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REVIEW ARTICLE

A comprehensive review on developments of additive manufacturing- a distinct parametric approach

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Abstract

The main advantages of 3D printing or additive manufacturing (AM) include the capacity to quickly prototype new designs, the freedom to produce unique items in large quantities, the reduction of waste, and the production of complicated structures. The most popular 3D printing techniques, materials, and recent advances in fashionable uses were analyzed in depth. In particular, we focused on the breakthrough uses of AM in the fields of medicine, aerospace, construction, and armor. Metal alloys, polymer composites, ceramics, and concrete are only few of the materials that were discussed as examples of the current status of materials development. Void creation, anisotropic behavior, the limitations of computer design, and the appearance of several layers were all mentioned as major processing issues in this work. As a whole, this paper provides a summary of additive manufacturing, including a survey of its advantages and disadvantages, to serve as a basis for further study for more improvement.

1. Introduction

The term "3-D printing" refers to an additive manufacturing (AM) process that uses 3D model data to make different structures and complex geometries. This method is all about printing materials in layers generated on top of each other. Charles Hull pioneered this technology in 1986 through the procedure of stereolithography (SLA), which has since been followed by other innovations such as powder bed fusion, fused deposition modelling (FDM), inkjet printing, and contour sculpting. Additive Manufacturing, which uses a wide range of techniques, resources, and tools, has advanced to the point that it can revolutionize production and distribution. The building, prototype, and biomechanics sectors are just some of the many that have found success using additive manufacturing. 3D printing reduces waste, improves design, and automates building, but its acceptance has been slow.

As cutting-edge materials and AM processes are continually refined, new applications emerge. Manufacturers have been able to make new 3D printing machines now that older patents have run out. This has made the technology more widely available. Recent improvements have lowered the cost of 3D printers, making them more useful in classrooms, houses, libraries, and labs. Due to its speed and cost, architects and designers employed 3D printing to create attractive and practical prototypes. Cost overruns during product development are reduced to a minimum thanks to 3D printing. 3D printing has been popular for prototypes and final things until recently. Manufacturers have struggled to customize products due to the high expense of doing so. The opposite is true with AM, which can 3D print low-cost, customised objects in small batches. This is especially helpful in the biomedical industry, where individualized treatments for individual patients are the norm. Wohlers Associates anticipated that by

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2020, over half of all 3D printing would be used in the production of commercial products [1], and this trend toward custom-made functional objects appears to be taking hold. Medical experts are interested in how this technique could be used to make a wide range of medical implants from CT-imaged tissue replicas [2]. 3D printing has recently found useful applications in the building sector. WinSun made a lot of cheap Chinese homes in less than a day [3], and each one cost about $4800 USD. The 3D manufacturing system's ability to fabricate intricate geometry with high precision, maximize material savings, promote design diversity, and facilitate individualization may explain its broad adoption. Metals, plastics, ceramics, and concrete are all used in 3D printing. PLA and ABS are the most prevalent composite materials for 3D printing. Since conventional procedures are more labor-intensive, expensive, and risky, the aerospace industry frequently turns to modern metals and alloys. Scaffolds are 3D-printed with ceramics, while buildings are additively manufactured using concrete.

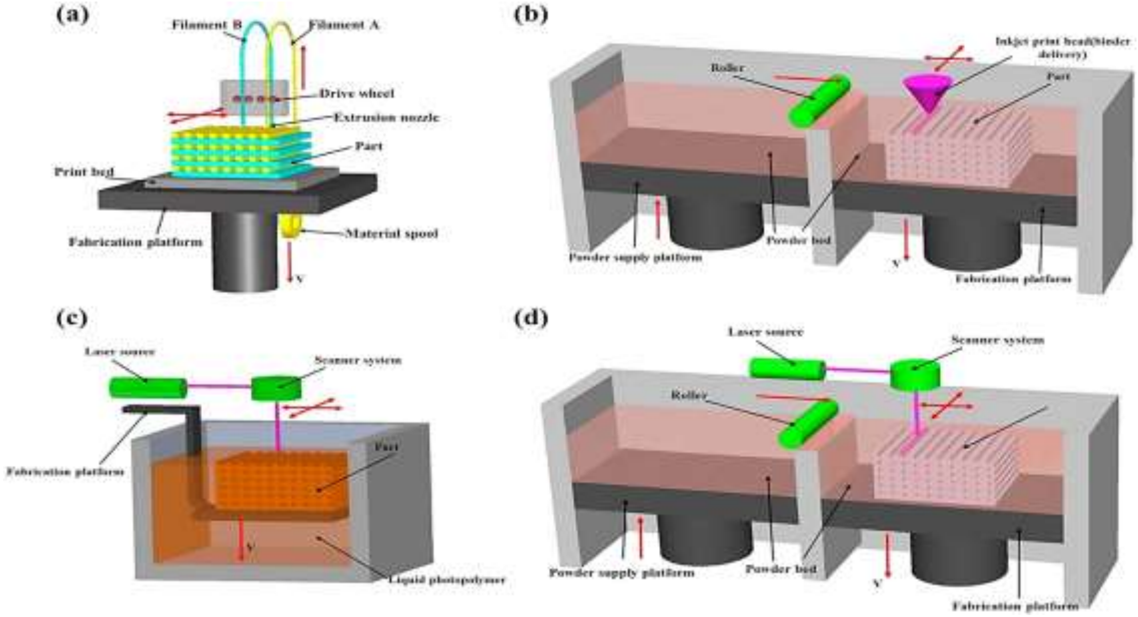

Figure 1: Shows simplified versions of the four most common additive manufacturing processes: (a) fused deposition modelling, (b) inkjet printing, (c) stereolithography, and (d) powder bed fusion [13]

The promise of large-scale additive manufacturing needs to be improved by the parts' subpar mechanical properties and anisotropic behaviour. To control how sensitive, we are to flaws and how we act differently, we need to use the best pattern of 3D priming. Environmental changes can also affect printed materials' quality [4]. Post-processing steps that may be needed for 3D printing on a small scale include sintering, post-curing, and surface finishing. But the limited number of materials for 3D printing makes it hard for this technology to be widely used. Since this is the case, creating materials that work well with 3D printers is essential. The mechanical qualities of 3D printed components also need to be improved with more research. Efforts to understand and remove the limitations that prevent the widespread use of 3D printing technology are ongoing and essential if the technology is to realise its full potential. Create methods of calculating total expenses over time specifically, there is a demand for more intuitive and sophisticated simulation capabilities in AM oriented com- puter-aided design (CAD) systems. Mass customisation, or the fabrication of a succession of unique, low-cost objects, is one of 3D printing's biggest advantages. Thus, mass production huge large number of identical parts can be as cost-effective for production of smaller number of individually customized products. Swapping in between different layouts is simple, requiring hardly any extra time or money and requiring no particular preparation. Traditional methods of production, like as casting, are not easily applied to complex geometries like lattice systems and require additional tooling and post-processing time, but AM could eliminate these obstacles. However, faster production and lower costs will only be achieved if advances in machine design are made. Another key barrier to mass production is additive manufacturing's (AM) high costs and lengthy production time. The goal of this article is to give a comprehensive look at 3D printing methods, including an examination of the most common approaches used, the materials used, where the technology stands right now, and the sectors that are benefiting from it. The paper will also discuss the difficulties in implementing this technology and the research gaps that have been found.

2. Major Schemes

AM techniques were developed to print complex structures at high resolutions. AM technologies have advanced due to the need for faster prototyping, larger constructions, fewer printing errors, and better mechanical properties. The most common 3D printing method, fused deposition modeling (FDM), uses polymer filaments. AM includes 3DP, inkjet, contour crafting, stereo-lithography, DED, and LOM. The methods, their applications, and their finest materials are briefly described. Bhushan and Caspers cover many forms Non-contact micro- and nanoprinting methods investigated in the study include two-photon polymerization (TPP), projection micro stereolithography (PSLA), and electrohydrodynamic printing (EHDP) [6-8]. Fused Deposition Modeling (FDM) 3D prints materials layer by layer using a thermoplastic polymer filament (Fig. 1a). In 3D printing, the filament is heated at the nozzle until it is semi-liquid and expelled onto the platform or on top of previous layers. This technology works because polymer filaments fuse together during printing and solidify at room temperature due to their thermos-plasticity. Inter-layer distortion is the leading cause of mechanical weakness [10], and layer thickness, width, and filament and air gap orientation (in the same layer or between layers) are the main processing parameters that affect the mechanical qualities of printed items [9]. FDM has a cheap cost, speed, and simplicity. FDM's key drawbacks [9] include its restricted thermoplastic material selection, lack of mechanical strength, layer-by-layer appearance, and poor surface quality. FDM-advanced fiber-reinforced composites improve 3D printed object mechanical properties [12]. Fibre alignment, matriX-fibre bonding, and void formation are the key issues with 3D printed composite parts [12, 13]. Powder beds synthesise. Powder bed fusion involves layering tiny powders on a platform. Lasers or adhesives melt powders in each layer into one solid object. Rolling and fusing powder layers creates the final 3D component (Fig. 1d). Coating, sintering, and infiltration can be done after vacuuming the powder. The powder size distribution and packing, which affect print density, are crucial to this technique's effectiveness [14]. Lasers can only be used with low-melting/sintering powders. SLS prints polymers, metals, and alloy powders, while SLM prints steel and aluminum. Laser scanning does not melt SLS powders; the higher local temperature on the grains' surfaces fuses them molecularly. SLM melts and combines particles, improving mechanical properties [15]. Analyses SLM's multiple material and application options [16]. Three-dimensional printing, or 3DP, is the name given to the process when a liquid binder is used. The powder particles' size and shape, the deposition rate, how the powder and binder work together, and the post-processing steps significantly affect the final 3D-printed product [13, 14]. As opposed to laser sintering or melting, which can print thick pieces, binder deposition typically produces products with a larger porosity [14]. The primary factors that affect the sintering process are the strength of the laser and the scanning speed. Lee et al. [15] provides more information on the effects of various laser types on 3D printing. Powder bed fusion is well-suited for printing complicated structures due to its excellent quality and fine resolution. The scaffolds used in tissue engineering, lattices in aerospace, and electronic components are only some of the cutting-edge uses for this technique. Using the powder bed as the support eliminates the need for tedious material removal, which is the main benefit of this technique. However, when the powder is fused with a binder, the process is time-consuming and expensive, and the resulting material is highly porous.

2.1 Printing with an inkjet printer and contours modeling

Ceramic additive manufacturing often makes use of inkjet printing as a common technique. Scaffolds for tissue engineering are only one example of an application that could benefit from the printing of sophisticated and advanced ceramic structures. Droplets of a ceramic suspension, such as zirconium oxide powder in water, are deposited using the injection nozzle [17], onto the substrate. The droplets then set in a continuous pattern that is sturdy enough to support future printed layers (Fig.1b). In addition to allowing for the design and printing of more complicated structures, the speed and efficiency of this approach makes it a viable option. Ceramic inks typically use waxes and liquid suspensions. Melting and depositing wax-based inks on cold substrates solidifies them. Evaporation can harden liquid suspensions. Extrusion rate, nozzle size, printing speed, ceramic particle size distribution, ink viscosity, and solid content all affect inkjet-printed part quality [18]. The primary problems with this approach are its low resolution and poor layer adhesion, as well as the difficulty in maintaining its workability. Contour crafting like inkjet printing is used in large-scale additive manufacturing. Larger nozzles and high pressure extrude soil and concrete paste. Moon contour crafting is prototyped [19].

2.2 Stereo-lithography (SLA)

The development of SLA in 1986 [20] makes it one of the earliest additive manufacturing techniques. A coating of resin or monomer solution is subjected to ultraviolet light (or an electron beam) to kick off a chain reaction. After being exposed to UV light, the monomers (often acrylic or epoxy-based) immediately cross-link into longer chains (radicalisation). The successive layers are held in place by polymerization of the resin, which forms a pattern within the resin layer (Fig. 1c). Wipe away unreacted resin after printing. Heating or photo-curing some printed products improves mechanical performance. When ceramic particles are mixed with monomers, ceramic-polymer composites or polymer-derived ceramics-able monomers, such as silicon oxycarbide, are formed [18, 21]. 10 m SLA printers produce quality items [13]. However, it is time-consuming, costly, and restricted in terms of what may be printed upon. The reaction and curing kinetics are also complicated. Each layer's thickness is mainly determined by the intensity of the light used, and the time it is exposed [20]. Additive manufacture of intricate nanocomposites using SLA is feasible [22].

2.3 Direct energy deposition

High-performance superalloys have been produced using direct energy deposition (DED) [23]. Laser solid forming, directed light fabrication, direct metal deposition, electron beam additive manufacturing (EBAM), and wire arc additive manufacturing (WAAM) are all names for this technology. Direct energy deposition (DED) melts powder or wire feedstock using a laser or electron beam concentrated on a tiny portion of the substrate. Following the movement of the laser beam, molten material is inserted, fused into the molten substrate, and then solidified [23]. In contrast to SLM, DED heats the feedstock before the deposition to melt the metals one layer at a time. Hence, it can be utilised for crack filling and retrofitting manufactured components when the powder-bed approach is not applicable. With this approach, the material can be deposited simultaneously along many axes [24]. DED can also be utilised in conjunction with subtractive processes to complete machining. This technique is often used with aircraft alloys like titanium, inconel, stainless steel, aluminum, and their alloys. Rapid speeds (0.5 kg/h for LENS [25] to 10 kg/h for WAAM [26]) and significant work envelopes (up to 6 m and 1.4 m for commercial printers) are two features of DED. Its precision (0.25), surface quality, and ability to make intricate objects are lower than SLS and SLM [23]. Consequently, DED is typically employed for low-complexity, large-scale components and for the maintenance of such components. DED shortens production times and costs while providing superior mechanical properties, microstructure control, and composition accuracy. This technique has potential niche uses in industries as diverse as the automobile and aerospace sectors.

2.4 Laminated article manufacturing

One of the earliest commercially available additive manufacturing techniques, cutting and laminating sheets or rolls of material layer by layer, constitutes laminated object manufacturing (LOM). Bonding (form-then-bond) or forming and then bonding (bond-then-form) use a mechanical cutter or laser to cut consecutive layers correctly (bond-then-form). Because surplus material may be removed before bonding, the thermal bonding of ceramics and metals lends itself particularly well to the form-then-bond approach. And it also makes it easier to build in-house features. Leftovers from cutting are used for the base, and once the job is done, they're taken out and recycled [28]. LOM benefits polymer composites, ceramics, paper, and metalfilled tapes. High-temperature treatment may be needed for certain materials and attributes. LOM that uses ultrasonic metal seam welding and CNC machining to laminate is known as ultrasonic additive manufacturing (UAM) [29]. With the exception of UAM, no other additive manufacturing technique can be used to build low-temperature metal structures [30, 31]. The paper industry, the foundry industry, the electrical industry, and the smart structure industry are just a few of the others that have benefited from LOM. One definition of a "smart structure" is one that incorporates multiple sensors and processors to perform multiple functions. When compared to traditional techniques, UAM allows for the integrated computer design of embedded electrical devices, sensors, pipelines, and other characteristics to specify cavities in the structureLOM, which uses direct-write technology to print electronic devices in the same lamination process as UAM, is one of the best ways to build more prominent buildings with additive manufacturing [28]. LOM methods have lower surface quality and dimensional accuracy than powder-bed procedures without post-processing. Laminates are time-consuming to work with since it is difficult to remove extra material after an object has been formed. As a result, it shouldn't be used on intricate designs. Table 1 lists the most prevalent additive manufacturing techniques' materials, uses, benefits, drawbacks, and resolution range.

3. Materials and Methods.

3.1 Metals and alloys

Potential for the use of 3D printing in the metals industry is high. AM system sellers climbed from 49% in 2014 to 51% in 2016 [33]. The aerospace industry has made extensive use of this technology for study, prototype, and sophisticated applications like Boeing's F-15 Pylon Rib [34]. It may also have been employed in the biomedical, defense, and automotive industries [33]. Metal additive manufacturing (AM) may create complex geometries with unique connections better than traditional manufacturing methods. In instance, structural, protective engineering, and insulation challenges can all be addressed by creating components with multiple uses. Metal 3D printing involves melting powder or wire with a laser or electron beam. Layering molten substance solidifies it. Binder jetting [35], cold spraying [36], friction stir welding [37], direct metal writing [38], and diode-based approaches [39] are some of the most recent advances in the field of metal 3D printing, which is dominated by powder bed fusion (PBF) and direct energy deposition. Accuracy and speed can both be improved with these methods. AM that uses PBF can make stainless and tool steels, titanium and its alloys, aluminum alloys, and nickel-based alloys [40]. Components with high precision (0.02 mm) and superior mechanical qualities can be fabricated using PBF methods [41]. But because of the sluggish speeds of these technologies (four lasers 105 cm3/h), these facilities are typically used for producing low-volume items. There are other investigations into the usage of femtosecond lasers and other types of lasers [42]. As a result of their high thermal conductivity (> 100 W/mK) and high melting point (> 3000 °C), ultrafast lasers can melt tungsten, rhenium, and some ceramics. AM-optimized alloys include titanium, steel, aluminium, nickel, cobalt-based, and magnesium alloys [40]. Titanium and the alloys of titanium are two examples of high-performance materials that find widespread use in a variety of industries [43,44]. Their manufacturing procedures incur high machining costs and long lead times. The ability to mass-produce complicated structures at cheaper costs and with less waste means that AM can provide considerable economic advantages. Both Ti and Ti6Al4V have been the subject of much research and are now employed in commercial applications in the aerospace and healthcare industries [45, 46]. Steel, especially austenitic, maraging, precipitation-hardenable, and tool steels, is the most frequent material used in additive manufacturing [47–50]. (AM). High strength and hardness conditions, such as those seen in tool or moulding applications, are well suited to these alloys. Particularly susceptible to AM parameters are austenitic steels and precipitation hardenable stainless steels [49]. Few Al alloys are utilized in AM nowadays for several reasons. Because of their low cost and ease of machining, they are a popular alternative to titanium alloys [51]. As a direct consequence of this, the financial motivation to use them in AM has significantly decreased. Also, aluminum by itself has a high reflectivity for the laser wavelengths used in AM [51], and some high-performance aluminum alloys are rarely welded because some of their elements, like zinc, are unstable [52]. PBF is favoured over DED because of the low viscosity of the molten Al, which prevents a sizable melting pool. In a positive light, Al's strong thermal conductivity helps AM processes to go more quickly while also reducing thermal stresses within the material. As of now, AlSi10 Mg [53] and $AlSi_{12}$ [54] are the most popular alloys in use.

Inconel 625 [55] and 718 [56] are two examples of nickel-based super alloys that have been developed for high-temperature applications, while CoCr alloys [57] have been investigated for use in the medical and dentistry fields. Also considered were the metals magnesium alloys [58] (used in biomedical resorbable applications), gold [59], and copper [60]. AM-produced dense metallic parts are on par with or even superior to their traditionally manufactured counterparts in terms of quality [40]. To do this, it is required to regulate porosity and microstructure. Altering volume energy [40] and feedstock quality [62] might mitigate the effects of porosity, the primary defect leading to fracture propagation [61]. Energy controls the formation of irregularly shaped voids [63]. However, when too much energy is applied, round pores form [61]. Denser powder beds and smaller, more uniform spherical particles enhance feedstock quality by facilitating better flow ability and homogeneity [62]. There must also be tight regulation of both the quantity and quality of impurities in the alloy. Because to their smaller microstructures, AM metal components have greater yield and ultimate strengths [40]. But its microstructure is anisotropic, meaning it depends on the orientation of the building. Thus, it is usual for materials to exhibit tensile strength and strain that are greater in the direction of printing, known as aniso-tropy [56]. Surface roughness and material defects affect AM component fracture mechanical behavior and fatigue strength. Surface roughness increases stress concentrations and fatigue failure [64]. Additionally, the fatigue resistance of an AM product is lowered by internal material flaws and inadequate layer bonding.

Table 1: A summary of the most prevalent additive manufacturing techniques, including their materials, applications, benefits, and drawbacks

Process	Materials	Uses	Merits	demerits	The Scope
Fused deposition modelling	Continuously Reinforced Polymers with Fibres Continuation of thermoplastic polymer strands	Fast prototyping of composite parts for toys	Low cost, High speed, Simplicity	Mechanically ineffective Reduced resources (only thermoplastics) Finishing in successive layers	50-200µm [13]
Powder bed fusion (SLS, SLM, 3DP	Little fragments of squished Metals, alloys, ceramics, and even specific polymers can now be 3D printed using selective laser melting (SLS or SLM) (3DP)	Healthcare, Technology, and Aviation Heat exchanger, Lightweight constructions (lattices)	High quality Fine resolution	Expensive, Sluggish Printing Using a binder with a high porosity (3DP)	80-250 µm [13]
Inkjet printing and contour crafting	Construction materials like clay, concrete, and soil are all examples of dense suspensions of solids in a fluid (ink or paste).	Biomedical Large structures Buildings	Having the ability to print big things Easy to print	Keep things manageable Very low detail resolution Insufficient layer adhesion Finishing in successive layers	Inkjet: 5–200µm Contour crafting:25–40 mm [32]
Stereolithography	Photochromic monomer resin Materials that combine polymers and ceramics are called hybrids.	Biomedical Prototyping	Fine resolution High quality	Not much to work with Slow printing costs a lot	10µm [13]
Direct energy deposition	Metallic powders and wires Ceramics, polymers.	Cladding and Retrofitting for Aerospace and Medical Use	Cost-effective manufacturing Mechanically strong Microstructure control Perfect.	Low accuracy Low surface quality Need for a solid base to stand on It's hard to print fine details.	250µm [23]

Laminated object manufacturing (LOM)	Polymer-composite Ceramics Paper Metal-filled tapes Rolls	Paper manufacturing, Electronics, Smart structures, Foundry industries	Tooling and production times are shortened. Infinite varieties of substances Expenses That Don't Break the Bank Perfect for creating bigger things	Poor finish and measurement precision Impossibility of producing complex shapes	Depends on the thickness of the laminates

Treatments applied after production have been shown to be effective at decreasing residual porosity, altering microstructure, and doing away with surface roughness. Hot isostatic pressing (HIP) reduces residual porosities, increases ductility at the strength price, and improves fatigue resistance [65-66]. Polishing or chemically etching surfaces reduces fatigue [64]. The spectrum of available materials for AM is expanding as new metallic materials and alloys are discovered via scientific study. Research focuses on high-strength alloys, magnetic alloys, bulk metallic glasses (amorphous metals), and functionally graded materials (FGM) [67-68] or metal composites. The atomic percentage of the main metallic elements in high-entropy alloys ranges from 5% to 35% [69,70]. This allows for the development of a wide variety of alloys with dramatically diverse characteristics. These alloys can outperform ordinary alloys in terms of strength-to-weight ratios, fracture resistance, tensile strength, corrosion resistance, and oxidation resistance. The materials CoCrCuFeNiAl [71], CoCrCuFeNiAlTi [72], AlCoCrFeNi [73], ZrTiVCrFeNi [74], and TiZrNbMoV [75] were developed to take advantage of the rapid cooling rates typical of AM and enhance microstructures [76].

As their name suggests, magnetic alloys are capable of producing a magnetic field that remains stable over extended periods of time. There are a wide variety of industries that put them to use, from aerospace and aviation to automotive and IT to healthcare. Only a few of the magnetic alloys being investigated for AM use include Ni-Fe-V, Ni-Fe-Mo, Fe-30%Ni, and Fe-Si-B-Cu-Nb. In contrast to the regular crystalline structure of most metals, the atoms in bulk metallic glasses (amorphous metals) are randomly arranged, making them a solid metallic substance with an amorphous structure [80]. In contrast to their crystalline counterparts, these materials have a higher tensile strength, high hardness, resistance to wear and corrosion, and a soft magnetic property. Standard ways to make amorphous metals require a fast cooling rate (100 K/s) and at least one thin dimension. As a result, metal glasses could only be made in rods or sheets. Shen et al. [81] demonstrate that AM may be used to create intricate, three-dimensional structures. Many different alloys are being tested and considered for use in AM. Most metal alloys (above 5500) cannot withstand AM processes due to inappropriate microstructures such columnar grains and periodic cracks [82]. Martin et al recent study [83] reveals that nanoparticles, which nucleate during AM, can control alloy solidification and overcome these difficulties. Using their technology, they were able to successfully fabricate two strong Al alloys (Al 7075 and Al 6061) using AM for the first time. In order to pick the nucleants, crystallographic data was used. Both wrought and produced Al alloys had the same mechanical properties, and their microstructures were smooth and fine-grained with no cracks. The method used by SLM can be used with EBM and DED, which are more traditional and additive manufacturing processes. It will also make AM possible with nickel superalloys and other materials that cannot be welded.

Another extremely important field of research that benefits from AM processing efficiency is the creation of FGM. Improving component effectiveness requires the development of processes for producing materials with site-specific characteristics. LENS [84] and friction stir AM [37] have been used to create seamless alloy transitions. To avoid unwanted phases, designers must use multi-component phase diagrams to predict what will happen at the interface of the alloy [84]. In a multi-component phase diagram, if there are three or more materials, the third alloy can be used as a bridge [85]. Changing the process parameters, such as the energy power, is another way to modify material properties without requiring a switch in alloy types [86]. A356 (which has a much lower melting temperature) has melted its way into a 316L lattice that was produced via additive manufacturing. By tweaking the lattice's form and density, we improved its stress-strain response and thermal conductivity. Meanwhile, tensile elongation was improved by an order of magnitude in comparison to the standard A356. The infiltration processing method used to achieve these outcomes was successful in addressing common issues with conventional AM methods for printing metallic composites, such as inter-metallic formation, cracking, and low resolution.

Additive manufacturing of metals is an excellent way to save money because titanium and its alloys are expensive but very important in the aerospace and medical industries. The field of additive manufacturing (AM) for metals is a dynamic one, with frequent announcements of new techniques, alloys, and applications that promise to greatly enhance quality while simultaneously decreasing production times. Governments, academic institutions, and commercial firms are all investing in research and development to improve AM's speed and precision and increase the range of alloys that can be used, with a keen eye on bringing costs down. When paired with more traditional methods of production, AM shows promise for speeding up the creation of high-quality goods at scale. Benefits of metal additive manufacturing include lower costs for tools, the ability to design and make complex and lightweight structures, and the ability to combine multiple parts into one, so you don't have to put pieces together.

3.2 Polymers & composites

Polymers are versatile and adaptable to many 3D printing methods, making them popular. Additive manufacturing uses thermoplastic filaments, reactive monomers, resin, and powder. Aerospace, architecture, the toy industry, and medicine have all been looking into 3D printing with polymers and composites for a long time. Fabricating composites with 3D printing has many advantages, including the ability to modify geometry with pinpoint precision. When compared to conventional formative techniques like moulding and extrusion, this procedure often results in more cost-effective, bespoke items. However, 3D-printed pure polymer objects are usually only used for conceptual prototypes due to their inherent weakness and usefulness. New methods and materials for making high-performance polymer composites are being developed to increase the mechanical properties of 3D printed polymers [13, 87]. UV light polymerizes photopolymer resins in stereolithography, 3D printing. Wohlers Associates' annual industry report attributes about half of the industrial 3D printing market to photopolymer-generated prototypes [88]. Photopolymers need thermomechanical improvements. As layer thickness increases, UV exposure gradients alter the molecular structure and alignment of the polymers used in 3D printing [89, 90]. The second most important material for 3D printing is SLS polymer.. Improvements in durability and heat resistance have resulted from ongoing research and development employing novel resins. Thermoplastic polymers, including acrylonitrile-butadiene-styrene copolymers (ABS), polycarbonate (PC), and polylactic acid (PLA) [91–93], can be printed using a variety of 3D printing techniques. Although it is difficult to use PLA because the resin loses its optimal viscosity at low temperatures, this issue can be fixed by either increasing the processing temperature or adding a plasticizer. The second option is preferable since it avoids thermal deterioration. Tissue engineering scaffolds made with 3D printing are currently being made using PLA-based composite blends. Senatov et al. [94] used SEM imaging, as depicted in Fig. 2, to confirm the existence of linked pores inside the framework of PLA-based scaffolds.To create 3D porous bio-compatible scaffolds for use in tissue engineering, researchers have 3D printed a combination of polylactic acid (PLA) and a bioactive CaP glass [95]. Polymeric cellular materials are also made by procedures that include chemical or physical blowing agents. Three triply periodic minimum surfaces (TPMS) were examined by Abueidda et al. [96] to create new polymeric cellular materials, and 3D printing is another way to make such materials. Stereolithography, selective laser sintering, fused deposition modelling, 3D bio-printing, and inkjet printing are all examples of 3D printing technologies that can be applied to polymers and composites. Materials with low melting points, such as polymer composites and thermoplastics, work well for FDM process [13]. However, commercially available 3D printing polymers such as ABS and PLA do not produce the desired results. As a result, FDM must prioritize the development of eco-friendly polymeric materials with superior physical properties. Both ABS and PLA have positive environmental impacts, however while PLA is biodegradable, it has weak mechanical qualities [97]. Song et al. did a study and found that 3D-printed PLA had better mechanical properties than injection-molded PLA. This was true for orthotropic and elastoplastic behavior, and the differences were evident when the material was stretched or compressed [98]. Mechanical properties were also enhanced through post-tensioning of natural-fibre reinforcement that had been immersed in PLA matriX [99]. Improved mechanical characteristics of polymers made possible by fibre reinforcement is a potential development in 3D printing [100,102]. Recent research has shown that it is challenging to increase the mechanical properties of 3D-printed polymer composites through continuous fiber reinforcement [12]. Tekinalp et al.'s [103] investigation into the difficulties associated with 3D printing fiber-reinforced composites included testing carbon fiber and ABS resin composite components. In terms of strength and stiffness, the samples made using FDM and compression-moulding (CM) showed substantial improvement. In addition, fibre orientation's reduced effect on tensile characteristics was demonstrated by the fact that the CM samples were stronger. The final 3D printed items will be stronger and stiffer thanks to the mixture of CF with polymer feedstock, and there will be less distortion as a result [104]. Bakarich et al. [105] demonstrated that fiber-reinforced hydrogel composites could be produced using 3D printing in a single step using an alginate/acrylamide gel as a precursor and a UV-curable glue. Complex composites based on hydrogel materials will be possible if ink resolutions are optimised. Cement mortar reinforcement elements utilising 3D printed fibres of photo-polymers and titanium alloy were designed and fabricated using AM technology.

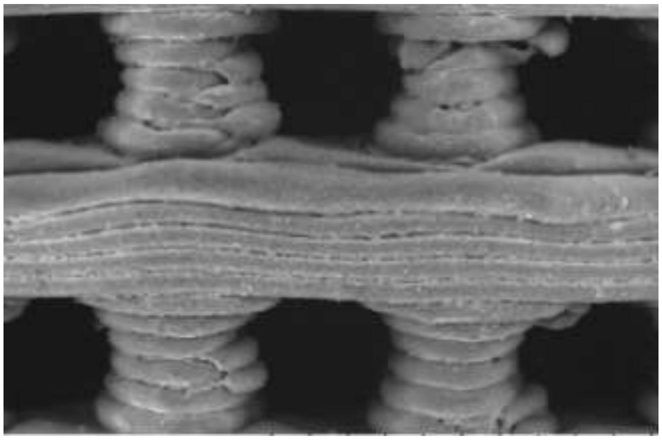

Figure 2: Scaffold is 3D printed using PLA (courtesy of Senatov et al. [94]).

This method was used to improve matriX's durability and resulted in a distinctive surface shape. This study emphasised the correlation between reinforcing fibre shear capacity, flexural strength, and fracture toughness. The energy absorption capacity of fiber-reinforced mortars was found to potentially increase when the fibre surface design was optimised [106]. To create a filament for FDM [107,108] or nanofillers for SLM [109] that is resistant to wear, polymer matriX was reinforced with alumina particles. Additional novel materials for 3D printing include nanomaterials, which have shown to decrease sintering temperatures and increase mechanical and electrical properties [110-114]. A 3D printed object can have nanomaterials inserted into it either manually, through pauses in the printing process, or automatically, through pre-mixing the nanomaterials into the host matrix. The use of nanomaterials and AM has many potential benefits, but the products may benefit from more consistency if they were made with a higher degree of uniformity. Industries are interested in nanocomposites because of its desirable features, which include high strength, low weight, high resistance to heat and fire, and high strength to abrasion. The integration and blending of nanoparticles into host matrices using 3D printing creates great possibilities for the production of nanocomposite materials. Hence, it may be possible to expand upon current applications by enhancing the homogeneity, reliability, cost, and thermal instability of nanocomposites. By combining polylactic acid (PLA) with multi-walled carbon nanotube polymer nanocomposite materials, Postiglione et al. [91] created a low-cost 3D printing approach for conductive 3D microstructures of varying geometries. This method was used to fabricate a woven construction for a basic electrical circuit, as shown in Fig. 3.

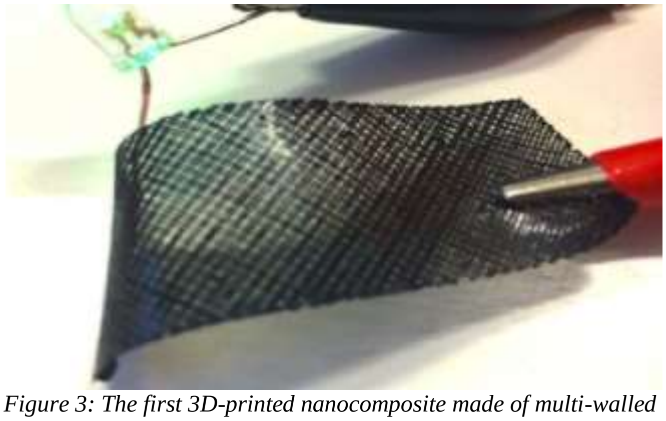

Figure 3: The first 3D-printed nanocomposite made of multi-walled carbon nanotubes (courtesy of Postiglione et al. [91].

Weng et al. [117] looked at the results of incorporating three different nanoparticles into the stereo- lithographic resin to make nanocomposites: nano SiO2, montmorillonite, and attapulgite. The researchers found that micro SiO2 provided the strongest reinforcement. Nanocomposites can now be used in desktop SLA 3D printing thanks to the findings of this study. Nanocomposite filaments based on Nylon 6 were studied for their potential as FDM materials. Electron microscopy (SEM) revealed that the nanoparticles are spread out evenly. Since Nylon 6 is a suitable replacement for ABS, it has the potential to find widespread application in the field of 3D printing [118].

Nanoparticle aggregation and light dispersion because of the composite's high nano-filler content continue to be the most significant challenges, despite efforts to develop nano-fillers for 3D printing composites [113]. Designing nano-fillers for 3D printing composites is difficult due to nano-particle aggregation and light dispersion [113]. In a different study, Shofner et al. strengthened ABS by using VGCF, a suitable single-walled carbon nanotube, as a nanofiller [119]. The improved thermal and electrical properties of a polypropylene matrix have attracted a lot of attention, and this has led to the rise of VCGFs. Extrusion, FDM, and Banbury blending produced a high-quality composite material with a regular fibre distribution and low porosity (used for mixing polymers and compounding plastics). Extrusion or shear processing was also proposed as a viable method for aligning nanofibers. Increases in tensile strength and stiffness were observed in ABS that was reinforced with VCGF. An observation of a brittle fracture mode, however, led to the recommendation that the fibres be treated further in order to boost adhesion. CNTABS and CFABS had improved mechanical properties [120-122]. Inkjet printing with silver (Ag) nanoparticle ink was used by Krivec et al. [123] to develop a quick packaging method for a basic radio frequency identification package appropriate for advanced package prototypes. Elliott et al.'s [124] experiments examined the effects of adding "quantum dots" (QD) nanoparticles to photopolymer resin for use in Polyjet direct 3D printing. Quantum dots (QDs) are a form of UV-absorbing nanoparticle with a diameter of 2-20 nm. Incorporating nanoparticles into a material was found to change its rheology. Unique optical qualities are achieved when this material is combined with 3D printing technology.

3D printing of polymer composites has improved, making it possible to test new materials. By combining 3D printing with a polymer matrix composite, exceptional functionality and mechanical performance can be obtained [125]. However, a major obstacle still stands in the form of a lack of printable materials that may allow the 3D printing process to be adapted for more widespread industrial applications of high-performance composites. The speed and reproducibility of additive manufacturing for composites are inferior to those of conventional techniques. Rapid prototyping has been popular, but there has been a steady rise in the need to mass customise functional components. Because of this shift, it is possible to synthesise additional matrix materials, which can result in superior mechanical qualities. More research needs to be done to find more materials and uses for 3D printing polymer composites.

3.3 Ceramic

AM has greatly improved biomaterials and tissue engineering ceramics like bone and tooth scaffolds [126]. Despite its accuracy, 3D printing ceramics is hindered by layer-by-layer appearance and a lack of materials [18]. Getting the desired shape by post-processing sintered ceramic pieces is a time-consuming and expensive operation. Thus, 3D printing complex shapes and sintering them to make complex ceramics is appealing. 3D printing porous ceramics or lattices has also enabled the creation of lightweight, cutting-edge materials for a variety of uses. Tissue engineering ceramic scaffolds are now made using faster and more practical methods [126].

In addition, one of the advantages of 3D printing is the capability to modify the porosity of the lattices that are produced [127]. The mechanical properties of 3D printed ceramic lattices have undergone some investigation to make them more comparable to those of conventionally produced ones. Li et al. [128] produced a porous alumina ceramic with high flexural strength by combining CaSO4 and dextrin. Nevertheless, Maurath and Willenbacher [129] demonstrated that crack-free and dimensionally stable honeycomb structures with a high specific strength may be manufactured by optimising the ink-printing procedure in terms of the rheology and homogeneity of the ceramic suspension, as well as sintering. Minas et al. [130] investigated the viability of utilising 3D-printed ceramic foam ink to produce a hierarchical porous ceramic with a high strength-to-weight ratio. Air bubbles amid the foam created narrower pores. Inkjet (suspension), powder bed fusion, paste extrusion, and stereolithography are among the most prevalent 3D printing techniques for ceramics. Most researchers agree that inkjet printing is the best option for creating dense ceramic samples that might not require any additional processing [18]. If we need a stable suspension with controlled rheology that flows smoothly, does not clog the nozzle, and dries quickly and efficiently for 3D inkjet printing [131], It is believed that the viscoelastic behaviour of inks is the governing factor in the breaking and thinning of the produced filament during inkjet printing of ceramic suspensions [132].

Ceramic powders can also be 3D printed using the widespread technique of selective-laser sintering (SLS). However, ceramic components can form cracks due to the thermal shock of fusion cooling and heating down to temperature of room [18]. Ceramic matrix composites [133] have also been created using the SLS/sol-gel hybrid SLG technique. Binders with a lower melting point are required for ceramic powders because they do not melt or fuse easily at the lower temperatures required for laser heating. For a limited time, the ceramic powder will be kept in place by the laser-activated binder. Then, the green body is sintered at a higher temperature to turn solid. After sintering, the binder is unnecessary and can be flushed away. Indirect SLS is typically used to produce ceramic-glass and ceramic-polymer composites. While using phosphoric acid as the binder in the production of beta-tricalcium phosphate ceramics, Vorndran et al. [134] observed an increase in printing resolution, mechanical performance, and setting speeds. Unless they are given a post-treatment called "sintering," ceramics made with the SLS process are often less dense and have more holes than cast ceramics [18]. Ceramics' printability, density, and shrinkage are all affected by the particles' size distribution. It has been demonstrated that an increase in the proportion of finer particles in a glass-ceramic system reduces flowability, leading to a drop in printing resolution and an increase in shrinkage during sintering [135]. Printing resolution, mechanical performance, and setting speeds were all improved when phosphoric acid was used as the binder in the production of beta-tricalcium phosphate ceramics, according to research published by Vorndran et al. [134]. Unless they are given a post-treatment called "sintering," ceramics made with the SLS process are often less dense and have more holes than cast ceramics [18]. It has also been developed to laser print a nano-ceramic resin [137]. In contrast, high-quality complex ceramic lattices can be 3D printed using polymer-derived ceramifiable monomers such as silicon oXycarbide, polymerized using ultraviolet light, and then sintered at a higher temperature [21]. Figure 4 depicts the procedure for 3D printing ceramics made from polymers. When compared to the process of using ceramic fillers, the time of production for polymer-derived ceramics is reduced because no additional processing is needed to remove the organic binder. Surfaces made from CSL can be polished to a mirrorlike sheen. But the main drawbacks [18] are that it's an expensive process and there aren't that many materials suitable for this method. Liu et al. [138] looked into infiltrating samples of alumina ceramics with zirconium or magnesium solutions before performing stereo- lithography. This was followed by in-situ precipitation.

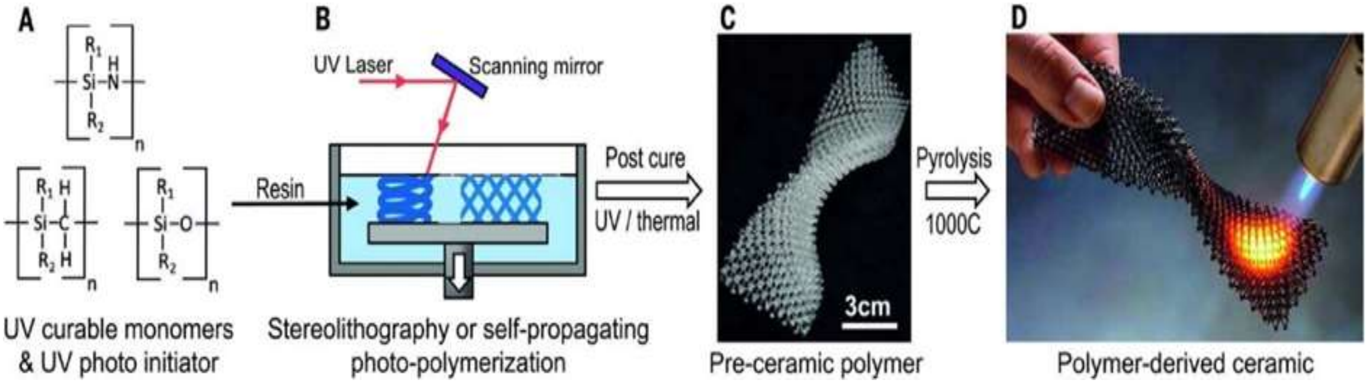

Figure 4: The process of making polymer-based ceramics that can be 3D printed (Eckel et al. [21]).

The infiltrated material was significantly stronger than the control material, but it had significantly lower fracture toughness. The size distribution of the ceramic powder in the paste still has an effect on the qualities of a 3D-printed object, unlike the powder printing using SLS method.A study by Dehurtevent et al. [136] found that the flexural strength and shrinkage of alumina dental crown samples produced through 3D printing are unaffected by particle size. But Wu et al. [139] showed that a mix of micro-sized and nano-sized alumina particles was more effective than either size alone (a bimodal distribution) resulted in greater density than the mono-sized distribution of alumina particles.

Figure 5: Concrete building that was 3D printed (courtesy of Zareiyan and Khoshnevis [148]).

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3.4 Concretes

Additive manufacturing is currently widely utilized in the building trade. The most common approach to additive manufacturing in the construction industry is the use of a contour crafting technology that is similar to inkjet printing [19]. The concrete paste is extruded via larger nozzles and higher pressure in this technique. A trowel-like device has been made and attached to the print head to make sure that the finish is even and not made up of layers. The application of 3D printing in the building trade is still in its early stages of development. Therefore, the technology's life-cycle performance has not been established. Following is a brief overview of the various approaches and materials that have been developed by the few recent academic studies on 3D printing concrete structures. Achieving a desirable contour is all about working with the concrete while it is still in its fresh state. In order to 3D print complex shapes, the material must have a high extrude-ability (also known as open time) for extrusion and a high early strength of concrete (also known as buildability) for supporting subsequent layers [140]. A mixture must have high early strength and long-lasting workability to be extruded successfully. Gosselin et al. [141] created a printing technique in which the accelerator and premix mortar is pumped separately and mixed at the printhead before being extruded. Using a six-axis robotic arm and material behavior control during and after extrusion, this technology might produce more significant, more complicated structures without temporary supports. Layering works well when the rheology of the premixed mortar can be controlled for a long time without affecting the early strength of the printed layers. Paul et al. found that pumping and printing depend on the concrete mixture's thixotropic rheology [142]. Perrot et al. [143] developed a theoretical framework for optimizing building pace without cracking and deforming foundation layers using cement mixture rheology. Portland cement, fly ash, silica fume, and sand were used to make high-performance polypropylene fiber-reinforced mortar by Le et al. [140]. (2-mm maximum aggregate size). Superplasticizers and retarders allow the material to be extruded through a 9 mm nozzle with a 100 m/sec open time. Up to 61 layers can be built with the developed mixture (about 400 mm).

When compared to conventional fibre-reinforced concrete, 3D printed fibre-reinforced concrete composites have the advantage of being able to precisely regulate fibre orientation within a printed structure. The flexural strength of materials printed in the x-y plane with parallel lines was found to be significantly improved by up to 30 MPa when the carbon fibres were allowed to be oriented in any of the possible directions [144]. The alkali-activated, Portland cement-free concrete used in 3D printing was studied by Zhong et al. [145]. Improved extrudability, higher compressive strength (around 30 MPa), and better electrical conductivity were all achieved thanks to the incorporation of nano-graphene oxide into the geopolymer system. To improve print quality, we used a composite made from rapid hardening cement and polyvinyl alcohol (PVA). However, post-curing of the samples in water reduced the visibility of layer delamination and void formation between the layers [146]. Using ordinary Portland cement (OPC) and sulphoaluminate cement (SAC), explored a mix design of a cementitious mortar [147]. Unlike OPC, which has a slow hydration rate and a long setting time, SAC can be used immediately after mixing and has a high early strength. After comparing and contrasting the properties of these two options, SAC was suggested as a better option for 3D printing mortar. Due to the layered nature of 3D printing, it is imperative that the material set quickly so that the lower layers can strengthen enough to hold up the upper ones. The printing directions determine the mechanical properties of the specimens, but printing parameters such as nozzle shape control these properties [142]. The difficulty of ensuring reliable adhesion between successive layers is a significant obstacle for 3D-printed concrete buildings. Bond strength between layers was investigated, as well as the roles of aggregate size, extrusion, and layer thickness [148]. A diagram of their 3D-printed concrete structure is presented in Fig. 5. They found that smaller maximum aggregate sizes and a higher ratio of cement to aggregates made the material stronger. This was because the layers stuck together better. Even though the bonding between layers got better with longer gaps, the printed structure got weaker because the layers got thicker. Also, a shorter setting time makes cold joints more likely to happen between layers [148]. Stability of printed layers against settlement and deformation due to printing of subsequent layers is what is meant by "shape-stability" of the printed part. Shape-stability in 3D-printed cement paste was significantly improved by the addition of silica fume and nanoclay, as demonstrated by Kazemian et al. [32]. Obtaining the right kind of external support and then getting rid of it afterward presents another major difficulty when 3D printing large, complex, tall structures [149]. Even though cement and concrete paste have received the most attention in 3D printing, the powder bed fusion technique has also been studied. The researcher created a powder bed from a mix of regular portland cement and calcium aluminate cement using an aqueous solution of lithium carbonate as the binder [150]. Due to the infrequency of powder-water contact, the material only hydrated to a minor extent, resulting in a compressive strength of about 8 MPa, a relatively high porosity of about 50%, and a lack of bulk density. With a geopolymer system in mind, Xia and Sanjayan [151] looked into the properties of a powder structure printed in three dimensions. Alkali activator, ground anhydrous sodium silicate, ground sand, and ground blast furnace slag make up the powder bed. Water and a trace amount of 2-Pyrrolidone make up the liquid binder. The printed cubes grow in size by less than 4% and have a weak strength of 0.9 MPa. The power increased to 16.5 MPa after being treated in an alkaline solution at 60 °C. However, full-scale 3D printed structures are unlikely to require alkali solution and high temperature treatment. The printed cubes have a very low strength and expand by less than 4% in size. One of the difficulties faced by 3D printers while working with wet concrete is regulating the concrete's new qualities to ensure sufficient workability and an available period for extrusion. Other structural properties, such as strength, inter-layer adhesion, deformation, and build-ability, also present difficulties. Examining 3D printed objects' longevity is also important. Water can evaporate more quickly from a 3D printed structure than from a traditionally constructed one because there is no formwork to shield it from air exposure. Consequently, this can heighten the potential for shrinking and cracking. If we want to build strong structures, we need to improve powder-bed AM. Researchers developing 3D printed concrete have been motivated primarily by a desire for greater design freedom and the ability to construct complex structures using less expensive materials like concrete. The printed cubes only grow by about 4% and aren't particularly sturdy. Since the advent of new concrete combinations for 3D printing, 3D printed buildings and homes may now be mass-produced everywhere on Earth; the next generation of these buildings will be used for lunar construction [19,152].

4. Comparison (3D printing materials)

Recent developments in additive manufacturing have opened the door to 3D printing in anything from chocolate to cutting edge multifunctional materials. 3D printing allows for the use of a wide variety of materials, including filaments, wire, powder, paste, sheets, and inks. Many different kinds of polymers have been created for use in various fields, including aerospace, automotive, sports, medicine, architecture, and toys. In FDM (the most common method), polymers are used as filaments, while in powder-bed and stereolithography, polymers are used as powders or auxiliary binders. The printed cubes have a very low strength and expand by less than 4%. Most 3D printers use thermoplastic polymers like ABS, PA, PC, and PLA, or thermosetting powders like polystyrene, PA, and photopolymer resins. 3D-printed polymers are typically used for rapid prototyping due to their poor mechanical properties. In recent years, however, attempts have been undertaken to improve the mechanical qualities of printed goods intended for use as load-bearing or functional components by reinforcing polymers with nano and fiber-based elements.

Waste from precious metals like titanium is reduced in additive manufacturing when compared to more conventional practises. It also greatly expands design flexibility by doing away with the assembly stage and decreasing the potential for localised stresses during assembly. The aerospace, defence, and automotive sectors all benefit from 3D printing metals and alloys to create complex parts of varying sizes. Powders are the most common physical form for metals (or wires). SLM, SLS, and DED use lasers or electron beams to fuse materials for 3D printing. Due to the paucity of metals and alloys that can be used in 3D printing, scientists are constantly developing new alloys and polymer-metal composites [153], adapting present procedures to more materials, and building composite structures. Possibilities for metal 3D printing are currently limited by faults such as porosity, bead accumulation, orientation-dependent material property and shape variability. However, there are still ongoing investigations into how to optimize processing parameters and post-processing treatments. Since this technology has made it easy to mass-produce complicated ceramic lattices for different uses and started a trend for specially designed materials with a high strength-to-weight ratio, the use of 3D-printed ceramics has grown. One of the primary uses is in tissue engineering, which makes use of strong, adaptable ceramic scaffolds of varying complex shapes. Mainly powders or inks are used for 3D printing ceramics. Lasers or auxiliary adhesives are used to "sinter" or "bond" powders into solid forms. On the other hand, a suspension of ceramic particles can be printed using ink-jet printing, then subjected to post-treatment like high-temperature sintering. The main problem with 3D printing ceramics with current techniques is the limited number of materials available, along with the issues of dimensional accuracy and quality. However, the micro-structure and composition of the part can be better controlled when using 3D printing with ceramics. Therefore, there is room for improvement in the areas of research and developmenting AM technologies and expanding the materials selection for 3D printing of ceramics. Concrete is the most widely used manufactured product, finding widespread application in building and infrastructure projects all over the world. Although the construction sector has been slow to adopt 3D printing, the technology's many advantages, including mass customization, the removal of the need for formwork, and the potential for automation indicate that it has a bright future. The additive manufacturing of concrete typically employs the extrusion technique, though the powder-bed approach has also been investigated. Due to its potential inability to maintain its form when printed using the formwork-free 3D printing method, self-compacting concrete may not be a good ingradients for additive manufacturing. Significant drawbacks include anisotropic mechanical properties, poor interlayer adhesion, and a layer-by-layer appearance. Even with these restrictions, the potential to create sophisticated yet lightweight structures are exciting. The advantages and disadvantages of the most commonly used additive manufacturing materials are outlined in Table 2. By combining different materials and precisely controlling their position, modern 3D printing technologies allow for the multifunctional properties of manufactured parts to be tailored to the individual application [154]. While some can only change materials between layers, others can also alter them within a given layer. But there are constraints that must be considered. High-pressure jetting systems can join polymers with good flow ability and equivalent curing temperatures, whereas FDM and other extrusion-based technologies can only link materials with comparable melting temperatures. [154]. In bio printing, multi-jet FDM techniques are becoming more popular, especially for making complex hydrogel scaffolds with cells that look like the tissue matrix [155]. Metal alloys and ceramics can be combined in other 3D printing processes, such as direct energy deposition (DED), allowing for a greater number of materials to be extruded simultaneously. Nonetheless, more must be done to avoid phase formation between two materials [85]. Powders with varying melting points have been successfully used in powder-based technologies [154,156]. Problems may arise, however, if powders with different melting points are stored too closely together, as the lower melting point materials may remelt or degrade. Numerical modelling and optimization for material processing can improve understanding of multi-material manufacturing processes and their functional responses [157].

5. Trending appliances

5.1 Bio-material

Additive manufacturing is expected to grow from $6.1 billion in 2016 to $21 billion in 2020, according to a recent report [33] by Wohlers'. One of the key sectors that will propel AM forward is the biomedical industry, which currently accounts for 11% of the total AM market share.

5.2 Biomedical complexity

The complexity and novel methods of biomedical research present significant challenges. By facilitating the creation of engineered tissues and organs, as well as managed drug delivery systems, AM will revolutionize the medical field [158]. Thanks to AM's adaptability, novel materials like semi-crystalline polymeric composites can be engineered to produce extremely complex shapes [159].

Table 2A summary of the primary additive manufacturing materials' Main Uses, Merits, and Challenges.

Materials	Main Uses	Merits	Challenge
Metals and alloys	Military and aerospace biomedical engineering.	Efficiency in a variety of contexts Mass-customization Lessening of the amount of resources wasted Less parts to put together metals can be repaired if broken or worn down.	Less alloys to choose from Problems with dimensions and surface polish Possible need for post-processing (machining, heat treatment or chemical etching)
Polymers and Its composites	Automobiles and aerospace, sports medicine, architectural toys, and biomedicine.	Quick prototyping Cost-effective Complex structures Mass-customization.	Poor mechanical qualities a small number of available polymers and reinforcements mechanical characteristics that are anisotropic
Ceramics	Automotive, chemical, and aerospace industries	Regulating the lattice's porosity creating elaborate human body scaffolds and structures through 3D printing organs Reduced fabrication time.	A small range of ceramics that are 3D-printable Dimensional errors and shoddy surface finishing Some post-processing, like sintering, might be necessary.
Concrete	Construction and infrastructure.	Mass-customisation No need for formwork; less labor is required, which is instrumental in harsh environments and space construction.	Layer-by-layer presentation a mechanical property that is anisotropic inadequate interlayer adhesion Problems scaling up to larger buildings bespoke concrete mix design and printing techniques.

5.3 Customization and necessities

From implants to drug dosing, biomedical applications must be individualized for each patient. Among the many biomedical products that could benefit from AM's precision is hearing aids [160], biomedical implants [161], individualized orthotics [162], and prostheses [163]. Planning surgeries with AM increases efficiency and effectiveness while decreasing the need for additional surgeries to customize the implant to the patient [162]. In addition, AM will be utilized to customize dose forms and release profiles for drugs [163]. In the biomedical business, where production numbers are often low, additive manufacturing is more cost-effective than conventional manufacturing processes. In addition, it permits the manufacturing of complex goods without the need to create new tooling fixtures regularly. Rapid prototyping using AM can be accomplished in a fraction of the time it takes using traditional manufacturing techniques like molding, forging, and milling [164]. Researchers can easily replicate the same design by sharing AM CAD files. The NIH, for instance, has launched 3D Print Exchange [165] to facilitate the open distribution of AM files. Biofabrication includes bioprinting, bio-assembly, and maturation in creating tissues and organs [166,167]. The primary distinction between fabrication and conventional AM is the integration of cells with biomaterials produced to produce so-called bio-inks [168]. Laser-induced forward transfer (LiFT), inkjet printing, and robotic dispensing are all used in bioprinting with bio-inks [167]. The literature [169] provides a wealth of discussion on these specialized methods. The desired form and tissue can then be matured using the biomaterials combined with biomolecules and cells. Biomolecules direct tissue regeneration, while biomaterials provide structural support and physical cues for tissue development. Tissues and organs of greater complexity will be printed using a combination of multiple bio-inks and cells. The shape, size, and material makeup of broken components will be precisely determined thanks to technological advancements in imaging. The potential for organ/tissue rejection is also diminished when auto-logous cells from the patient are used. The production of aortic valves [170], bone [171], bioresorbable tracheal splints [172], and cartilage [170] has all been accomplished in vitro or in vivo. One of the primary goals of bio-fabrication is the in situ generation of tissues for organ and tissue repair, something that has been partially realized with skin [173], bone [174], and cartilage [175]. Shortly, bio-fabricated parts will be utilized in toxicity studies [176], disease models [177], and assessing adverse drug reactions, even on an individual patient basis. Since current bioprinting methods require handling delicate cells, they have their limitations. Microextrusion bioprinters, for instance, need to use a pressure that is low enough so as not to distort the cellular structures and damage cells as the bio-ink is expelled. There can be a 40% drop in usable cells when extrusion pressures are high [178]. Although inkjet bioprinting can expose cells to temperatures of up to 300 °C in the nozzle, this does not cause them to die or become damaged because the localized heating only lasts for 2 s and only increases the local temperature by 4 °C to 10 °C [179]. The selection of bio-ink scaffolds is a more pressing problem. Not only must cells be able to stay put on the scaffolds, but they also need to be adequately protected from mechanical and thermal stresses. In addition, they need to promote the desired proliferation and growth of cells without encouraging the unintended proliferation or development of other cell types [180]. Material must be cytocompatible to prevent immune and inflammatory responses and the premature differentiation of stem cells [181]. Despite developing several bio-ink scaffolds meant to address the problems mentioned above, there are still obstacles to overcome before 3D printing biomaterials can be optimized for their intended use [182]. Creating vascularized organs presents a significant challenge for bio-fabrication [167]. Using 3D bio-printing, Zhang et al. [183] analyzed the current state of the art in printing functional vascularized tissue and blood vessels. Before 3D-printed tissues can be made, more research needs to be done.

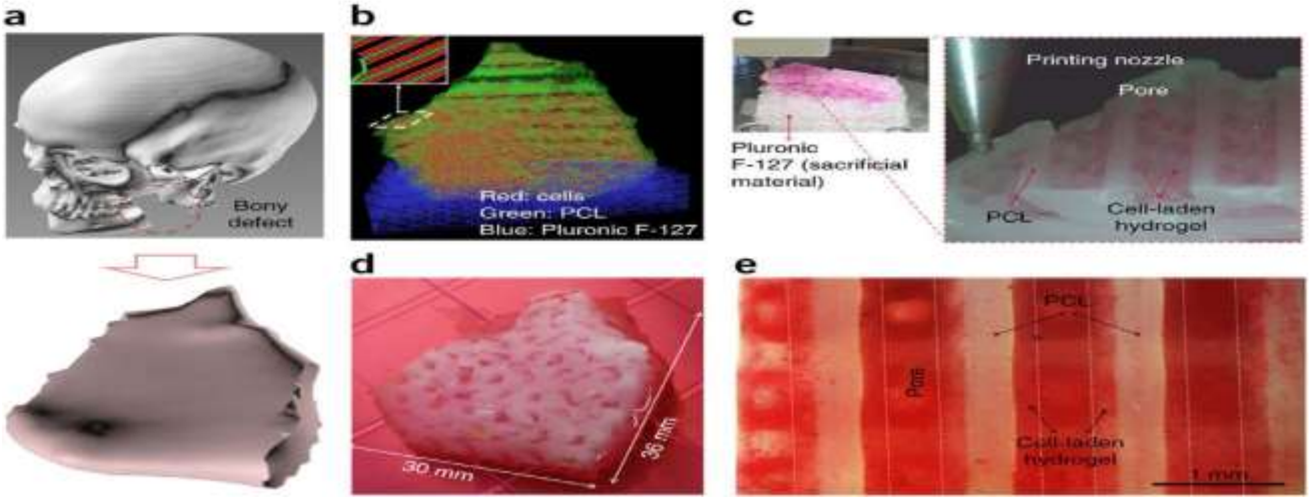

Figure 6. (a) From CT scan images, a 3D CAD model identifies a defect in the mandible; (b) Motion distribution of print from the developed software. (c) Additive manufacturing method; (d) Bony defect implanted using 3D printing and cultured for 28 days in osteogenic medium; (e) Alizarin Red S staining, which reveals calcium deposition, confirms osteogenic differentiation; [185].

This is because it is hard to print with a high resolution on a small scale, and vascularized tissues must have mechanical properties. However, recent advances in versatile bio-ink highlight the promise of additive manufacturing for tissue engineering of sensitive human organs and tissues. To develop bio-printed components with the required properties, researchers are studying bioreactors in conjunction with factors that promote angiogenesis and innervation [184]. Amplified success in printing human-sized tissue constructs with various bio-inks and AM methods is depicted in Fig. 6 [185]. The biomedical field will undergo another paradigm shift with the development of in situ bioprinting for tissue regeneration. To a great extent, AM will help the pharmaceutical industry. As a result, the pharmaceutical industry and drug distribution methods will undergo profound shifts. In 2015, the FDA authorized the first drug specifically for AM [163]. Solid dosage forms [186], drug delivery systems that can be implanted [187], and drug delivery systems that can be applied to the skin [188] are just a few of the new ways to take AM that are being made. Solid dosage forms (which have attracted the most attention because they are straightforward to commercialize) [186]. AM could control the release profiles of drugs by changing their 3D shape, the microarchitecture of the drug delivery system, or the location of the active agent [186, 189]. AM makes it possible to make things like microcapsules, antibiotic micro patterns, synthetic extracellular matrices, mesoporous bioactive glass scaffolds, nano-suspensions, and drug delivery systems with more than one layer [190]. Both specific dosing and pharmacogenetic profiles can be accommodated in the on-demand production of personalized medicines. The most effective medication could be developed, taking into account factors like age, race, and gender [190]. In the future, multiple medications may be combined into a single tablet, each released gradually [190]. Additive manufacturing of unstable, time-sensitive medications is expected to be in high demand [163]. Multiple active ingredients have been investigated [190]. These include caffeine, acetaminophen, theophylline, and nonsteroidal anti-inflammatory drugs. The analysis of computational geometrical design, microarchitecture, and placement of active and passive agents in AM delivery drug systems will allow for predicting the release profile of these systems. The pressure from microextrusion bioprinters must be kept low enough to prevent cell damage and distortion. There can be a 40% drop in usable cells when extrusion pressures are high [178]. Since the localized heating only lasts for two seconds and only increases the temperature locally by 4 to 10 °C, inkjet bio printing exposes cells to high temperatures (up to 300 °C in the nozzle), but it does not kill or harm them [179]. The selection of bio-ink scaffolds is a more pressing problem. Not only must cells be able to stay put on the scaffolds, but they also need to be adequately protected from mechanical and thermal stresses. In addition, they need to promote the desired proliferation and growth of cells without encouraging the unintended proliferation or development of other cell types [180]. Material must be cytocompatible to prevent immune and inflammatory responses and the premature differentiation of stem cells [181]. Despite developing several bio-ink scaffolds meant to address the problems above, there are still obstacles to overcome before 3D printing biomaterials can be optimized for their intended use [182]. Creating vascularized organs presents a significant challenge for bio-fabrication [167]. Understanding how to construct complicated vascular systems and innervation will be critical since blood vessels are crucial to the metabolic processes of huge organs. Using 3D bio-printing, Zhang et al. [183] analyzed the current state of the art in printing functional vascularized tissue and blood vessels. More research is needed before 3D-printed tissues may be manufactured due to the inability to print at high resolutions on a small scale and the absence of known mechanical properties for vascularized tissues. However, recent advances in versatile bio-ink highlight the promise of additive manufacturing for tissue engineering of sensitive human organs and tissues. To develop bio-printed components with the required properties, researchers are studying bioreactors in conjunction with factors that promote angiogenesis and innervation [184]. Amplified success in printing human-sized tissue constructs with various bio-inks and AM methods is depicted in Fig. 6 [185]. Tissue regeneration using in situ bio-printing is another innovative paradigm that will shake up the medical industry. The implant industry is also being revolutionized by AM, as customized implants for individual patients are now possible [192]. These days, CAD software is used in every step of the process, from acquiring an image of the body part to elaborating on it to designing and producing an implant [166]. Inexpensive and dependable AM techniques allow for the rapid production of anatomically complex geometries. Though patient-specific AM implants are currently on the market, most have only been used in clinical trials with the patient's informed consent [193]. Future definitive approval from regulatory authorities will depend critically on process and material consistency. Implants can even include complex geometric features. To reduce or do away with stress-shielding between the implant and the bone, researchers are looking into low-rigidity, high-strength lattice structures [194]. Biological models can be a starting point for designing certain lattice structures [195]. Along with other aspects like tissue ingrowth, osseointegration, nutrition, waste, antibiotic delivery, biocompatibility, and bioresorbability, AM's mechanical performance can be enhanced [196]. Altering local features to improve implant behavior is another possibility enabled by lattices with graded architectures [197]. A lattice can have a porous interior to facilitate bone ingrowth and a stiff exterior to support heavy loads. However, recent advances in versatile bio-ink highlight the promise of additive manufacturing for tissue engineering of sensitive human organs and tissues. To develop bio-printed components with the required properties, researchers are studying bioreactors in conjunction with factors that promote angiogenesis and innervation [184]. Amplified success in printing human-sized tissue constructs with various bio-inks and AM methods is depicted in Fig. 6 [185]. Another cutting-edge paradigm that will revolutionize the biomedical field is in situ bio printing for tissue regeneration.

Biodegradable materials, including polymer-based and metal-based materials, and biocompatible titanium alloys, have been subjected to in vitro and in vivo testing. Mechanically and for promoting bone tissue growth, Ti6Al4V lattice structures show great promise. In some medical situations, a temporary material support is required to aid in the growth and healing process, so biodegradable materials are developed for this purpose. Positive mechanical and degradation responses were observed after implantation of Mg stents and screws, and no adverse reactions or inflammation were observed [198]. Incorporating complex geometrical characteristics into implants will be aided by the development of numerical tools to design them [192]. In the field of prosthetics and orthotics, AM has been used to create individualized devices that better match the patient's anatomy and enhance their functionality [199]. The reduced complexity of low-priced gadgets allows for their mass production in developing nations at a fraction of typical manufacturing costs. The literature is full of proposed solutions [200,201]. Enhanced features and more advanced AM methods are being developed for high-end market devices. Research is also being done to develop simple devices that can be mass produced and assembled to improve the health of populations with limited access to medical care. The biomedical industry is already reaping the benefits of AM, and it will be a major player in the field's future. However, there are obstacles that must be overcome:

5.3.1 *Dogmatic issues*

AM biomedical products need to be approved by the Food and Drug Administration [202]. Class I devices, which are easier to get authorized, are the focus of the biomedical industry. Some Class II implants have been approved though, so research and development into Class II and III devices is still ongoing [203].

5.3.2 *Restricted materials*

However, the most effective AM materials are not bio-compatible [166], and traditional biomaterials are often incompatible with the 3D printing process. That's why it's crucial to work on new methods and materials;

5.3.3 *Inconsistent eminence*

There is a lack of characterization for the mechanical properties of AM materials [204]. The final properties of AM products can be significantly impacted by both the materials used and the process parameters.

5.3.4 *Patient-centric applications*

Manufacturing implants tailored to each individual patient will become possible with the advent of automated methods that integrate CT scan data and design analysis with additive manufacturing techniques [164]. Patients' needs and characteristics will also be taken into account during the research and development of new medications and delivery methods [190].

5.3.5 *Multifarious parts*

Mechanical properties, cell attachment and growth, transport of nutrients, waste, and antibiotics, biocompatibility, and bioresorbability are crucial elements for a biomedical implant [192]. AM's ability to create novel designs that simultaneously optimize these properties is promising. Composite materials, such as metal implants covered in ceramic, can be engineered to have superior functionality and efficiency.

5.3.6 *Bio printing*

Bio-printed scaffolds and tissues may be scaled up for clinical applications with the aid of research and development, which could also increase the cost-effectiveness of AM for tissue engineering. Organ and tissue repair could one day be done directly on the patient's body, onsite [205]. Research into the production of AM artificial organs is ongoing, and this includes investigating how to achieve the multi-functionality afforded by each organ through means such as vascularization and innervation [192]. The bionic ear, which was used as an inductive coil to receive electromagnetic signals for hearing [206], is an example of a cyborg organ that will likely be connected to these organs.

5.3.7 *Aero-space*

According to Wohlers' report [33], the aerospace sector, one of the most promising industries, accounts for 18.2% of the entire AM market. Because of their exceptional properties, aerospace components made with AM methods are a great fit.

5.3.8 *Geometry*

Integrating structural, thermal, and ventilation needs necessitates the use of complex shapes. GE Aviation, for instance, is working on fan blade edges with optimised airflow [207]. Additionally, GE fuel nozzles, for example, can be combined with other parts to reduce complexity [208]. Finally, it is simple to implement (or print) functional electronics as AM parts [209];

5.3.9 *Materials ratio*

Among the high-tech, expensive materials used in the aerospace industry, titanium alloys, nickel-based superalloys, high-strength steel alloys, and ultra-high temperature ceramics are just a few [210]. AM provides complex shapes and significantly decreases waste (by as much as 10–20%) [211].

5.3.10 Customized fabrication

Manufacturing in the aerospace sector is typically done on a small scale. Since airplanes can be used for up to 30 years, AM is a more cost-effective way to make small batches than traditional methods because it doesn't need expensive tools like molds or dies. To reduce costs and emissions, aerospace components must be light and have good strength- and stiffness-to-weight ratios [212]. AM reduces maintenance by making parts on demand. (Low earth orbit) LEO, a 2000 km orbit above Earth, costs $2500 per kg [213]. Aeroengine components, turbine blades, and heat exchangers can be made or repaired using AM. Stereo lithography, multi-jet modelling, and fused deposition modelling are non-metal AM methods used to rapidly prototype parts and create fixtures and interiors from plastics, ceramics, and composites (FDM). Significant structural components are produced using DED technology, which is faster (up to 10 times) than PBF but less accurate than PBF (1 mm vs. 0.05 mm) [24]. Norsk Titanium AS's "Rapid Plasma Deposition TM" technology melts titanium wire in argon gas to make structural parts for the Boeing 787 Dreamliner [218]. Two to three million dollars were saved per plane using this method [219]. The lead time was cut in half, and the buy-to-fly ratio was decreased by half. [220]. It was the efforts of Thales Alenia Space and Norsk Titanium AS. For the "Vulcan 2.1" engine manufactured by "Airbus Safran Launchers" (see Fig. 7a), "GKN Aerospace" designed and built the first generation "Ariane 6 nozzle (SWAN)" [221]. Due to large-scale DED, which reduced the number of parts needed (from 1000 to 100), production costs (by 40%), and production times (30%), the nozzle with a diameter of 2.5 m was able to be produced. Powder bed fusion (PBF) technologies are precise, allowing component design optimization and function integration. Complex, microscopic components use this technology. Brackets for the Airbus A350 XWB are 30% lighter and 75% faster to produce (Fig. 7b) [224]. For the test versions of the Airbus A350 XWB and A320, Arconic manufactures titanium fuselage and engine pylon components. [225, 226]. GE Aviation's next-generation jet engine components are made on metal PBF equipment [227]. Increasing the lifetime by a factor of five the number of components needed went from 18 down to 1, and the overall weight was cut by 25%.

The aerospace industry also relies heavily on non-metallic components. Manufacturing with stereo lithography, multi-jet printing, and FDM is possible for a wide variety of materials including plastics, ceramics, and composites. Piper Aircraft, Bell Helicopter, and NASA were among the many aerospace companies that worked with Stratasys [228] to implement FDM for rapid prototyping, manufacturing tooling, and part production. Using Stratasys FDM technologies, NASA printed 70 parts of the Mars rover to achieve a lightweight and strong structure [229]. Within 2.5 days (from 6 weeks), Bell Helicopter used FDM [230] to mass-produce polycarbonate wiring conduits for the V-22 Osprey. The Aeronautics Research Institute at NASA wants to develop a gas turbine engine that doesn't use any metals [231]. Researchers are looking into lightweight composite materials that can withstand high temperatures. In this study, FDM and binder-jet processes were used to create composites of polymer matrix, polyetherimide, and ceramic matrix. A prominent topic at the moment is the additive manufacturing (AM) of ultra-high-temperature ceramics, including ZrB2, ZrC, TiC, and others [232].

Costly materials and intricate production methods go into making high-performance aerospace components [233]. Corrosion, impacts, stress, and multiple temperature swings are all hazards these components face and can cause flaws or cracks. The high price of these parts makes replacement preferable to repair. However, unlike conventional welding processes, AM technologies don't produce nearly as much heat when repairing expensive metal components. Metal-to-metal connections are forged between the substrate and the additional metal using a laser beam during repairs (i.e., the powder). This method can be used for complex and thin-walled aerospace components with minimal distortions.

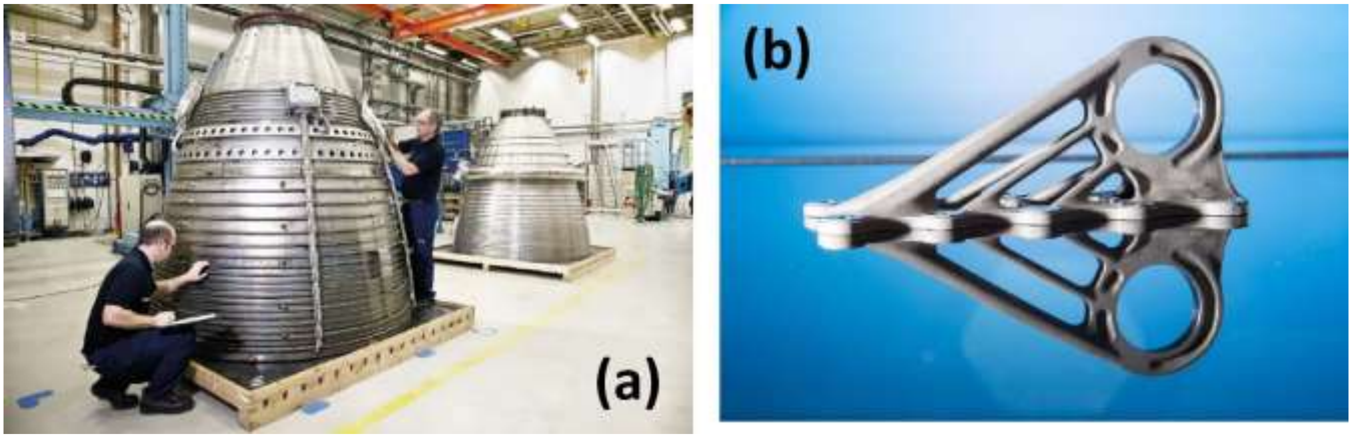

Figure 7(a) More than 50 kg of DED material was used as the demonstration nozzle for the Vulcain 2 [222]; (b) AW350 XWB AM Titanium Brackets [223].

AM can be used to fix things made of "non-weldable" materials or is especially sensitive to distortion [235]. Before CNC milling machines improve the repair, DED machines spray and melt metal powder onto the injured area. This technique allows for increased construction capacity, improved accuracy, and enhanced surface finishing [236]. The supplementary material has superior fatigue properties to the initial wrought material without distorting beyond permissible parameters [237]. In addition, this method effectively repairs any damage, even in inaccessible areas [238], and significantly reduces the degradation of mechanical properties brought on by thermal stresses. We calculated the price of repairs to be 50% of what it would cost to have the component remanufactured [237]. To repair damaged components, AM and CNC machines are being developed automatically [239]. This includes diagnosing damage, aligning the original CAD files with the physical system (to determine material placement), and restoring damaged components. REPAIR [240] was funded by the European Commission to create a semi-automated system for defect monitoring, analysis, and repair. This setup should cut down on the following: the weight of components by 20%, the time it takes to inspect them by 30%, the cost of complex spare parts by 30%, the amount of scrap and toxic chemicals produced by 80%, and the cost of the scrap by 80%. The distribution networks for replacement components are another area where AM will cause shifts [241]. Distributed production of spare parts will cut down on overhead costs and downtime while also limiting the scope of inventory management and logistics information systems. AM will also boost customer satisfaction, adaptability, capacity, and resilience in supply chain disruptions. If, however, the price of AM equipment and raw materials were to fall, these adjustments would be made.

Furthermore, AM allows for producing legacy components without maintaining dated tooling, molds or dies. Repairing and modernizing F-15 aircraft with AM has been done with substantial cost savings [242]. AM technologies are promising for rapid prototyping, part production, and semi-automated repair. Aerospace can evolve while overcoming restrictions [211]. DED techniques allow for producing items up to 5.79 m [243] in height. Therefore, AM can be used for mass production if new methods are developed to alleviate internal stresses and subsequent distortions in large-scale parts, such as ultrasonic tools [244]. Before this is possible, machine and raw material costs must fall [245]. Additive-made materials cost more per weight than conventionally created materials [246]. Some users don't have to worry about this problem because the buy-to-fly cost of AM components is lower (and almost no waste is made, unlike when titanium brackets are made traditionally [247]). Good-strength aluminum alloys [83], Ceramic-matrix composites [248], and ultra-high-strength ceramics [21] are among the AM-adapted materials being developed. The mechanical characteristics of AM-produced complex structures are unknown [204]. The manufacturing process and its characteristics heavily influence porosity and thermal stress. Improvements to the final design can be made through process monitoring and CAD-integrated process-structure-property interactions [249]. With the ability to mass-produce complex parts with multiple functions, designers have more leeway to create unique solutions. The need for assembly and connections, as well as fixtures and tools, can be eliminated (or greatly reduced) when using AM, which results in significant weight and material savings [250]. In addition, sensors, circuits (printed with conductive inks), and wiring can all be incorporated into the structure [251], and thermal and acoustic insulation can be combined [214]. For the high temperatures and pressures experienced during space travel, ceramic materials are a common choice. There are piezoelectric devices that use ceramics as well. However, traditional production methods restrict the variety of shapes that can be achieved. Research into AM of ultra-high-strength ceramics is also ongoing [21]. The mechanical and thermal responses of components could be optimized by combining materials made using AM techniques. Metals can lessen the ceramic thermal barrier's brittleness, which is used during re-entry [252]. Combining various alloys requires computational phase diagrams and material compatibility assessments [253].

Production of parts is done on demand, saving money and preventing damage that could occur if they were stored [254]. For instance, AM is currently being evaluated on the ISS [255] and has the potential to be used in the production of a Moon settlement [256]. By extending their usefulness through maintenance and repair, high-value components save money over their lifetime. However, automatic methods for defect detection and repair process automation must be developed. REPAIR [240], a European project, and GKN Aerospace [239] research, both funded by the company, are working to find effective solutions. Only 3% of the whole AM market is devoted to architectural applications, as stated in Wohlers' research [33]. While this business shows promise, it is still in its infancy, with residential construction only beginning in 2014 [257]. The use of 3D printing technology to automate the building process is attracting more and more interest. Aside from offering astronauts an easier way to build on the moon, it has the potential to completely transform the construction industry as a whole [258]. It allows builders to use fewer resources and finish projects faster [3]. Casting, molding, and extruding are some of the time-honored methods employed by the building sector. Constrained areas, such as geometric complexities and hollow structures, are ideal candidates for 3D printing's application in the construction industry. Therefore, its reliability stems from the fact that it can be manufactured with high precision and thus allows for a wide range of design options. For robotic Earth and space construction, Khoshnevis [19] developed the contour crafting (CC) technique. Because it makes use of native resources, it can be applied to the creation of affordable housing as well as lunar bases. In 2014, Amsterdam's first 3D-printed house was built using the fused deposition modeling (FDM) method [257]. Architects from Dus Architects pushed for the project to be completed so that they could demonstrate the printer's portability with minimal material wastage and transportation costs. Also in 2014 (Fig. 8b), the Chinese architecture firm WinSun successfully mass-printed dwellings in Shanghai in under twenty-four hours. Due to their bulkiness, traditional 3D printers hampered the technology's expansion into the commercial sector. However, this project used a 3D printer with dimensions of 150 m, 10 m, and 6.6 m instead of cement and glass fiber. During the course of the project, WinSun faced challenges related to brittleness, the integration of building services, and indirect printing [3]. Three different large-scale 3D printing systems, all of which are suited to the construction sector but use different materials and approaches, were detailed by Lim et al. [259]. Frame-mounted and gantry-based D-shape and concrete printings are both often made off-site. However, robot- or crane-mounted contour crafting methods can also be used in the field. Nadal [260] summed up the methods used to expand upon standard desktop 3D printing as two main approaches: 1) methods similar to CC, and 2) those involving a bridge crane. Off-site procedures, however, present their own set of difficulties, such as increased material waste and inaccuracies that would otherwise necessitate more manpower to correct [260]. Cementitious materials, thermoplastics, and ceramic goods were used to develop a promising technique similar to CC technology by Hager et al. [261]. Since CC technology can print layers locally, it opens up the possibility of printing large components with unprecedented freedom and accuracy. In the pioneering instance of CC building, a combination of cement and sand was used. There is a general consensus that CC was the first practical AM technique for building construction. The powder deposition process is used in the D-shape method to bind the powder together with a chemical agent, such as a chlorine-based liquid (e.g., sand or stone powder). Mechanical properties are improved in the structural components produced by this method. D-shape printing in hostile environments and utilizing local resources were the topics of Cesaretti et al.'s [263] investigation. However, the authors concluded that the control instructions and the need for more maintenance remained the most pressing issues. D-shape printing and lunar soil (regolith) were evaluated as potential methods for constructing Moon-based infrastructure. The outpost's design needs have been identified, and a rough layout of the habitat has been created as a result. Whether or not the printed material will survive the severe circumstances on the moon is a crucial factor to think about when using 3D printing. The European Space Agency's proposed Moon Village would make use of AM, and this use was recently reviewed by Labeaga-Martnez et al. [258]. Different AM techniques were evaluated, and lunar regolith was to be used as the raw material. It was decided that powder bed fusion was the most practical and appropriate technology to accomplish the goal. Another technique developed at Loughborough University is called "mesh-moulding," and it involves the use of a six-axis robot control to create pieces without the use of any sort of temporary support. Thermoplastic polymers are used in the mesh-moulding process so that the printed structure can serve as rebar in concrete. After the concrete has been poured, it is smoothed out with a trowel. Fabrication times for complex structures can be drastically cut down by using this method. The printed mesh density can also vary with loads. A mesh increases concrete tensile strength; thus steel reinforcement may not be needed [264]. Concrete printing is an off-site procedure, but researchers say it can be made on-site with the correct tweaks [259]. Concrete 3D printing has recently used four-axis gantry and six-axis robot printers.

Figure 8 (a) shows the first 3D-printed home by DusArchitects [257] and (b) shows a 3D-printed home by WinSun [3].

3D printing has become a crucial tool for cataloging and maintaining cultural artifacts in addition to its use in manufacturing. Cement mortar 3D printing and 3D scanning were used by Xu et al. [265] to recreate a section of a historic building. As compared to more conventional practices, construction projects that incorporated this technology saved both money and time. Sobotka and Pacewicz [266] used a strength, weaknesses, opportunities, and threats (SWOT) analysis to characterize the use of 3D printers in the workplace has several potential outcomes, including but not limited to in challenging conditions. Researchers have found this technology could make it possible to use heavy machinery and construction equipment less often and for materials to be recycled. A sustainable composite made from recycled polypropylene was developed by Stoof and Pickering [267].

A further barrier for AM in the construction industry is the need for skilled workers who can integrate robotic and civil work, as 3D printing uses different raw materials and manufacturing processes than traditional construction methods [264]. The construction industry uses an estimated one-third of the World's resources. Effective construction strategies and material efficiency are crucial in mitigating negative effects on the environment. Thorough familiarity with the technology is necessary to maximize the benefits of 3D printing in a large-scale construction project. The freedom of mix design in geopolymer concrete [271] and the production of lightweight concrete composites [268-270] with a customized pore size distribution are two particularly intriguing ideas for the future of AM. Although AM is just getting started, it may completely alter the way traditional building is done. More investigation and development of this technology is anticipated, leading to expanded prospects and tougher challenges for the construction sector.

5.4 Protective structures

The ability of AM to analyze sandwich panels with the widest variety of lattice cores and implement novel snap-through concepts has allowed for the rapid evolution of protective structures. Vehicle armor is typically made of solid monolithic plates of high-strength steel or aluminum, while personal protective equipment is generally made of stochastic foams. These plates are heavy and expensive, however. While they can be effective as a form of protection, stochastic foams often exhibit erratic responses to loading and aren't optimized for any specific use case. The growth of technologies for making materials, such as additive manufacturing (AM), drives the trend toward intelligent, lightweight structures with high maximum tensile and stiffness ratios. Because of the decrease in weight, the protective system is better able to do its job (improve mobility and safety for military vehicles) and improve economic efficiency (possible future AM cost reduction). By using AM, engineers have created composite structures that take cues from nature and are resistant to the shock waves generated by impact and blast. The well-distributed damage in cohesive and inter-laminar adhesion strength between the weakest part of aluminum tablets of the required multi-layer reinforced polymer structure allowed it to dissipate significantly more energy under impulsive loading than a comparable monolithic panel of equal mass [272]. More so, lattice structures are being created with AM technologies [273]. Large densifying strains, specific solid strength, and the potential for smooth and smooth peak stress under loading are characteristics shared by cellular materials. In light of this, they have been extensively studied for energy absorption [274,275]. Specific features of AM lattice structures include:

AM makes it possible to manufacture surface-based lattices like the gyroid and beam-based lattices like the body-centered cubic (BCC). Small (a few micrometers) or large (centimeters) structures are possible (a few metres). Various reactions can be elicited, from the more common stretching and bending to more unusual snap-through mechanisms. Moreover, extra materials can be incorporated into a structure to improve its ductility or rigidity. Due to this flexibility, parametric (based on the adjustment of geometric parameters) and topological optimization [276] can be utilized to achieve superior responses than typical metallic foams. The uniform response to sudden loads is a hallmark of lattice structures because of the precision with which they are manufactured. There have been fewer mistakes made while making smaller components thanks to the development of AM technologies. The absence of design restrictions imposed by manufacturing methods is one of additive manufacturing's most important benefits. Thus, it is possible to design shapes that simultaneously optimize several functions. In particular, protective lattice structures are being enhanced for thermal applications (such as heat exchangers [278] and thermal shields [277] for spacecraft re-entry to Earth). AM can also improve acoustic applications like sound insulation and cloaking.

While metal alloys have traditionally been used to create lattice structures for energy absorption, there have been some new studies looking at polymers like silicone and rubber. Metal lattices release mechanical energy by plastic deformation, whereas new methods try to absorb it through elastic deformation by employing bistable structures [279]. In metallic lattice systems, the basic cubic cell (BCC) and its modifications [275,280], lattice-walled honeycomb (LWH) [281], and gyroids [282] have been investigated (Fig. 9). TiAl6V4, SS316L, and AlSi10 Mg have also been studied. As lattice topology changes, the structure bends or stretches. Consequently, impulsive loads may be carefully controlled in metallic lattice structures. The energy-absorbing properties of LWHs were found to be higher than those of other lattices [281], while those of triply periodic minimal sur- face gyroids were found to be both lower in stiffness and higher in strength [282,286]. The studies also demonstrated the importance of selecting the right material for achieving the best results. AlSi10 Mg [285] and Ti6Al4V [283] are very brittle as produced, which hinders the efficiency of the lattice response. As a result, ductility (at the expense of strength) must be increased via thermal [285] or hot isostatic pressing [283] treatments to obtain a more regular response. Yin et al. [287] and Craddock [288] have discussed how AM polymer lattices absorb impact energy. In particular, Crad-Dock [288] examined numerous lattice topologies and demonstrated that helical struts are superior to straight braces in energy absorption. General Electrics (GE) and the National Football League put on a contest called the Brain Health Challenge [289]. (NFL), various researchers and industries developed practical applications of these polymer lattices intending to increase NFL players' safety on the field. Specifically, AM techniques were used to prototype the most protective helmet against impact [290]. The use of direct ink writing and other forms of additive manufacturing has allowed for the realization of novel structures and the exploitation of novel energy absorption concepts employing a wide variety of polymers. The negative stiffness of a cellular architecture was achieved, for instance, by Duoss et al. [291], who used direct ink writing. They performed "simple cubic" (SC) and "face-centered tetragonal" (FCT) arrangements by superimposing struts of polymeric material measuring a few hundredths of a millimeter apart. These structures have the potential to be tuned to achieve exceptional characteristics like negative shear stiffness (SC structures). The mechanisms that have been developed have potential as absorption tools. In particular, the stresses and reaction forces on protected elements are reduced because these structures snap suddenly at a certain (tuneable) load. Once the load is removed from the SC structure, it will return to its normal shape. With only ink and paper, researchers have probed various stable structures. In particular, a snap-through idea has been studied to see if it could absorb energy in a controlled way. A snap-through is a sudden change in geometry caused by instabilities like buckling. To store energy via the (reversible) transition between beam states, Shan et al. [279] designed systems made up of many such bistable elastic beams (Fig. 10a). Only the elastic and geometric properties of the 3D-printed structures are used in this process. So, it can be undone and is not affected by factors such as size, speed, or previous loading history. It can also be adjusted to fit a variety of uses and requirements. Restrepo et al. [293] have created a similar idea with various permutations. Functionality is not limited in AM metallic lattice structures. The auto, aerospace, and defense sectors are particularly interested in materials that can manage heat and absorb impact. The potential for AM to be used in commercial applications has been demonstrated in studies, and it is currently being put to use in the creation of multi-functional heat exchangers [278] and de-icing systems [294]. For the European Space Agency's Earth Return Capsule (ERC) (Fig. 10b) [277], Magna Parva and MTC collaborated to develop a crushable material by fabricating and testing a variety of AM metallic lattice structures. The crushable structure has to meet certain criteria, including a low density, poor thermal conductivity, and a high absorbed energy rate. All of these conditions were optimized temporarily using AM metallic lattice structures. Innovating new forms of defense is a key area where AM is enabling significant progress. Although many lattice structures and novel approaches have been developed and proven effective, there is still room for enhancement. Although the precision of modern metal AM techniques is quite high (0.02 mm), the effectiveness of smaller elements is diminished by defects and porosity. The yield strength and stiffness of smaller specimens were 20% lower than those of standard ASTM specimens [295].

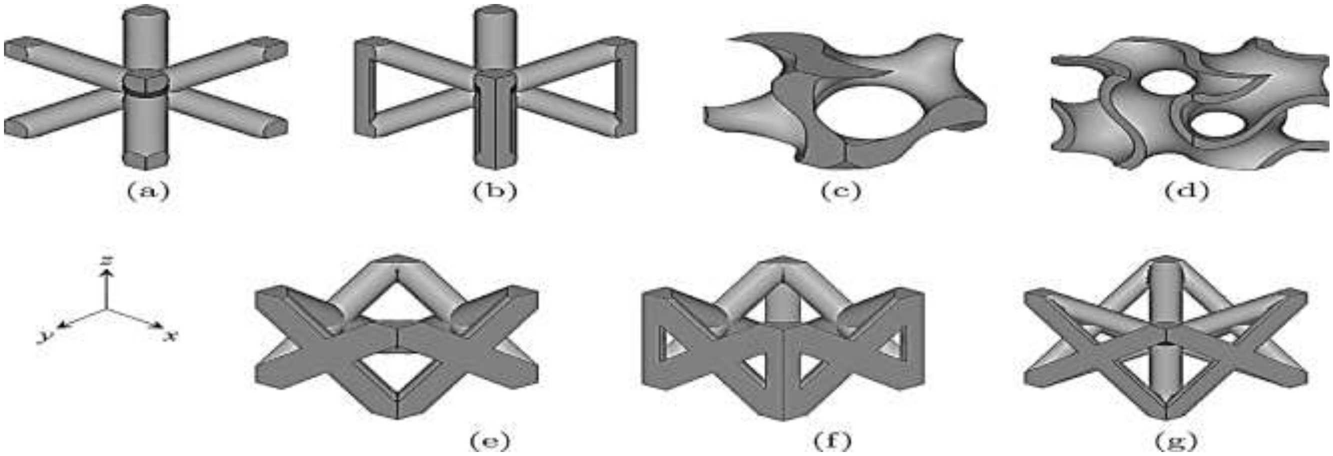

Figure 9. There are seven possible lattice topologies: (a) the gyroid, (b) the matrix phase of the D-gyroid, (c) the gyroid, (d) the face-centered cube, (e) the face-centered cube with vertical struts, (f) the Boolean combination, and (g) the face-centered cube with vertical struts (PFCC) [286].

Treatments after production, like heat or chemical treatments, are needed because the materials lose their pliability and aren't good enough for impact applications [296]. Additive manufactured lattice structures' future uses and developments will include the following: In aerospace, however, acoustic optimization might be used in tandem with bird-impact shielding and temperature regulation. For optimal outcomes, multi-physics simulations will need to be developed. Maximizing the structures' efficiency will require cutting-edge optimisation algorithms and numerical models [297,298]. AM allows for rapid testing of novel ideas, such as resonators for dynamic load mitigation [303] or optimised auxetic structures [299-302]. Further novel ways are possible, for instance, if graded structure (graded struts [304] with graded toughness for robotic bodies [305]) can be made. Plastic deformation, local wrinkling, and plastic buckling can absorb a lot of energy per unit mass in metallic hollow wall micro-lattice structures [306]. Particularly, they excel at their tasks more than regular lattice structures. Research into methods of mass producing hollow struts at a lower price without sacrificing quality [307] can be of paramount significance. The use of additive manufacturing [83] has enabled the production of high-strength metal alloys (such as Al 7075) that have been historically utilised for blast applications with the purpose of strengthening their resilience to impulsive loading. New possibilities will also arise from the use of AM to produce Shape Memory Alloys (SMA) [308] and SMM [309]. With the same initial mechanical properties and minimal external stimulation, it can build lattices that deform and restore their original shape [310]. Finally, more research into composites [311] could be carried out, such as using a softer material close to plastic hinges and a stiffer material to increase the lattice structure's resistance to localised forces.

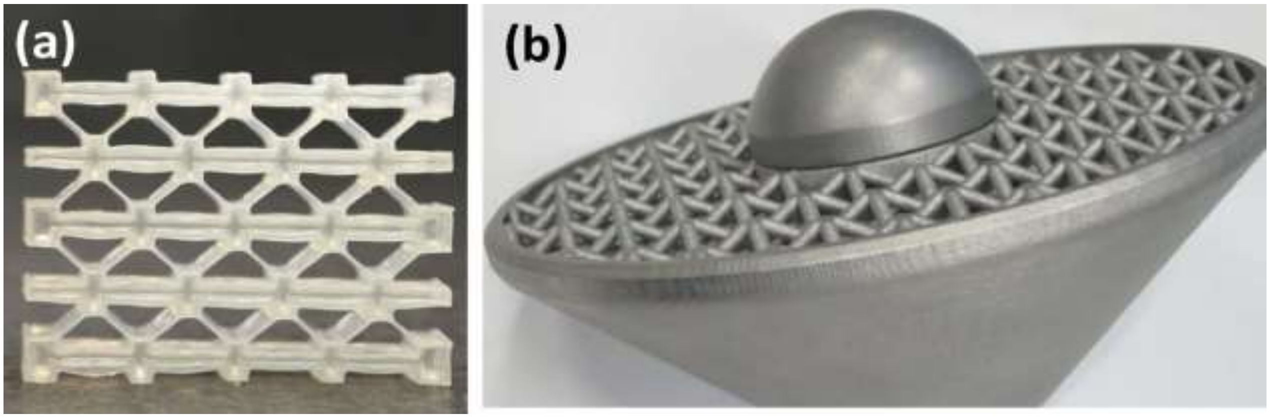

Figure 10(a) an additively created protective framework for Mars specimens re-entering Earth from Mars [292], and (b) a 3D printed various-stable architectural structure [279].

6. Main challenges

3D printing intricate structures and providing designers with a ton of creative space are just two of the many advantages of additive manufacturing. However, it has shortcomings that call for further research and development. There are a variety of limitations, such as high costs, limited application in big constructions and production is the main, poor and asymmetrical mechanical characteristics, a lack of material flexibility, and faults. Some of these obstacles have been overcome thanks to the study and development of new materials and techniques. But before additive manufacturing (AM) can be used in more settings, there are some hurdles that need to be cleared. Although some challenges are unique to particular printing methods or materials, many AM methods face similar challenges. For example, compared to traditional methods like casting, extrusion, fabrication, or injection molding, the amount of time it takes to make a part with AM is often very different. The powder bed method and stereo lithography take much longer than inkjet printing and fused deposition modeling. In addition, powder-bed (SLS or SLM) 3D printing methods require a lot of energy and money to process due to their high re-solution. It is difficult to mass produce any repetitive parts using 3D printing because of the lengthy processing time and higher cost, especially when other, more standard approaches may complete the same work in far less time and for much less money. But AM can be cheaper when making a complicated, custom product, like a 3D-printed scaffold for bone tissue engineering [312]. In the next section, we'll look at four of the biggest problems with AM and compare them to the materials and processes that can be used for 3D printing, regardless of cost or time, which should be discussed for each application. With 3D printing, void formation between material layers is a significant problem. AM's high porosity levels can make it hard for printed coatings to stick together, hurting mechanical performance. Both the 3D printing technique and the printed material greatly influence the severity of void formation. With filament material processes like FDM or contour manufacturing, voids are often thought to be one of the main flaws that lead to poor and uneven mechanical properties [13,148]. When it happens, delamination between printed layers is possible [146]. The porosity of an FDM 3D-printed composite was decreased, but the cohesion declined as the filament thickness rose [313]. The composite's water absorption increased, and its tensile strength decreased. Better interlayer bonding and less void formation occurred in additively manufactured concrete when layer thickness was increased and more time was allowed to pass between subsequent layers. The high porosity of AM can be significantly reduced, though, by reducing the height of each layer when printing an alumina/glass composite on a powder bed [314]. Due to the decreased height, laser penetration through the top layer is enhanced, and interlayer void formation is mitigated by the diffusion of ceramic powders. Paul et al. [142] also demonstrated that compared to cylindrical nozzles, voids are significantly reduced when using rectangular nozzles due to the increased layer-to-layer contact. However, rectangular nozzles make it more challenging to 3D print complex shapes, especially at the joints. In applications like tissue engineering's porous scaffold design, increased porosity in 3D printed objects might be a benefit. In order to their advantage, Minas et al. [130] exploited void formation caused by 3D printing. On top of the microscopic pores made by the air bubbles within the foam filament, they incorporated new, larger pores into the lattice structure. Bio composites can benefit from the incorporation of hygroscopic properties, made possible by the 3D printed part's increased porosity and thus its enhanced capacity to retain water [313]. Anisotropic behavior is a significant obstacle for AM. Because each layer is printed separately, one can expect a different microstructure of the material inside each layer than at the layer boundaries. Because of this anisotropic behavior, the mechanical behavior of the 3D printed part will vary depending on whether it is being stressed or compressed in the vertical or horizontal directions. Heat fusion (SLS or SLM) 3D printing of metals and alloys reheats the boundaries of preceding layers, changing grain microstructure and anisotropy [315]. Controlling the sintering process and stopping off-axis deformations depend on how deep the heat from the laser beam goes into each layer [316]. Titanium alloys that are 3D printed using the SLM technique have greater tensile strength and ductility in the transverse (build) direction due to morphological and textural changes ([315,317]). Alloys [316], ceramics [317], and polymers [318,319] have all been observed to exhibit this anisotropic behavior. Anisotropic behavior is more noticeable when the body's shape is very different from that of a sphere, like ceramic particles that are mainly oriented along the direction of printing because of their shape [316]. Fig. 11 shows ABS 3D-printed polymer densification strain fields as a function of printing angle [319]. As an added note, ABS's tensile strength is drastically altered depending on how it was printed. The correlation between printing angle and elastic constants was calculated by Zou et al. [320]. The direction of printing can influence the mechanical behavior of nanocomposites [321]. 3D printing carbon fiber-reinforced concrete in a pattern that runs parallel to the beam's length, as demonstrated by Hambach and Volkmer [144], significantly increases flexural strength in comparison to a cross-hatch pattern. They also showed how the compressive strength of the 3D-printed specimens is significantly affected by the force's direction, whether it is parallel to or perpendicular to the printing direction. 3D-printed materials exhibit anisotropic behavior, which can be problematic in some contexts but useful in others. Adjusting 3D printed filament speed and spacing can create a surface anisotropic wettability. For uses like breathable water repellent surfaces, a 3D-printed poly-dimethyl siloxane film with super-hydrophobic and anisotropic properties and excellent thermal durability has been developed [322]. Computer-aided design (CAD) software is the leading way to make a file that can be used for 3D printing. Because AM has its limits, the printed part may have some things that need to be planned for in the designed element. The CAD system combines boundary conditions with solid geometry. In most cases, tessellation theory is used to get a close approximation of the model. However, inaccuracies and defects, especially in curved surfaces [323], frequently result when CAD is transferred into a 3D-printed part. In theory, a fine tessellation could help with this issue, but it would take a lot of time and effort to compute, process, and print. Therefore, it is sometimes considered necessary to perform additional processing (using heat, laser, chemicals, or sanding) in order to remove these imperfections.

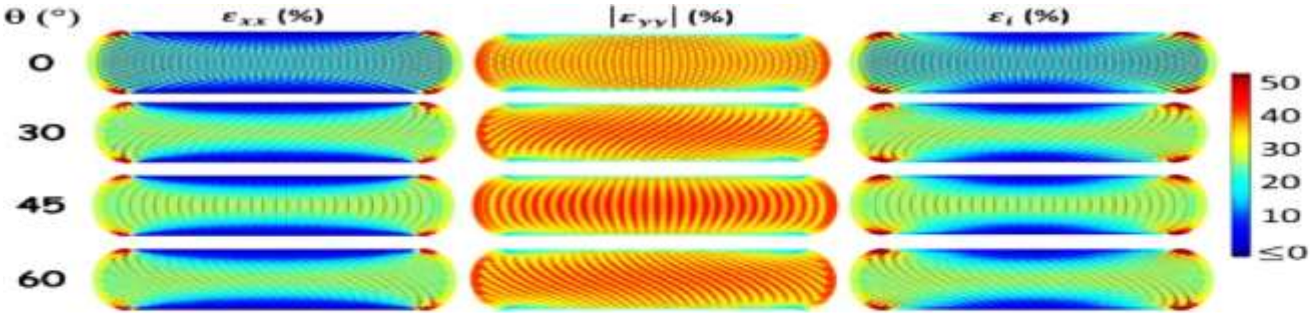

Figure 11. ABS 3D-printed polymer densification strain components as a function of printing angle (courtesy of Guessasma et al. [319]).

Limiting design-to-execution divergence requires planning, identifying the best part orientation, slicing it into enough layers, and creating supporting materials that can support following layers and be easily removed after printing. Using unbound powder as the support in the powder-bed method has the benefit of being easily removed by air pressure once the print is complete. Furthermore, the appearance and mechanical properties of a 3D printed part can be greatly affected by printing process parameters such as extrusion pressure and filament orientation (FDM, inkjet, and counter crafting), laser power (SLM and SLS), layer thickness, printing direction, temperature, and speed, and material properties such as rheology, thermo-plasticity, powder packing, and so on [142,324]. Given the additive nature of manufacturing, layer-by-layer visual appearance is yet another hurdle to overcome. This flaw in 3D printed concrete is depicted in Fig. 12. The aesthetics of a 3D printed component may not matter if it will be concealed in the final product, as is the case with scaffolds used in tissue engineering. While the layered appearance is desirable in some contexts, such as paper craft, some construction and play applications, and aerospace, a flat surface is preferred. Reducing this defect [325-327] through chemical or physical post-processing techniques like sintering will, however, lengthen the processing time and increase the cost. Khoshnevis [19] removed the layered look by attaching tools like trowels to the contour craft print head. The layer's thickness and the part's height establish how many layers it has. Hence, fewer layers reduce the layer-by-layer look. FDM, inkjet, and contour crafts produce multilayer 3D prints, unlike powder-bed or stereolithography.

7. Conclusions

The freedom of design, the capacity for mass customization, and the capacity to print intricate structures with little waste are the main benefits of 3D printing. The current state and trending applications of 3D printing across industries were examined, along with the methods and materials used to create them. We also discussed the most critical problems that can be traced back to how 3D printing differs.

Fused deposition modelling (FDM) is one of the most widely used 3D printing technologies due to its low cost, ease of use, and fast processing speed. It was made for 3D printing with polymer filaments, but now it can also work with other materials. Compared to powder-bed methods like selective laser sintering (SLS) and selective laser melting (SLM), Fused Deposition Modeling (FDM) is primarily used for rapid prototyping but produces lower quality and mechanical properties in printed parts (SLM). The printing of larger structures like buildings is possible with contour crafting, which uses the extrusion of materials (concrete). One of the earliest forms of 3D printing, stereolithography is best suited for photopolymers and their ability to create highly detailed components. However, the procedure is time-consuming and difficult, and it can only be done with a restricted set of materials. Finally, laminated object manufacturing (LOM) involves cutting and laminating sheets or rolls to generate numerous layers.

It can be 3D-printed filaments, wire, powder, paste, sheets, and inks. When it comes to rapid prototyping, polymers have proven to be the most ubiquitous material. The most common polymers used in 3D printing are thermosetting powders, such as polystyrene, photo-polymer resins, and copolymers of polyamide (PA), polycarbonate (PC), and polylactic acid (PLA). Improved mechanical properties were achieved in the 3D printed composite by reinforcing polymers with fibres and nano-materials. SLS, SLM, and DED are the most prevalent metal 3D printing technologies. Most metals are powders or wires. Due to the limited amount of metals and alloys available for 3D printing, current techniques are being applied to more alloys and composite constructions. Ceramics have made complicated ceramic lattices, such as tissue engineering scaffolds, possible and launched a trend towards custom-designing materials with high strength-to-weight ratios. The main issue is the lack of materials for 3D printing ceramics with enhanced microstructure and composition. Although 3D printing of concrete has seen slow adoption in the construction industry, its mass-customizability, absence of formwork, and automation are all promising features. The primary focus of recent research has been on improving the concrete mixture in terms of its flow, process ability, mechanical performance, and aesthetics. Recent advances in biomaterials research and development have been greatly aided by additive manufacturing (AM) for prototyping intricate, patient-specific designs. However, it has difficulties like scarce resources and bureaucratic hurdles. Aerospace companies have poured money into AM for uses including on-demand production, rapid aircraft maintenance, and the creation of lightweight, custom parts. Nevertheless, a shortage of acceptable materials, exorbitant costs, and inconsistent 3D printed component quality prevent the aerospace industry from widely using AM. There have only been a small number of major successes with AM technology in the construction industry so far. The primary drawbacks are the high price and the low mechanical performance in comparison to the more conventional methods. Nonetheless, thanks to AM's automation in the building trades, we may soon be able to build without using any human labour whatsoever. Before becoming extensively used, additive manufacturing must overcome its disadvantages. If voids exist between materials during manufacturing, interfacial adhesion between printed layers' decreases, reducing mechanical performance. AM's anisotropic behaviour, which causes mechanical differences between vertical and horizontal tension or compression directions, is another issue. CAD's tessellation principle, which approximates the design, also transfers flaws and imperfections to 3D-printed parts, especially in curved surfaces. In addition, the layer-by-layer aesthetic of AM is undesirable in fields like construction, toys, and aerospace. Development and research of technologies and materials have helped overcome some of these problems. 3D printing has the potential to transform the manufacture of bespoke items and specific applications, but it is still a long way from competing with traditional manufacturing processes for mass production of common items. Yet, recent AM development has been extraordinary. 3D printing will quickly replace existing production processes as research and development funds increase.

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