 10.1039/C7BM00315C.

[94] B. Derby, "Additive Manufacture of Ceramics Components by Inkjet Printing," *Engineering*, vol. 1, no. 1, pp. 113–123, Mar. 2015, doi: 10.15302/J-ENG-2015014.

[95] M. Rosa *et al.*, "Zirconia nano-colloids transfer from continuous hydrothermal synthesis to inkjet printing," *Journal of the European Ceramic Society*, vol. 39, no. 1, pp. 2–8, Jan. 2019, doi: 10.1016/J.JEURCERAMSOC.2017.11.035.

[96] F. H. Liu, Y. K. Shen, and Y. S. Liao, "Selective laser gelation of ceramic-matrix composites," *Composites Part B: Engineering*, vol. 42, no. 1, pp. 57–61, Jan. 2011, doi: 10.1016/J.COMPOSITESB.2010.09.011.

[97] E. Vorndran *et al.*, "3D Powder Printing of β-Tricalcium Phosphate Ceramics Using Different Strategies," *Advanced Engineering Materials*, vol. 10, no. 12, pp. B67–B71, Dec. 2008, doi: 10.1002/ADEM.200800179.

[98] C. Sun *et al.*, "Effect of particle size gradation on the performance of glass-ceramic 3D printing process," *Ceramics International*, vol. 1(PA), no. 43, pp. 578–584, Jan. 2017, doi: 10.1016/J.CERAMINT.2016.09.197.

[99] H. SJ, "Porous scaffold design for tissue engineering," *Nature materials*, vol. 4, no. 7, pp. 518–524, 2005, doi: 10.1038/NMAT1421.

[100] C. Oztan *et al.*, "Microstructure and mechanical properties of three dimensional-printed continuous fiber composites:," *https://doi.org/10.1177/0021998318781938*, vol. 53, no. 2, pp. 271–280, Jul. 2018, doi: 10.1177/0021998318781938.

[101] W. Zhang, R. Melcher, N. Travitzky, R. K. Bordia, and P. Greil, "Three-Dimensional Printing of Complex-Shaped Alumina/Glass Composites," *Advanced Engineering Materials*, vol. 11, no. 12, pp. 1039–1043, Dec. 2009, doi: 10.1002/ADEM.200900213.

[102] T. Mühler, C. M. Gomes, J. Heinrich, and J. Günster, "Slurry-Based Additive Manufacturing of Ceramics," *International Journal of Applied Ceramic Technology*, vol. 12, no. 1, pp. 18–25, Jan. 2015, doi: 10.1111/IJAC.12113.

[103] T. Niendorf, S. Leuders, A. Riemer, H. A. Richard, T. Tröster, and D. Schwarze, "Highly Anisotropic Steel Processed by Selective Laser Melting," *Metallurgical and Materials Transactions B 2013 44:4*, vol. 44, no. 4, pp. 794–796, May 2013, doi: 10.1007/S11663-013-9875-Z.

[104] W. Oropallo and L. A. Piegl, "Ten challenges in 3D printing," *Engineering with Computers 2015 32:1*, vol. 32, no. 1, pp. 135–148, Jun. 2015, doi: 10.1007/S00366-015-0407-0.

[105] N. Coniglio, T. Sivarupan, and M. El Mansori, "Investigation of process parameter effect on anisotropic properties of 3D printed sand molds," doi: 10.1007/s00170-017-0861-5.

[106] Hwayyin, R. N., Hammood, A. S., & Ameed, A. S. The Effect of Acrylic Reinforcement with Different Types of Composite Material on the Impact Energy. *Jordan Journal of Mechanical and Industrial Engineering*, *16*(3), 2022.

[107] Ghalme, S. G. Improving Mechanical Properties of Rice Husk and Straw Fiber Reinforced Polymer Composite through Reinforcement Optimization. *Jordan Journal of Mechanical and Industrial Engineering*, 15(5), 2021.

[108] Kazem, B., & Khawwaf, J. Estimation Bending Deflection in an Ionic Polymer Metal Composite (IPMC) Material using an Artificial Neural Network Model. *Jordan Journal of Mechanical and Industrial Engineering*, *10*(2), 2016.