

A Review on Additive Manufacturing – Methods, Materials, and its Associated Failures

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ABSTRACT

Nowadays, additive manufacturing (AM) has surpassed traditional machining in the realm of dawning manufacturing. In the case of conventional machining, where the material is removed by different processes (subtractive manufacturing), there is a possibility of warping and internal stress development. Rapid prototyping is another option to avoid all drawbacks of conventional machining in terms of manufacturing cost, time, accuracy, and quality. Rapid prototyping of a product by adding material (additive manufacturing) is gaining commercial traction. Additive manufacturing is frequently employed for the fabrication and bulk customization of all kinds of intricate geometrical designs that are absurd by traditional manufacturing techniques. Additive manufacturing techniques are broadly divided into four categories: (a) material extrusion, (b) chain polymerization, (c) laser or electron beam-assisted sintering, and (d) direct writing-based processes. This article is a cutting-edge review that focuses on additive manufacturing processes and materials used in additive manufacturing. The process parameters for experimentation are chosen based on the application for which the part is designed. Some input process factors influence others for a specific response, and these critical process parameters are identified and optimized. This paper also gives a synopsis of failures associated with some additive manufacturing methods and their preventive actions.

Keywords: additive manufacturing, materials, polymers, failures, fused deposition modelling.

INTRODUCTION

The market increasingly perceives the need for quick, reliable working parts that can be given to customers as a consequence of the enormous industrial and technological advancements revealed over the past few decades [1]. Rapid prototyping (RP) is a term that was coined for this technique and is being employed in a wide range of industries. The term “RP” is frequently used to characterize the technologies that leverage digital data to produce tangible products [2, 3]. Additive Manufacturing (AM) and 3D printing are the same terms; people plump them accordingly. The synonym of additive manufacturing is 3D printing and vice-versa. Both terms allude to a process in which data is transferred from the computer-aided design (CAD) file to the machine, and the final product is made up by adding up the material

extruded from the nozzle in a layer-by-layer fashion, as shown in Figure 1.

Although additive manufacturing is a departure from traditional manufacturing, which involves removing material to create a finished product, it has gained popularity in many industries. While people in the industry tend to use additive manufacturing instead of 3D printing, the latter has been embraced by networking, marketing, and media professionals. Rapid prototyping is the method used for 3D printing or additive manufacturing. Rapid prototyping products tend to have better mechanical properties than products made by other methods [4]. 3D printing uses rapid prototyping as a technique to fabricate the prototypes of different structures [5-9]. Additive manufacturing has various applications in fields such as defense, aircraft, automobile, and manufacturing industries, as well as medicine

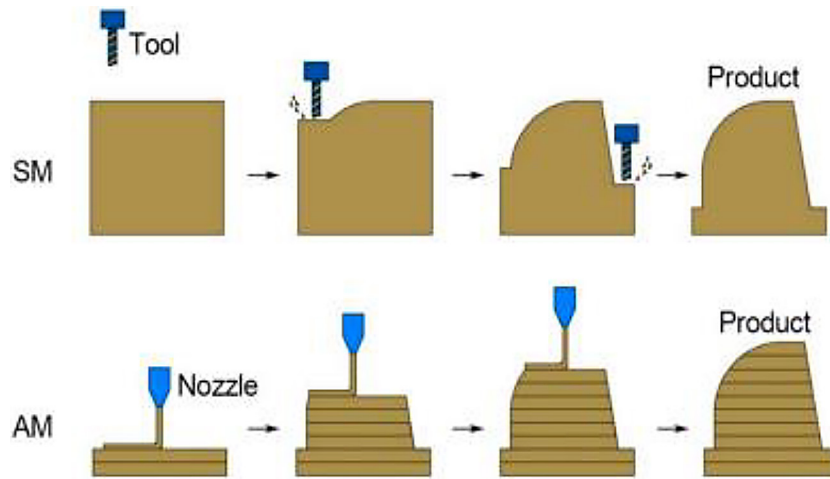


Figure 1. Difference between subtractive manufacturing (SM) and additive manufacturing (AM) [11]

and customized parts [10]. Figure 2 illustrates the importance of opting for additive manufacturing. The bars indicate the contribution (in %) of different sectors where AM is applied. Whereas the fitting curve is the cumulative percentage of the sectors. The major application of AM lies in product prototyping which is around 24.5% followed by innovative product developments.

Although 3D printing has a wide range of applications, the quality of the finished product depends on the optimization technique and experimentation levels used [9]. The process starts with creating a CAD model using modeling software, which is then saved in the STL file format. Using slicing software, the STL file is further sliced into layers before being directed to the additive

manufacturing equipment. The printer then initiates the 2D layer formation, which occurs layer by layer to form a 3D model.

MAIN METHODS

Fused deposition modelling (FDM)

FDM is the simplest AM method for RP and 3D printing. Researchers and industries generally employ the Fused Filament Fabrication (FFF) principle for product manufacturing owing to its good accuracy, low cost, and less time. FDM is also a Fused Filament Fabrication (FFF) process-based and user-friendly rapid prototyping

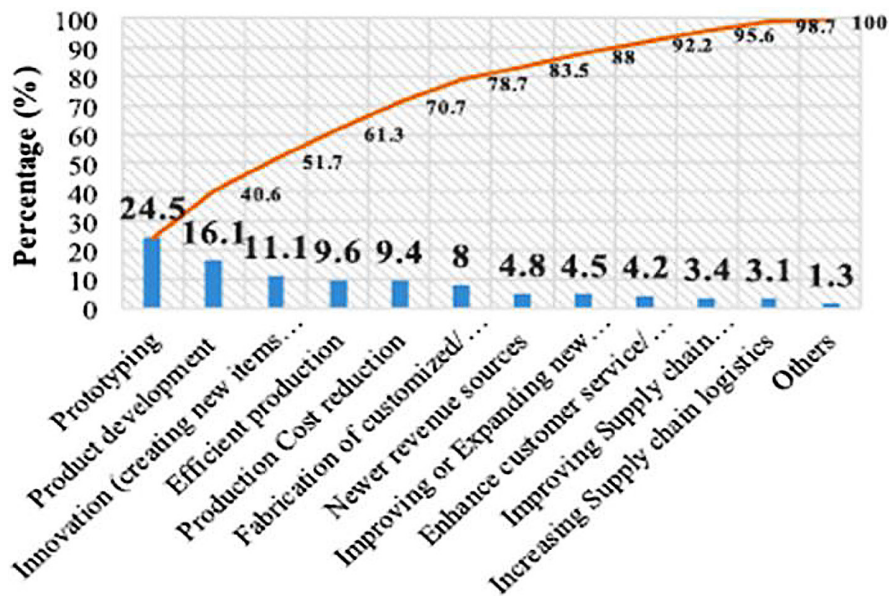


Figure 2. Need for pursuing AM [10]

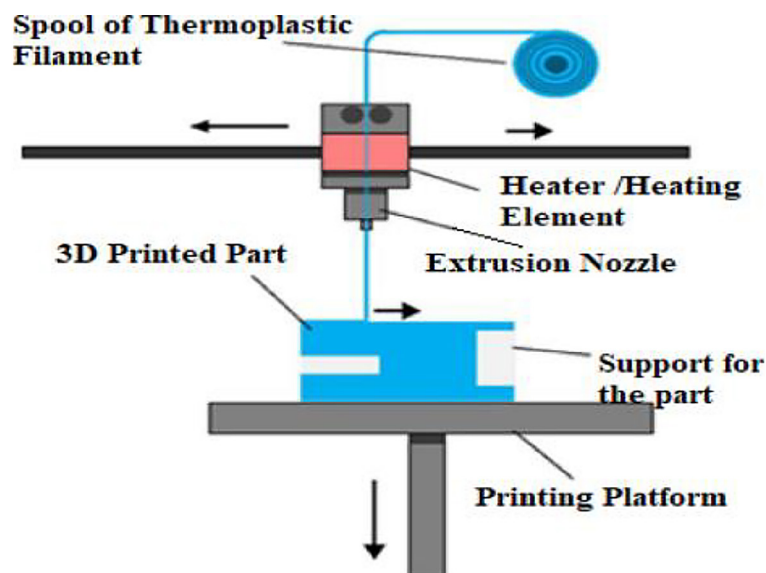


Figure 3. FDM process and material extrusion [12]

machine available in the market. An optimum combination of input variables may yield sound additively manufactured printed parts on this machine [13]. The pseudo-solid thermoplastic filament material slowly solidifies when it is expelled out from the nozzle orifice through extrusion onto the build platform; these pseudo-solid thermoplastics for every layer to be formed by bonding, blend with each other well before solidification occurs in a layer-wise manner in ambient temperature as shown in Figure 3 [14].

Process variables are crucial when conducting research, thus it is important to properly tune them to obtain sufficient part quality. Numerous process variables used in FDM have a significant influence on the characteristics of the finished product. The most used process variable is layer thickness. It is the vertical height measured on the Z-axis of the extruded layers [4, 15–23]. The deposition bed direction w.r.t. the platform's X-axis is known as the raster angle [4, 15, 19, 23]. The air gap is the deposited layer gap between two corresponding rasters [4, 15, 19, 23]. Also, the negative air gap occurs when overlapping is noted between two adjacent layers. The width of the deposition beds on the machine platform is referred to as raster width [4, 15, 18, 19, 20, 23]. It is reliant on the diameter of the extrusion nozzle. Build orientation is coined as the positioning of the product on a machine platform w.r.t., different axis [4, 15, 16, 19, 21, 23, 24]. Infill density: The part's outer layers are solid. While internal structure layers, called infill, is generally unseen internal part surrounded by solid layers. Infill density can be defined as the

amount of infill volume of filament that is utilized for creating the internal structure of the part [17, 22]. Infill patterns are usually utilized in building parts to manufacture a sound internal structure and bonding [21]. While extruding, the distance travelled per unit of time by the nozzle extruder is the printing speed [16, 20–22]. Printing time is purely dependent on print speed.

FDM technology comes into the equation because of its sound printing speed and lesser cost. This technology is best for proof-of-concept models and simple prototyping. FDM has a number of disadvantages, including poor mechanical characteristics, high surface roughness, and a restriction in the use of various thermoplastic materials [25]. FDM has a resolution range of 50–200 μm [26].

Stereolithography (SLA)

Chuck Hull introduced stereolithography as one of the earliest AM techniques in the 1980s [27, 28]. The vat photopolymerization principle is the basis for stereolithography (SLA) and its related procedures. The chain reaction is initiated on a resin layer or monomer solution using a source of light, usually UV rays or electron beams, as shown in Figure 4. After activation, the monomers immediately transform into polymer chains, referred to as radicalization. Post polymerization, the resin pattern layer is hardened to hold the subsequent layers in place, and process parameters are optimized according to the desired application [30–34]. Some of the process parameters utilized by researchers in SLA technology are laser

thickness [30, 35–36], printing bed temperature [35], laser power [35], stratification angle [30], post curing time [35], and fabrication orientation [36] as shown in Figure 5. The key parameters determining the thickness of each layer are the light source’s energy and exposure [37]. SLA may be incorporated to develop complex nanocomposites [38]. It has the highest resolution and accuracy with versatile material selection. SLA is often used for functional prototyping, patterns, moulds, and tooling. SLA has several disadvantages despite having higher resolution, including restricted materials and sluggish printing. The resolution of SLA is 10 μm [26].

Laminated object manufacturing (LOM)

LOM is the AM method that was the earliest commercially accessible. In this method, thin layer sheets of material, usually (metal, plastic, and paper) are machined to replica (the intended product’s cross-sections) using lasers or mechanical cutters. Layers are fused one after the other until the object is complete [11]. LOM is additive manufacturing that involves cutting and laminating sheets or rolls of materials layer by layer. Consecutive layers are cut accurately and then joined together using a mechanical cutter or laser as an energy source. There are two methods of material joining in LOM, i.e., bond-then-form and form-then-bond. The form-then-bond approach is convenient for ceramics and metallic material’s thermal bonding, and it aids internal feature creation by eliminating superfluous material before coalescing. Excess materials are used as support after machining and can be removed and repurposed when the operation is completed [39]. LOM may be utilized for various materials, including ceramics, polymers, composites,

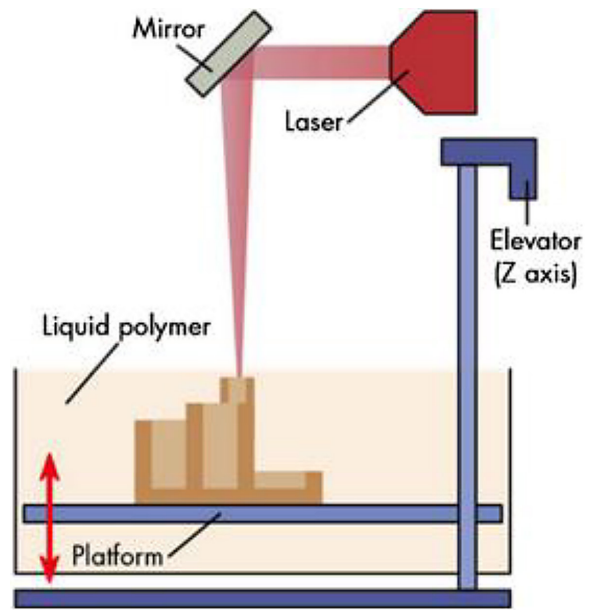


Figure 4. Stereolithography (SLA) process [29]

and paper. The LOM system employs a source of the laser beam to cut off anticipated contours from a continuous roll of the sheet, resulting in final part layers, as shown in Figure 6. The layers are adhered to by a heat-activated plastic coated on one side of the paper and the desired component [40]. The primary disadvantage of the method is that it causes significant shrinkage (12–18%) owing to thermal post-processing, which might result in dimensional errors [40]. LOM resolution varies depending on laminate thickness; however, it is typically 50 μm [41].

Selective laser sintering (SLS)

SLS employs powder material to manufacture various parts straight away from CAD drawings.

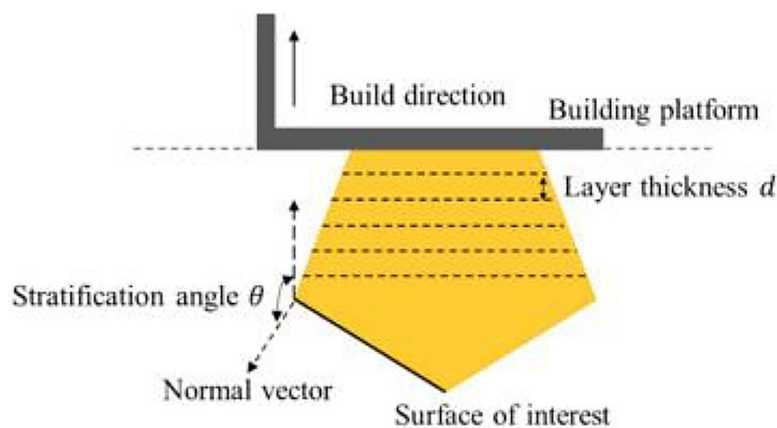


Figure 5. SLA process parameters [30]

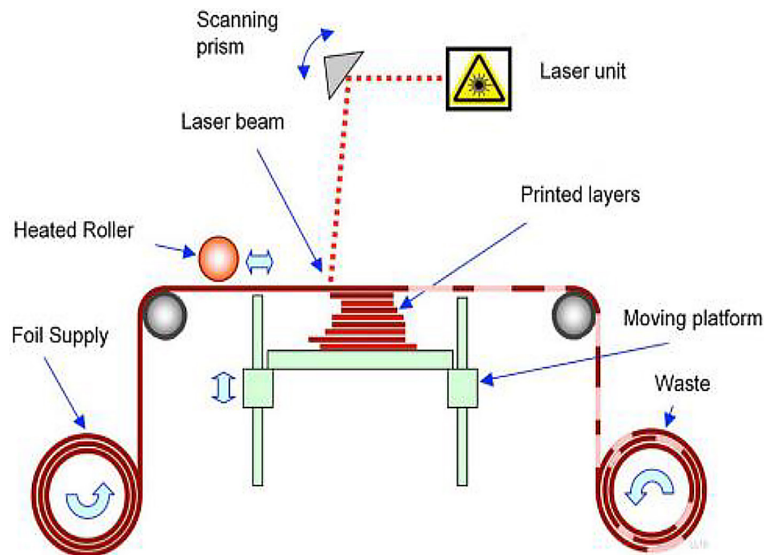


Figure 6. LOM setup [29]

Thermoplastics such as polyamides, ABS, polycarbonate, and nylons and metal components such as Ti, SS, and tool steel are widely utilized in part manufacturing [42].

SLS powder-based 3DP technique selectively fabricates models using a CO₂ laser beam in the given procedure. The two-dimensional (2D) slice data is first supplied to the available machine. In turn, it controls the laser's guided path over a layer of powder that has been already placed on the tray provided (Figure 7). The laser beam then heats up the powder, cementing them together to form a solid layer. Further, it travels to the X and Y axes to construct the products based on the CAD data provided. The build tray slides lower after the first layer fuses, a fresh layer of powder is placed, and then the sintering of a new layer occurs. The procedure is carried out again until the part fabrication is accomplished. Sandblasting is

used to finish the prototype's surface. Prototypes made by SLS are opaque with a rough and porous surface in nature; this is the main drawback of this method. The SLS model has reasonably good precision with errors deviating from 0.1 to 0.6 mm, and multiple components are manufactured simultaneously because of the high-cost materials used for manufacturing [43]. Some process variables used in SLS:

Layer thickness is the material thickness of a single layer being hoarded on a power bed at the inception of the process [44]. The power through which the laser beam is collimated from the scanner in the SLS process is laser power. The space between successive laser movements is known as hatch spacing. The laser beam power utilized for sintering is inversely proportional to the hatch spacing. The whole bed where the prototype is manufactured within the sinter station must be

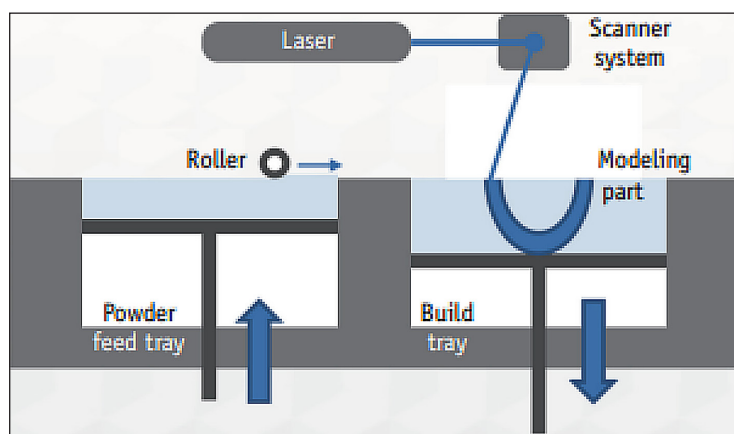


Figure 7. SLS apparatus [43]

stowed at a specific vacuum level. As a result, that compartment is regulated at a temperature higher than the ambient temperature, referred to as part bed temperature. The surface smoothness of an SLA part is good as compared to an SLS part. In addition, due to the utilization of costly equipment for high melting temperature materials, setting up an SLS machine is expensive [45]. But still, it has a low cost per part, high efficiency, and excellent mechanical properties resembling injection-moulded parts. There is no requirement for support and post-processing; also, the resolution is a function of the diameter of the laser beam [46–48].

Direct energy deposition (DED)

High-performance superalloys have been made via direct energy deposition (DED). DED works by concentrating a power source (laser or electron beam) on a small region of the substrate while simultaneously melting a feeding material (powder or wire). Following the movement of the laser beam, the molten material is deposited and fused into the melted substrate, hardening it. DED is a non-equilibrium processing technology with extremely rapid cooling rates, generally on a scale of 10^3 to 10^5 K/s [49].

There are different types of DED systems, as mentioned in Figure 8. The powder-based DED method is the most widely used metal DED technology and has been extensively explored in the literature. As a heat source, it primarily employs a laser beam. In comparison with laser-beam and

powder-based DED techniques, wire-based DED procedures have a lower resolution but a greater deposition rate and the capacity to create larger parts [50, 51]. Layer thickness, laser power, laser beam spot size, feed rate of material, scanning speed, and clad angle are some of the important process variables often used for experimentation in DED.

In comparison to SLS or SLM, DED has lesser precision of 0.25 mm, poor surface smoothness, and can produce fewer complicated components. As a result, DED is frequently utilized for big, low-complexity components. DED has excellent mechanical characteristics, and it helps to reduce production lead time and cost. Table 1 shows a comparison of different AM techniques.

MATERIALS

Materials play a significant role in AM, specifically engineering materials. Materials must be shaped into given feedstock, have adequate properties, and have acceptable service attributes to get sound parts [54]. Freeform design and optimization are typically employed to enable performance tuning and the establishment of innovative applications [55]. Figure 9 depicts the distribution of materials used in AM.

Polymers

Because of the cheaper cost of production, various polymers in the form of filament, resin,

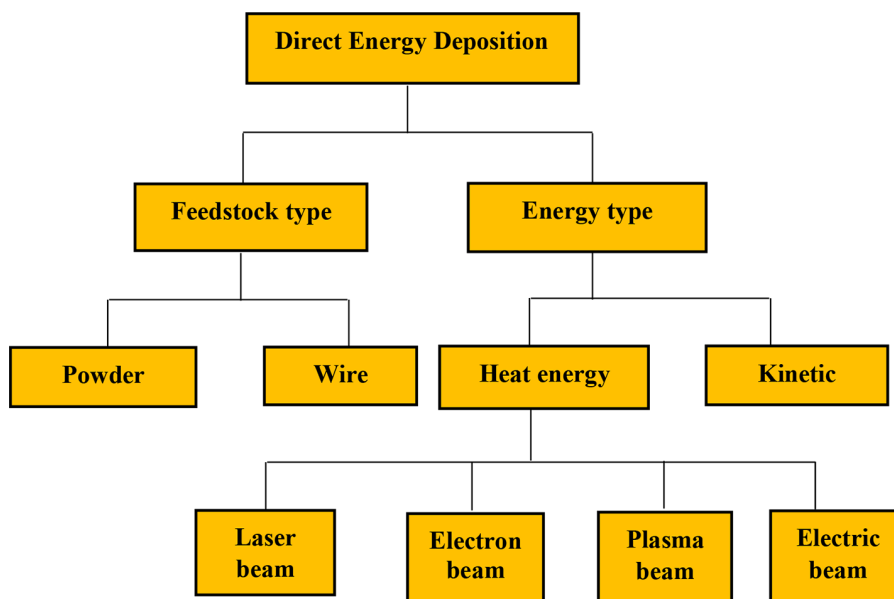


Figure 8. Classification of DED systems [49]

Table 1. Additive manufacturing methods and their principle, applications, and resolution

No.	Additive manufacturing method	Principle	Significance (when to use)	Specific applications	Resolution
1.	Fused deposition modelling	Material extrusion	Proof-of-concept models and simple prototyping	Scaffolds, prosthetics, automobiles, drug delivery devices	50–200 μm [26]
2.	Stereolithography	Vat photopolymerization	Versatile material selection and functional prototyping	Master patterns for vacuum casting, sacrificial patterns for metal casting tools, molds, dies casting, assembly parts casting, jewellery-specific casting, dental models' production	10 μm [26]
3.	Laminated object manufacturing	Sheet lamination	Versatile materials selection and support materials repurposed	Paper architectural models and single-use patterns for sand casting	Depends on laminate thickness but typically is 50 μm [41]
4.	Selective laser sintering	Powder bed fusion	Multiple components manufactured simultaneously	Ducting, flame-retardant parts, Jigs, fixtures, tools, casting patterns, parts with snap fits/living hinges, automotive design, aerospace parts, gaskets, seals, and hoses	80–250 μm [52]
5.	Direct energy deposition	Laser or electron beam melting	Big, low-complex components	Aircraft parts, refractory metal components, ballistic material tooling repair and reconditioning, and Marine propulsion	250 μm [53]

and powder are gaining ground for AM [56]. In recent years, benefits like energy-efficient materials and low-maintenance printing systems have become a great choice. Some AM systems, on the other hand, may have system instability, necessitating periodic system calibration. Thermoplastic polymers are generally applied in material extrusion and powder bed fusion principles of AM. Amorphous thermoplastics are generally considered for material extrusions, such as in FDM, while powder bed fusion utilizes semi-crystalline

polymers for sintering. Because of their melt properties, amorphous thermoplastics are chosen for material extrusion. These polymers, which include the well-known “ABS,” an acronym for Acrylonitrile Butadiene Styrene, and “PLA,” an acronym for polylactic acid, soften across a wide temperature range, resulting in a visco-elastic material suitable for the extrusion method via nozzle diameter of 0.2–0.5 mm as in FDM technology. Thermoplastic polymers such as ABS, PLA, PEEK (polyetheretherketone), PVA (polyvinyl alcohol) [57], TPU (polyurethane) [58], nylon [59, 60], are some of the mainly used polymers used in additive manufacturing.

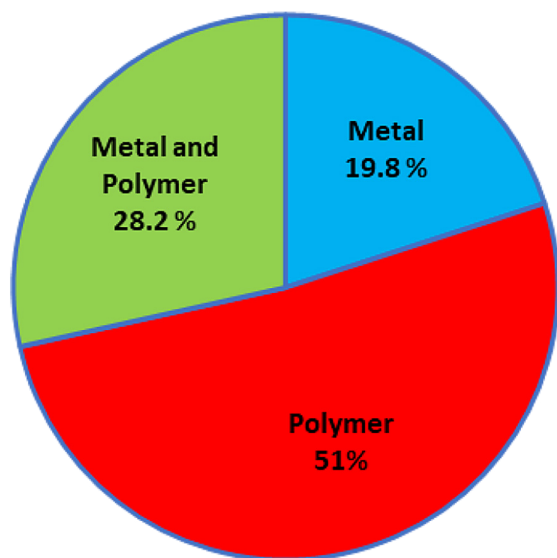


Figure 9. Materials used in AM [29]

PLA

Polylactide (PLA) is a prominent biopolymer amongst biodegradable polymers available in the market that may be used as fixations. PLA products have been authorized as a biopolymer for clinical use by the “US Food and Drug Administration (FDA)” because of their biocompatibility, biodegradability, excellent mechanical characteristics, and processability [61]. PLA is a biodegradable thermoplastic that has undergone extensive processing in order to be used in biodegradability applications. Its biodegradation products (CO₂ and H₂O) are completely non-toxic, and its bioresorbability neither overburdens nor produces foreign

material in the body [62]. The impacts of numerous production factors (input parameters) on the mechanical characteristics (output parameters) of PLA FDM parts were studied [63]. The maximum flexural force in PLA specimens was optimized using process variables: layer thickness, filling percentage, and deposition angle [64]. The effects of several input parameters such as build orientation, layer thickness, and feed rate on the mechanical characteristics of PLA specimens were analyzed [65].

ABS

ABS is an illustrious material in AM. It is the earliest polymer to be utilized with commercial 3D printers. ABS is preferred because of its inexpensiveness and better mechanical characteristics. ABS is recognized for its high impact strength and toughness, enabling the printing of 3D parts for wear and tear applications. ABS material can sustain higher temperatures prior to its deformation because of its great range of glass transition temperature; hence it can be preferably used in outdoor or high-temperature applications [66].

PEEK

PEEK has a higher melting point than PLA and ABS wires resulting in increased thermal stress and thermal fractures. As a result, precise parameter settings are required for PEEK material to adjust its own properties [67]. With varied printing parameter settings in FDM, the mechanical strengths and thermal deformation were investigated for PEEK material [68, 69]. PEEK may be made into a filament, and specimens can be made utilizing a variety of build orientations and extrusion paths. The mechanical characteristics of extrusion freeform porous PEEK components were studied [70]. The bending strength of PEEK samples was analyzed at 0° , 90° , and $0^\circ/90^\circ$ raster angles and was found to be greatest at the 0° raster angle [71]. The tensile characteristics of PEEK parts printed through material extrusion using the FDM method were studied [72]. Finally, it was established that the PEEK filament showed superior mechanical attributes when compared to other filaments. The mechanical characteristics of 3D-printed products are crucial indexers for assessing the grade of print done on the machine.

Reinforced polymers for AM

A lot has already been documented on 3DP of reinforced materials previously. The disruption to the fibers throughout the various pre-processing procedures, such as filament fabrication and 3D printing, is a critical impediment for reinforced materials with fibers. In this regard, printing polymers reinforced with continual carbon fiber is noteworthy. For illustration, researchers investigated the efficiency of the 3D printer to produce carbon fiber reinforced thermoplastic (CFRT) variants [73]. In the same year, other researchers developed an approach to print CFRT relying on FFF [74]. In this instance, the reinforcements were carbon fibers or twisted skeins made of naturally occurring jute, with PLA acting as the parent material. Consequently, unidirectional carbon fiber reinforced thermoplastics outperformed jute- and unreinforced thermoplastics in terms of mechanical characteristics.

Li et al. described an exemplary case of CFRT printing [75]. In their article, they provide a method for rapid prototyping printing of CFR-PLA. Using the blend of carbon fiber and PLA resin, curve surfaces were printed utilizing a unique extrusion nozzle and trajectory adaptive controls. Figure 10 depicts the extrusion device principle. CFRP may be successfully printed in both straight and curved 3D routes. Considering the fragile bonding barrier between carbon fiber and PLA, pre-treatment of carbon fibers increased the interfacial strength.

The proposed method was evaluated on three different designs (unidirectional flat part, hollow-out aerofoil, and a circle as observed in Figure 11(a, b, c)). The findings showed that the modified CFRT had substantially higher tensile and flexural strengths than the actual specimens. The storage modulus of the modified CFRT specimens was 166% and 351% greater than that of the PLA and the fiber reinforced parts. The SEM pictures showed that the CFRT composites were modified to produce the intended bonding interfaces. This continuous carbon fiber composite rapid prototyping process can produce intricate and efficient composite parts, particularly for intricate airplane components [76]. A second method for synthesizing composites with minimal fiber damage known as localized in-plane thermal aided 3D printing (LITA) was developed [77]. This approach makes a composite with sound mechanical qualities, high thermal stability, design flexibility, cheap cost,

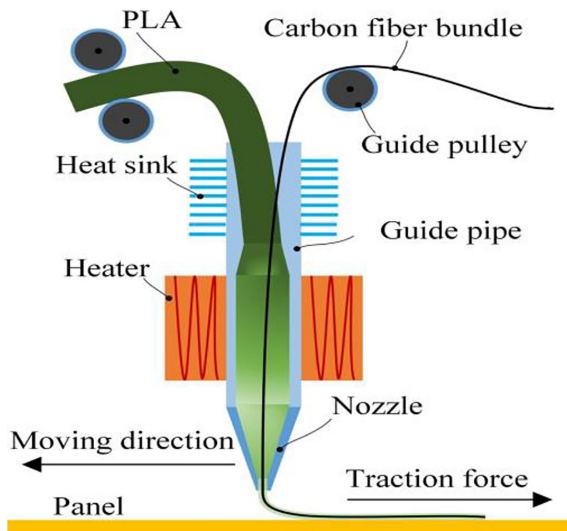


Figure 10. Principle of extrusion device for fabrication [75]

and durability via thermoset polymers and carbon fiber. Pores or gaps are selectively incorporated into carbon fibers to allow for the absorption of a liquid polymer. After that, a 3D-printed structure can be developed by heating the fibers. The method is based on the principle of capillary effect that develops from a temperature difference flowing on the carbon fiber interfaces, permitting liquid polymer to move more effortlessly in space and take on the shape of a tube in between adjacent carbon fibers. The polymeric resin is then cured after being applied to heated fiber interfaces and their adjacent region. Then, the liquid resin fills any gaps as it flows toward the carbon fibers' heated locations. The printing mechanism consists

of a carbon fiber-filled printing head, a Joule heater, a resin distributor, and a robotic arm that moves the printing head in three dimensions (Figure 12).

Such kind of reinforcing polymeric matrix has a downside. Often, the polymer and reinforcement may not be well-compatible, which reduces the material attributes that might be attained [78-80]. In sheet molding compounds for conventional injection molding procedures, the introduction of additives to enhance material qualities for manufacturing and deployment is a typical practice [81, 82]. To alter melt flow, boost strength, and reduce warpage, additives can be incorporated [83, 84]. Recently, fillers have been added to FFF filaments to tweak material characteristics like warpage [85], and rheological properties, or to add functionality like magnetic characteristics [86].

Metals and alloys

Currently, AM is used to process steels, titanium, aluminium, and nickel alloys, which are exploited in a variety of applications [87]. For producing high-quality metal components in the industry, two powder-based AM techniques are powder bed fusion and directed energy deposition. Steel alloys were the foremost to be treated, and it has subsequently deployed in industries, most notably automotive and aerospace [88]. Pure metals are also making inroads in additive manufacturing [89]. Titanium alloys, primarily Ti-6Al-4V, are indeed the finest choice in medicine for load-bearing implant applications [90]. Nickel alloys such as Hastelloy X, In625, and

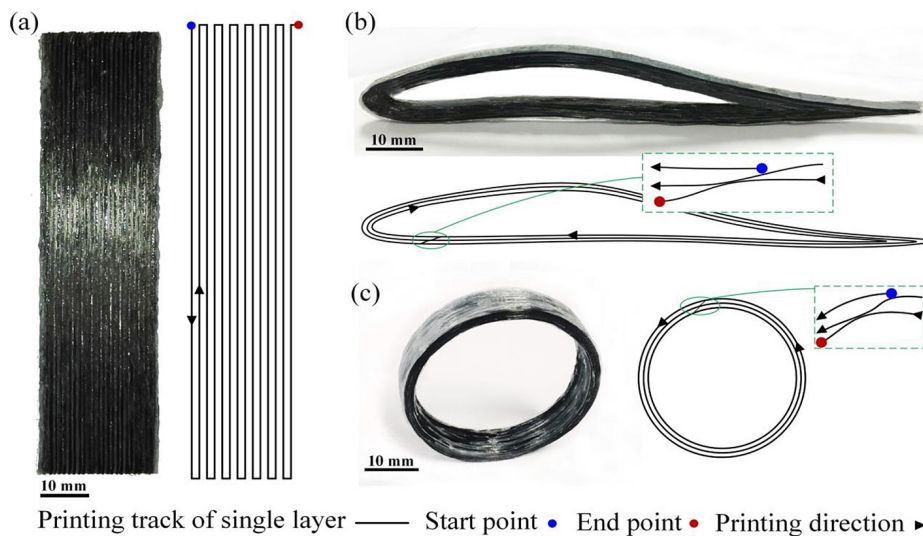


Figure 11. Different reinforced PLA composite parts [75]

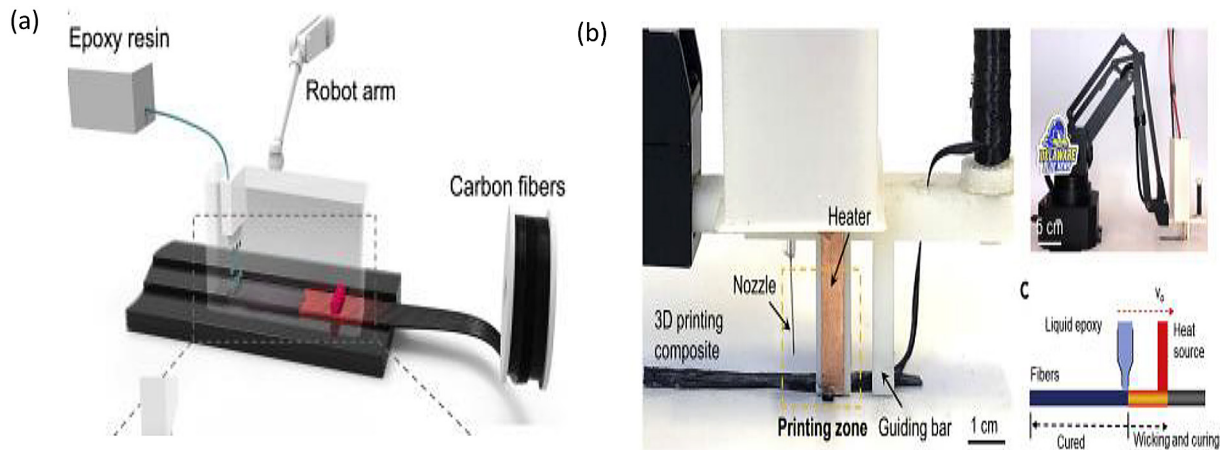


Figure 12. (a) LITA 3D printing configuration (b) LITA 3D printing working [77]

In718 are used to produce 3D printed parts such as engine turbine blades, turbochargers, heat exchangers, and petrochemical equipment which requires high creep and corrosion resistance [91].

Aluminium (Al) and its alloys are lightweight, strong, corrosion-resistant, and easy to weld, making them ideal for a variety of applications in sectors including automotive, aerospace, defense, and construction. Aluminium-silicon based alloys, especially AlSi10Mg, AlSi12, A356 (Al-Si7Mg0.3), and A357 (AlSi7Mg0.7), have been widely utilized among the many alloy combinations used in the SLM process because of their good fabricability [92].

Metal-polymer hybrid

One of the primary difficulties with thermoplastic 3DP is that the material does not, on its own meet the mechanical, thermal, or electrical properties intended by the industries [93]. For this reason, there is a surge of interest in discovering a viable technique to accomplish metal 3DP. While 3D printing with thermoplastics is extremely developed and can easily produce complicated topologies at a minimal cost and within a short amount of time, it is still difficult to 3D print with metals owing to their cost. Bulk metallic glasses (BMGs) are a class of metallic materials that, when heated, exhibit a continuous softening behavior akin to that of thermoplastics.

By using FFF techniques, researchers showed that BMGs can also be used for extrusion-based 3DP [94]. A schematic overview of the apparatus utilized to print metal components is shown in Figure 13a. Figure 13b, c represents products fabricated by the same technique. Liu et al. recently

presented an innovative technique for fabricating 3D-printed components made of metallic materials [95]. This process, known as Fused Deposition Modeling and Sintering (FDMS), is based on FFF printing using a composite filament comprised of a metal and polymer. A diagrammatic representation of the FDMS procedure is shown in Figure 14. Initially, FFF is used to print the green parts using metal/polymer composite filament. During this process, the polymer serves as the binder and is melted, but the metal particles are left solid. Subsequently, brown parts were produced by debinding the green parts. The left binder in the brown sections prevents the metal particles from spreading and keeps the form of the components.

The brown part is then sintered to combine the metal atoms and produce dense FDMS parts. The materials used were stainless steel 316L microparticles dispersed together into a polymer matrix of polyformaldehyde (POM) and additives like polypropylene (PP), dioctyl phthalate (DOP), dibutyl phthalate (DBP), and zinc oxide (ZnO) to improve the composite's flowability, plasticity, and thermo-stability. A technology for additive manufacturing (AM) called AddJoining is focused on the creation of layered metal-polymer hybrid parts. It combines the fundamentals of AM with materials joining approaches. Using printing combinations of the materials aluminium 2024-T3/ABS and aluminium 2024-T3/unreinforced polyamide 6 (PA6)/carbon-fiber-reinforced polyamide 6 (CF-PA6), Amancio-Filho et al. group [96] established this methodology and verified its viability.

In AddJoining process is explained in Figure 15a. First, a build platform serves to position the metallic substrate. Next, a metallic substrate is coated with an additional layer of polymer. Till

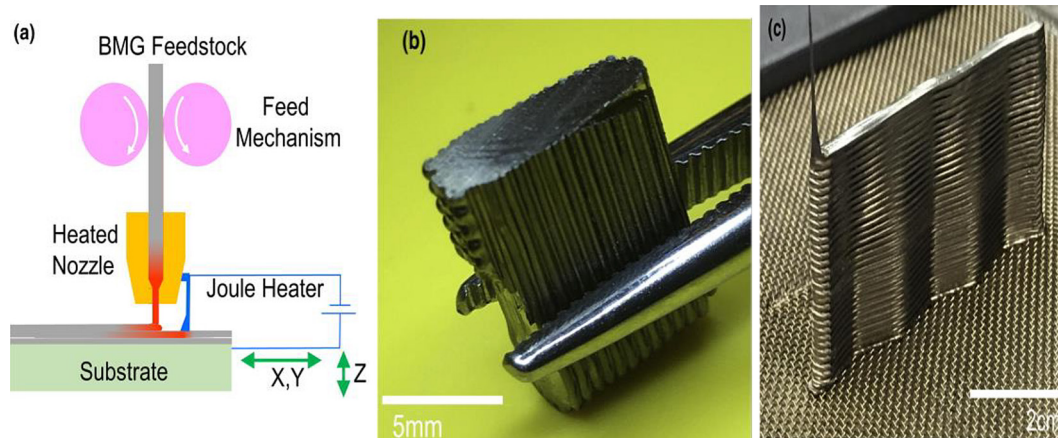


Figure 13. (a) Setup of direct-write extrusion of BMGs, (b) 3DP of the BMG extrude, (c) fully dense and pore-less specimen [94]

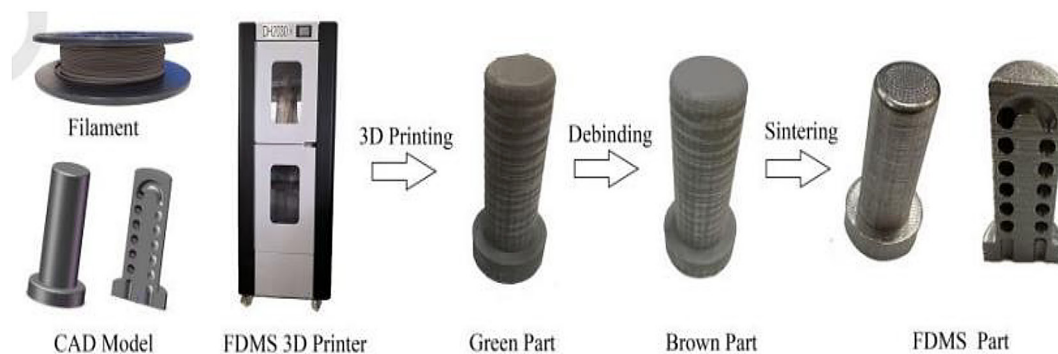


Figure 14. Schematic illustration of the FDMS process [95]

the requisite thickness and sequencing of the polymeric component are attained, subsequent polymer coatings are deposited. The outcomes reveal that the joining method is feasible when employing AM technologies. Figure 15b displays the cross-sectional microstructure of the joints. For both investigations, it was feasible to accomplish direct contact between the coated polymer film and the aluminum surface. As no bond line could be seen connecting the deposited polymer and coating layers, it is likely that strong bonds have formed at the interfaces by intermolecular diffusion. However, gaps between the CF-PA6 and PA6 layers were found (shown with white arrows in Figure 15b, right-side).

The proposed methodology's printing parameters were recently optimized by the same researchers. When the mechanical testing was accomplished, they also glanced at the specimens' fracture morphology and joint structure [97,98]. These findings showed that the coated metal substrate and the 3D-printed polymer were successfully mechanically interlocked.

Ceramics

According to the ISO 17296 standard, mainly there are two types of AM processes: (i) single-step processes (also known as “direct” processes), which involve fabricating components in a single operation that achieves the anticipated product's fundamental geometrical form and basic material characteristics at the same time and (ii) multi-step processes (also known as “indirect” processes), where the desired product is manufactured in more than one operation, former provides the required geometrical shape and latter one provides basic material properties to the intended product [99]. The majority of AM methods for shaping ceramics are multi-step (indirect) procedures that form ceramic powder particles using a sacrificial binder ingredient. In most cases, the binder is removed via subsequent ‘debinding’ treatments in the furnace. Powder bed fusion and DED are the only single-step methods for shaping ceramics. Multi-step (indirect) AM techniques are better for shaping diverse ceramics, but single-step (direct) AM

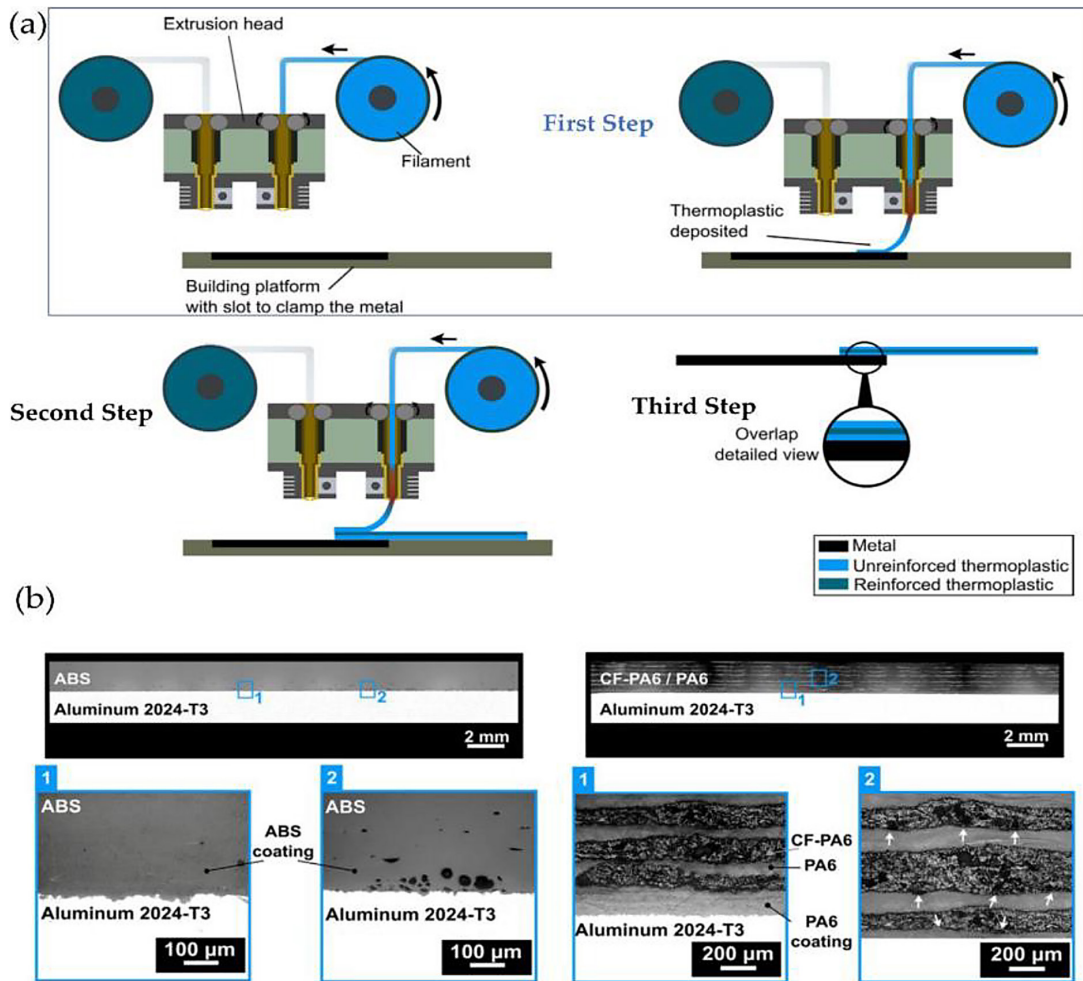


Figure 15. (a) AddJoining process, (b) microstructure of hybrid joints [96]

methods may manufacture components in less time. Furthermore, ceramic components with no fractures or big pores have mechanical characteristics similar to traditionally manufactured ceramics. AM parts like this may be made by process parameters optimization or adding finishing stages once the post-AM process is completed. It is well recommended to include colloidal processing methods in the process of AM to get crack and pore-free ceramics parts from manufacturing [99]. The use of yttria-stabilized tetragonal zirconia polycrystals (Y-TZPs) in the fabrication of medical implants has numerous advantages: Y-TZP, for example, offers excellent mechanical characteristics as well as better corrosion and wear resistance, making it ideal for dental implants [100]. Meanwhile, it also may be able to meet the growing aesthetic expectations of many dental patients, as well as their metal-free requirements. AM technique was used to make the dental prosthesis, in which the Al_2O_3 or Y-TZP was mixed into a 0.8 percent aqueous ammonium polyacrylate in a 1:1 solid: liquid ratio [101]. Some

researchers proved that direct inkjet printing has a lot of potential for producing high-performance silicon nitride ceramics and for evaluating structural and mechanical properties like Young's modulus, Weibull modulus, and 4-pt. bending strength is intended to create a reliable number of test specimens by direct inkjet printing [102]. Paper-derived carbide ceramics were used in nuclear technologies since the materials used there may be enough resistance to γ radiation, high-speed nuclear fission fragments, and neutrons [103].

FAILURES ASSOCIATED WITH ADDITIVE MANUFACTURING

Although there is a range of possible challenges when adopting AM to fabricate parts, comprehending these constraints is the first step in producing significant quality, robust components. AM still faces numerous practical difficulties, such as poor product quality, resilience, material

characteristics, manoeuvrability, and so on, which impede its industrial-scale deployments. Several entry-level AM systems are currently inadequately competent to fabricate products with a desirable level of reliability, and users typically rely on the basic trial-and-error technique to generate products with appropriate geometrical and structural accuracy [104]. Future generations of AM machines will entail the incorporation of monitoring systems capable of identifying typical material flaws and process failure modes. Metallic materials manufactured via additive manufacturing have a high degree of mechanical strength. However, they often fail prematurely due to external defects (pores and unmelted particles) that give rise to crack initiation [105]. In fact, many defects arise within the material volume during the layer-by-layer process in AM, which is characterized by local fusions of unmelted powder with different heating sources [106]. Addressing failure in 3D printing is exacerbated by the fact that building layer by layer potentially results in anisotropic or non-homogeneous components. Layer-by-layer processing of metal may result in changes in material properties or the formation of inclusions. Within the component material, porosities, lack of fusion flaws, and defects brought on by insufficient bonding may develop and serve as the perfect breeding grounds for cracks that eventually cause premature failure. For these reasons,

conventionally built components, which are normally devoid of significant flaws and have sizes equivalent to those of AM parts, routinely outperform AM parts in terms of fatigue response.

This study examined porous parts based on triply periodic minimum surfaces to see how topology and porosity affect plastic deformation and failure patterns [107]. Five distinct porosities of P and G-type cellular lattice parts were considered for the experiment. Static and dynamic compressive tests were performed on the scaffolds to examine their mechanical properties, and the effects of the porosity value and strain rate on the scaffold's deformation pattern were assessed. The stress-strain curve of the bulk material's compressive test was analogous to the behavior of rigid polymers, demonstrating the independence of the structures' outcomes from the studied parts. High porosity G parts collapse owing to the development of the first and second shear bands at strain rates of $1 \times 10^{-4} \text{ s}^{-1}$ compressive loading. Furthermore, by reducing porosity, these parts' load-bearing capability rises since a second shear band is prevented from developing. The P parts fail the static compression test layer by layer, starting with the top layer for high-porosity parts and ending with the middle sample for low-porosity parts.

Figure 16 illustrates the collapse stress of both P and G parts at various porosity levels. According to this figure, the greatest difference in

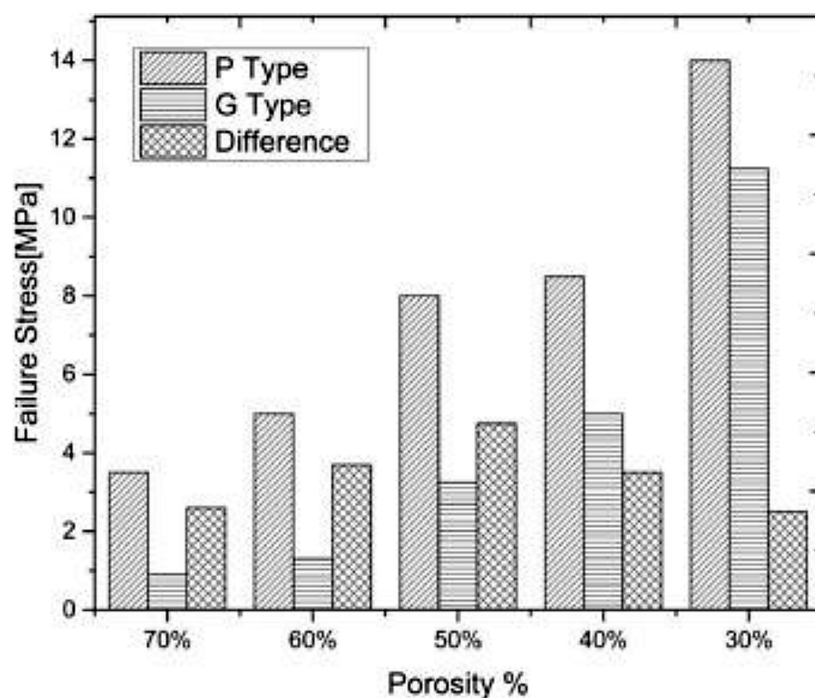


Figure 16. Comparison of failure stress in P and G parts [107]

porosity is 50 percent. Studying the impact of strain rate on the failure mechanisms of G and P parts at two 1×10^{-3} and $1 \times 10^{-2} \text{ s}^{-1}$ strain rates reveals that, in contrast to static testing, increasing the strain rate causes various failures of the parts. When the strain rate is increased in the G part, the first shear band forms at $1 \times 10^{-2} \text{ s}^{-1}$ at the upper part of the printed part, close to the loading platen, where it would not have had time to form at $1 \times 10^{-3} \text{ s}^{-1}$.

All parts on the top layer in all porosities fail when the strain rate in P parts is increased. Struts cannot transmit stress waves to lower layers through accelerating displacement, and as a result, the stress concentration causes top-layer parts to fail. For P and G parts, which are often utilized in compression cycle loading, cyclic loading was performed. As a result, P parts outperform G parts in terms of cyclic compressive endurance and cycles to failure as shown in Figure 17.

Amateur learners, hobbyists, and those with an interest in 3D printing could overlook these issues, which can result in subpar prints, failed prints, and damaged printers. Three categories of failures that occur in AM processes, their most likely causes, and potential solutions to printed part challenges are mentioned below [108].

Design deficiencies

Inadequate part design is included in the first of these categories. Amateur 3D printing and part design are typically confined to flaws in the

part's structural integrity. Design problems with parts are frequent, and they are typically solved through iteration. This is typically restricted to a mix of material and design structural faults in early prints. FFF 3D printing is anisotropic, which means that the bonded connections between the individual fused layers will be weaker in the direction perpendicular to the build surface.

As depicted in Figure 18, modest amounts of stress applied to the highlighted areas' borders led to cracking and breaking in the opposite direction from where the material was deposited. The areas served as stress concentrators because there were no transitions of any type between the segments of these components in the design.

The problem of part anisotropy is a frequent reason for failure because part designs do not account for them. In the wing box, the design was modified to include fillets to soften the part's pointed edges. This decreased stress levels and was maintained until the very last iteration.

Suitability for the specific application

The second category of issues pertains to problems with the chosen production technique. This means that the material or method (FFF) chosen was unable to produce a part that met the specifications required for the intended application. The key to successful 3D printing is selecting the appropriate fabrication process and raw materials that suit the chosen application. Figure

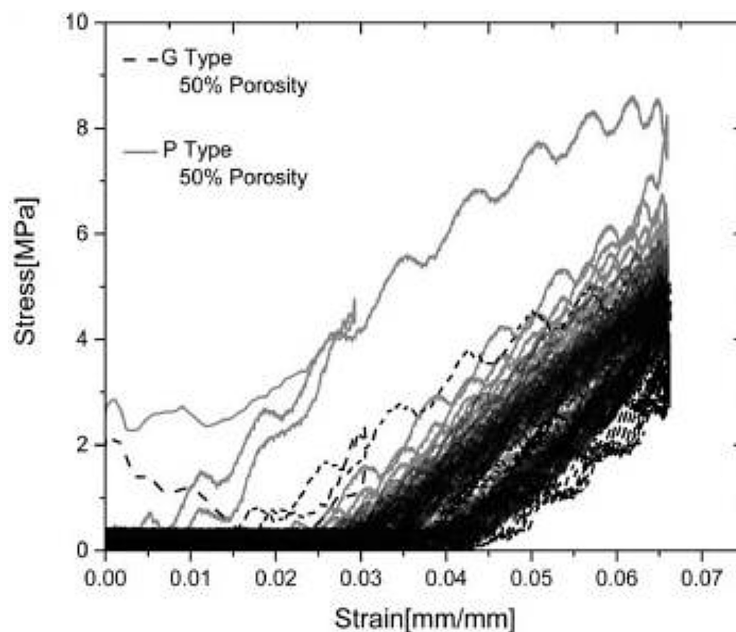


Figure 17. Stress-strain curve cyclic loading with a porosity of 50% [107]

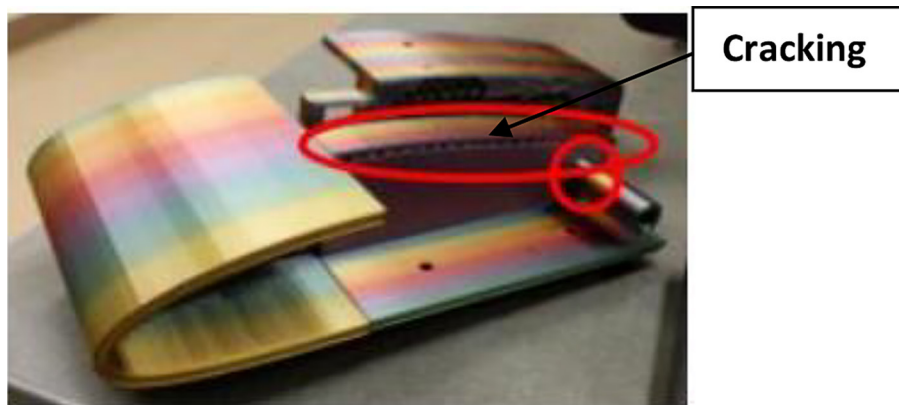


Figure 18. A failed PLA wing box prototype was intended to hold an unmanned aerial vehicle's wings in place while dissipating the force of wing loading throughout the vehicle's frame. A layer of the print failed around a stress concentrator [108]

19 illustrates an instance where the wrong material selection resulted in shortcomings in the finished product. In this case, the cello was 3D printed using nylon-6 and carbon fiber chop composite to benefit from the acoustic characteristics of carbon fiber. Unfortunately, the composite's nylon substrate proved too pliable, causing the entire instrument to bow when the strings were pulled taut. The components were originally supposed to be printed from ABS or PLA, which are significantly stronger and stiffer than nylon 6.

Print parameters

The third type of failed 3D print is focused on the printing parameters. There are many different components of printing that may be controlled while it is being done. The elements of the AM process that are dependent on the slicer settings or that may be adjusted while printing is referred to in this context as printing parameters. Unfavorable print parameters can cause a variety of failures while printing materials. Part warping during a print is another frequent failure that can be brought on by insufficient printing parameters. Part warping can be brought on by a variety of print factors, and it is more prevalent in high temperature materials like ABS. Rapid temperature

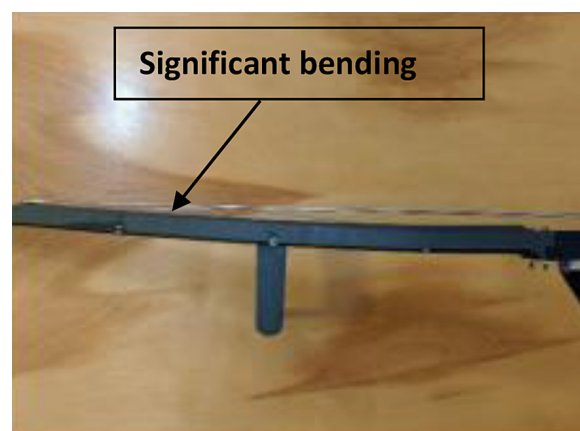


Figure 19. Cello having significant bending due to underneath tension of the strings [108]

changes are frequently the cause of warping because they weaken the adhesion of the part to the build plate, which allows the part to distort even more. By decreasing the likelihood that the part will peel off the build plate, this temperature difference can be ameliorated by employing a heated build plate and hence preserving the geometry of the part. Depending on your slicer, you can also accomplish this by printing a bed adhesion structure like a brim, raft, or skirt. Figure 20 illustrates a warped part as an example.

Further, the design deficiencies can be classified into geometrical failures. A printing



Figure 20. A severely warped PLA dog bone [108]

failure might arise from one source or from a multitude of variables acting concurrently. For instance, it might be related to a “complex” STL mesh, a “flaw” in the CAD model design (such as a very thin feature), the constraints of the AM machine, particularly in relation to a particular model application area, or a combination of the aforementioned factors. [109] presents a geometric examination of the printability of STL meshes and suggests an approach for automatically fixing “unprintable” STL meshes. The method examines the many kinds of “faults” in the initial STL file and then proposes fixes using groups of triangles. The problem of print failure is explored in [110]. A worksheet for design for additive manufacturing (dfAM) was developed and brought into use by the researchers, which could be deployed at either the conceptual stage of design or the CAD stage. The frequency of print failures dropped because of utilizing the worksheet. For users (especially amateurs) to learn methodologies for designing models for AM manufacturing with the Fused Filament Fabrication (FFF) technique, a MATLAB-based virtual prototyping tool is described [111]. This tool examines the geometry of the part, looks for problematic topologies (such as small features or thin walls) or orientation complications, and then offers recommendations to the user for improved printing outcomes. It assists in averting numerous, expensive, troublesome prints and can be used as a training tool for students and others without access to an AM machine. [112] presents a method for estimating the geometric precision of an AM part. Using a set of eight predictive factors that correspond to the geometric characteristics of the triangular mesh model employed for printing, this shape-driven methodology relies on machine learning. The geometric deviation of a vertex can be predicted using a unique method that involves training a random forest. The dimensional deviations of other models, including those with free-form design, can subsequently be anticipated using this model. Self-organizing maps are used by the authors to measure the geometric errors of AM components from a huge data set of laser-scanned coordinates [113]. The objective of the research was to establish a connection between the parameters of the AM process and the geometric precision of the final product. In [114], the issue of automatic error compensation is addressed. We provide a framework for training a neural network to estimate the deformation function, which defines how the input is distorted

to the real printed product, using data collected by techniques like 3D scanners and other Coordinate Measuring Machines (CMMs). The second stage involves approximating the inverse deformation function using the output model as the training set to build the input model. In order to replicate the shape deformation of the P- μ SLA process, a deep learning method using the convolutional encoder-decoder network is proposed in [115]. These techniques do have added benefit of taking neighbouring vertices into account while figuring out a vertex’s deformation function. Since these methods use simulated models rather than real production data, they are sluggish and their applicability is challenged.

CURRENT STATE AND FUTURE OF AM

In order to enable geometrical variations in 3D-printed components, various researchers have centered their endeavours on developing and creating smart materials, or materials that can react to a specific stimulus. As a result, the third dimension of 3D printing has given rise to the fourth dimension of 4D printing, which is time. This innovation was first presented by Skylar Tibbit in association with Stratasys.

According to the researchers, printed material can be programmed to alter over time in reaction to an outside stimulus, such as swelling [116]. This innovative illustration act as a springboard for several inventions that used various smart materials [116]. We will confine our discussion to polymers, and since shape memory polymers (SMPs), hydrogels, and shape memory composites (SMCs) are the most widely used. According to Ryan et al. [116], these materials could go from a transient state to a stable one. What’s more intriguing is that this switching tendency can be spurred on by exposures to perturbations in electromagnetic radiation, wetness, pH levels, and electrical and magnetic fields, as shown in Figure 21a.

It is important to note that single and multi-material components can be easily created via AM and engineered to respond to various inputs (Figure 21b top). Multi-stimuli setups can sometimes be used to achieve structural alterations. Khare et al. [117] presented a conceptual model predicated on this process and demonstrated it using an artificial bug made of many smart materials (Figure 21b bottom). The goal of this audacious

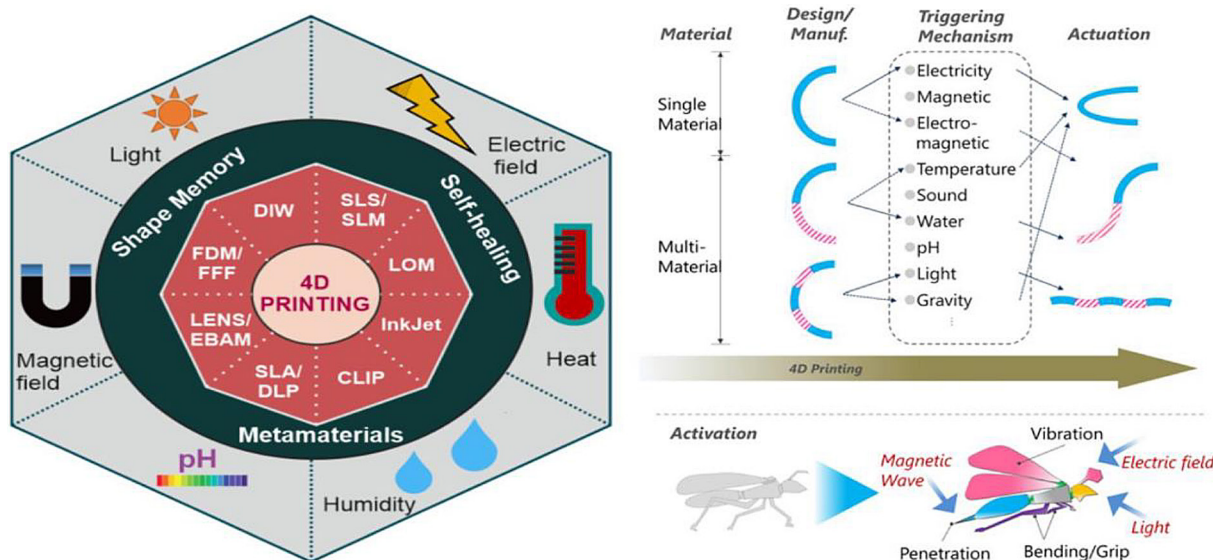


Figure 21. (a) Advancements in 4D printing [116], (b) mechanism proposed to achieve control and shape flexibility using single or multi-stimuli responsive materials and illustration of an artificial bug actuated by a multi-stimuli activation process [117]

complicated architecture is to concurrently attain elongation, mobility, shrinkage, or transformation in order to satisfy a certain intended application. This is accomplished by using a variety of form types and alterations offered by various multi-stimuli configurations. It is true that the range of stimuli-responsive materials and design concepts is somewhat constrained owing to the current stage of 4D printing technology developments, necessitating future development to accomplish complex structures.

Gladman et al. [118] provided a fascinating demonstration of the potential of 4D printing by designing a composite hydrogel ink that resembles plant cell walls as depicted in Figure 22. It is dreamed up of a cellulose fibril-reinforced soft acrylamide matrix. A viscoelastic ink consisting

of N, N-dimethyl acrylamide in an aqueous solution, Irgacure 2959 as a photo-initiator, nano-clay, glucose oxidase, glucose, and nano-fibrillated cellulose is employed to print the composite (NFC). The rheologic and viscoelastic characteristics required to produce the desired ink for printing were altered by the clay particles. Clay content that is more substantial results in higher crosslink densities and lower swelling ratios. Since glucose and glucose oxidase salvage the oxygen in the area, oxygen hindrance in UV curing is decreased.

The material outlined above is in an irreversible state of shape-shifting. The poly (N, N-dimethylacrylamide) must be swapped out for the thermos-responsive polymer N-isopropylacrylamide in order to produce reversible shape-shifting behaviour in both hot and cold water.

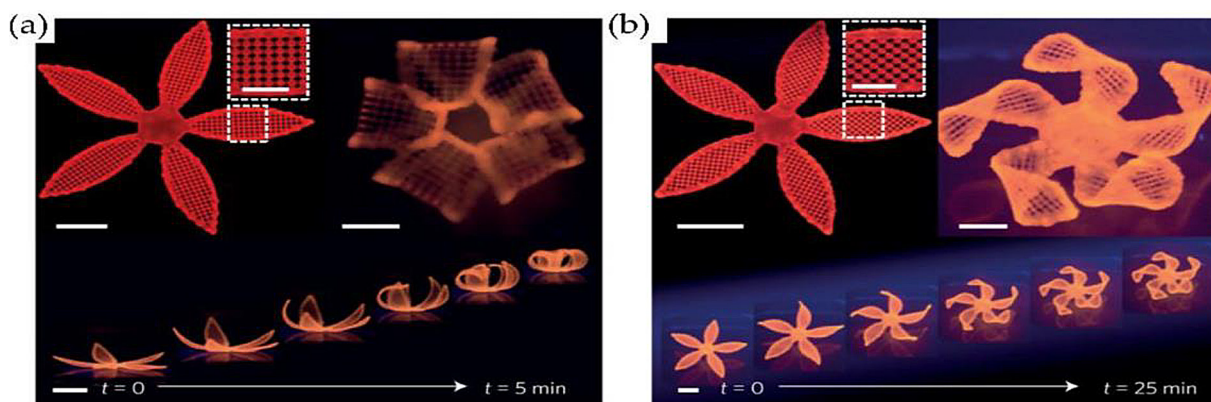


Figure 22. Different flower shapes and geometries produced by biomimetic 4D printing. (a, b) Simple flowers consisting of $90^\circ/0^\circ$ and $-45^\circ/45^\circ$ bilayers positioned in accordance with each petal's longitudinal plane [118]

Sustainable materials for AM

As has been thoroughly discussed, AM makes it possible to fabricate countless 3D geometries that other methods are inefficient at fabricating. Although AM holds enormous promise as a cutting-edge type of manufacturing in the future, there are still important sustainability issues that need to be tackled. In this context, sustainable supplies of printing inks, resins, and filaments are still needed, along with methods for polymer re-purposing, and chemical circularity. According to a comprehensive assessment, when bio-sourced and biodegradable polymers are coupled with AM capabilities, the artifacts manufactured can be recycled back into the source or disintegrated into harmless products after they have fulfilled their desired function [119]. With an emphasis on biodegradable and bio-sourced polymers, the authors compiled the most recent research on the design and chemistry of the polymers that enable sustainability in the field of AM. They also talk about various applications for sustainability that have come about as a result of the advancement of AM technologies. The high molecular weight of naturally occurring biopolymers (such as DNA, proteins, and polysaccharides) results in naturally viscous polymer solutions. Because

of this, preparing and printing these biopolymers using AM techniques might be difficult. In order for certain of these biopolymers to undergo light-initiated cross-linking, chemical modification is also necessary. To meet the needs of the printing technology, synthetic polymers can provide better control over polymer composition, molecular weight, and polymer architecture. Figure 23 provides an overview of some biopolymers and man-made polymers for AM.

In the global manufacturing industry, AM techniques have figured prominently. It is also anticipated that these technologies will continue to have an impact on how markets are disseminated presently, even though not expand it. Without a doubt, the low cost (especially for material extrusion and vat photopolymerization) is a contributing factor in the ongoing rise in machine sales, but it's also noteworthy that technological breakthroughs have enabled it to be possible to fabricate items using a broad spectrum of materials. The stringent selection of processing material that is a constraint of practically all commercial AM processes is still an issue. Due to this, the part created by additive manufacturing needs post-processing to improve its surface properties. Particularly in the field of biomedicine, AM has

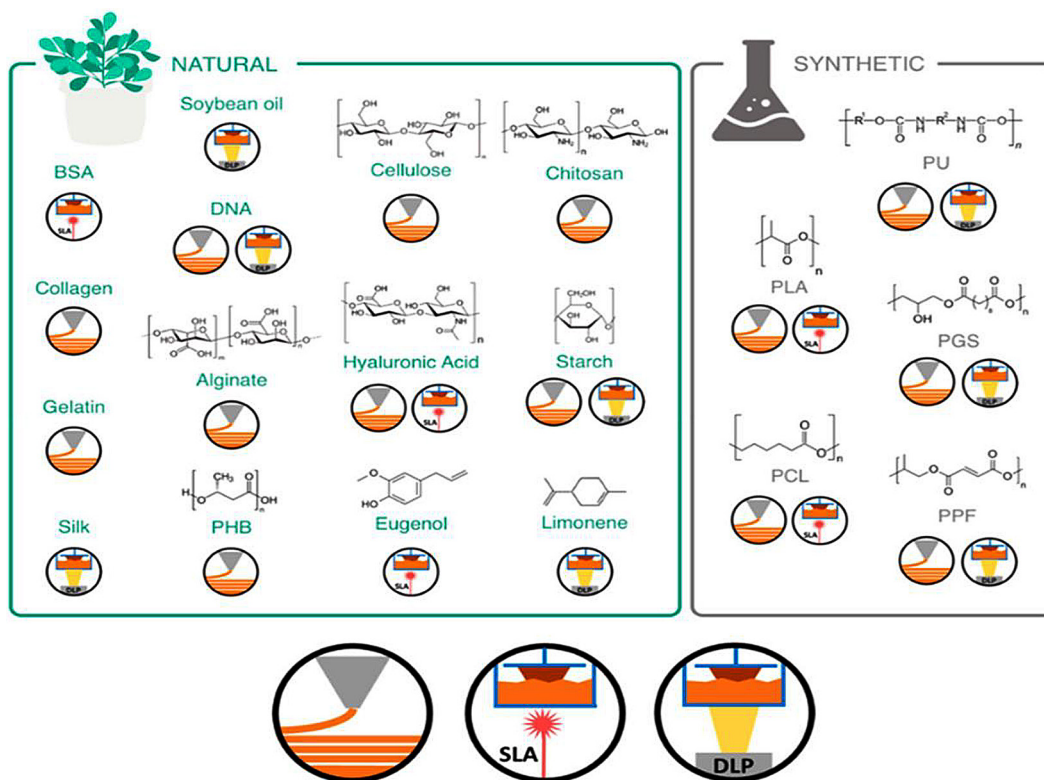


Figure 23. For sustainable AM, several renewable feedstocks have indeed been proposed [119].

demonstrated its capacity to fabricate personalized implants that successfully surpass most of the traditional production processes and occupy a major place. Typically, AM processes are developed in order to process a specific category of materials, and once that category has been reached, one must either adjust the hardware of the machine or discover a replacement material that is compatible. The development of novel materials is expected to constitute the next major advancement in this domain and will give researchers a technique to address substantially different processing challenges. The growth of novel materials that are suitable for each technique is also prompted by progress in AM technology. In essence, using a specific material is preferred to modifying ones that are already on hand. This review also provides exemplary instances of reinforced polymers for AM in this regard. Moreover, discussions have emphasized smart materials to further develop shape-changing parts or sustainable materials. The prevention of failures associated with additive manufacturing processes needs to be addressed in the future by novel post processing techniques. With the massive development of 3D printing, we may witness an increase in the adoption of additively manufactured parts in industrial applications. Traditional Metallurgical processes have years of research that can create large pieces of parts with relatively predictable properties. Standards in 3D printing have helped provide a foundation to start, but more standards and testing are necessary.

The present article provides an overview of AM and its advantages over traditional machining. It categorizes AM techniques and provides valuable insights into the materials used in the process. The article also emphasizes the importance of choosing the appropriate process parameters for experimentation and highlights critical process parameters that affect specific responses. It discusses the common failures associated with AM methods and outlines the measures that can be taken to prevent them. Lastly, the paper typically provides an overview and summary of current leading research, trends, and future challenges within the field of AM. In a nutshell, the article provides useful information for those interested in AM and its potential applications. This review might also provide readers with a better understanding of the broader context in which research operates and how different pieces of research fit together to form a larger picture. The significance of this review paper in a research study might

help researchers identify gaps in the literature and areas where further investigation is needed. Additionally, the paper might help researchers develop hypotheses for their own research and design studies that build on and address limitations in the existing body of research. This might be especially helpful for researchers who are new to the field or who are interested in gaining a deeper understanding of the context and background of a particular topic. Overall, the review paper may play an important role in advancing research by summarizing and analyzing the existing body of knowledge, identifying areas for future investigation, and helping to guide the direction of future research in AM.

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