An overview of additive manufacturing technology: generic processes, fundamental categories, advantages, disadvantages, and applications

Md Nazmul Hasan Dipu [1, *]
dipu.ipe.sust@gmail.com
OrcID: 0000-0001-6838-4918
[1] *Department of Industrial and Production Engineering, Shahjalal University of Science and Technology, Sylhet, Bangladesh.*
[*] *Corresponding author*

Abstract: *Many industries, such as automotive, aerospace, healthcare, education, and art, have already embraced additive manufacturing technology for its power of customization, product weight reduction, waste minimization, and capacity to cope with sophisticatedly designed components. For these reasons, it may be speculated that additive manufacturing technology may have an extensive influence on the next industrial revolution. Understanding additive manufacturing seems to be essential for this contemporary era. Therefore, the purpose of this article is to present an overview of additive manufacturing technology: general additive manufacturing steps, additive manufacturing categories, advantages, disadvantages, and applications.*

Keywords: 3D printing; Additive manufacturing; Rapid prototyping;

1. Introduction

Do you know that the value of additive manufacturing is likely to be approximately $196.8 billion in 2035 [1], which was nearly $6.1 billion in 2016 [2] ? Additive manufacturing — also known as 3D printing or rapid prototyping [3] — is capable of transforming a geometrical representation into physical objects by successively depositing material [4]. To put it another way, additive manufacturing is a process by which intricate components are created successively by the addition of layers by means of a computer-aided design model [5] [6] [7]. It has a huge significance in this modern era, because of its capability for enhanced performance, complicated geometrical fabrication, and easier production. For these significances, it is currently accepted by a number of industrial sectors such as automotive, aerospace, dental, medical treatment, education, art, culture, and so on [8]. Since there are versatile domains where additive manufacturing technology may be employed, it provides new prospects and brings hope to many possibilities for companies trying to enhance manufacturing efficacy and dimension [4]. Additionally, it has the ability to revolutionize present manufacturing industries with its capacity for vast customization of items on a huge scale [9]. For instance, additive manufacturing might be an appropriate technological solution for the fourth industrial revolution — known as Industry 4.0 — that requires a production setting for quick prototyping with agility in developing complicated designs and large-scale customization that requires low waste [10]. Thus, the widespread use of additive manufacturing would enable industries to incorporate the tenets of Industry 4.0 [11]. In addition to its influence on manufacturing industries, this additive manufacturing breakthrough is a forthcoming household necessity as it offers a personally customizable environment [3]. It can be inferred that it may give an opportunity to revolutionize personalized manufacturing in imminent years. Therefore, due to the significance of additive manufacturing, it has sparked unprecedented fascination and focus from industry, research laboratories, and end users [15].

There is a history behind the development of additive manufacturing. The earliest additive manufacturing concept — photo-glyph recording — was introduced as an official patent document by Munz Otto John in 1956 [12]. Albeit the following few decades witnessed an ongoing improvement of new additive manufacturing techniques, the development of commercially accessible instruments did not begin until 1986. It started after granting a patent in 1986 to Charles Hull — who was the co-founder, executive vice president, and chief technology officer of 3D Systems — and eventually launched the first stereolithography system to the market in the same year through a new company called 3D Systems [13]. Numerous individuals today regard Charles Hull as the progenitor of additive manufacturing, given that his patent from the middle 1980s coined the term "stereolithography" and facilitated the commercialization of the first additive manufacturing instruments [4] [12] [14] [8].

From the aforementioned significance and history of additive manufacturing, it can be acknowledged that a clear understanding of additive manufacturing is important. Therefore, the objective of this paper is to offer an overview of additive manufacturing technology: generic additive manufacturing processes, additive manufacturing fundamental categories, benefits, drawbacks, and applications.

The organization of this article has five more sections. ***Section 2*** shows eight generic additive manufacturing processes. It has two paragraphs: the first paragraph is briefly the name of each process, second paragraph deals with details. ***Section 3*** depicts seven fundamental additive manufacturing categories. There are seven subsections for each category. Besides, each subsection has three paragraphs: a clear concept for each fundamental category; the relationship between process factors and fabricated parts' characteristics; and relevant usable materials as well as covering techniques. ***Section 4*** represents the benefits as well as the drawbacks. There are three paragraphs in this section: an outline paragraph, a paragraph for showing advantages, and a paragraph for showing disadvantages. ***Section 5*** illustrates three impressive applications of additive manufacturing in three subsections: glass materials, space, and biodegradable materials. Finally, ***Section 6*** summarizes the paper and draws conclusions.

2. The generic additive manufacturing processes

Understanding the generic additive manufacturing processes could be beneficial for effectively apprehending additive manufacturing studies. Typical additive manufacturing, from the CAD model to the actual part, needs many steps to accomplish: CAD, STL conversion, file transfer to machine, machine setup, building the parts, removal of the parts, post-process, and application [15] [16] [17] [18] [19]. These steps are illustrated in ***Fig. 1***.

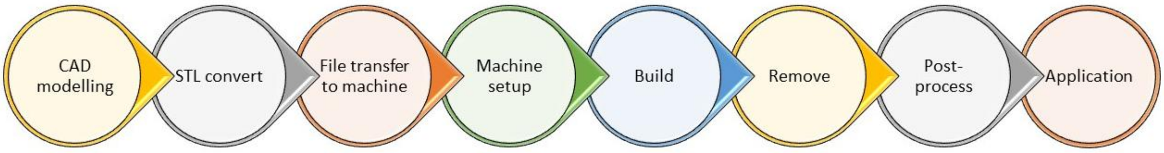

Fig. 1: The generic additive manufacturing processes.

Firstly, all components must commence with a CAD model that completely represents the external geometry. This can entail the usage of practically any professional CAD modeling software. Secondly, almost every additive manufacturing machine supports the STL file format, which is considered a norm, and almost every CAD system can export output in that STL file format. This file represents the external closed surfaces of the original CAD model and is the foundation for the calculation of the slices, but the output needs to be a 3D solid or surface representation. Thirdly, the STL file illustrating the part should be transmitted to the additive manufacturing printer. There might be a few general processing of the file so that it is in the correct position, size, and orientation for fabrication. Fourthly, the additive manufacturing machine should be correctly set up before the build process. Such settings pertain to the build factors such as layer thickness, material restrictions, timings, energy source, etc. Fifthly, building the part is primarily an automated operation and the machine can mostly operate with no supervision. Only cursory monitoring of the machine may be required to take place at this period to ensure no problems have taken place including software glitches, running out of material, or power, etc. Sixthly, once the additive manufacturing machine finishes its creation, the parts ought to be removed. Careful attention must be given while performing this stage such as checking safety interlock conditions if available, or there are no actively rotating parts. Seventhly, once separated from the machine, pieces may require some amount of extra cleaning up before they are suitable for use. Parts may be weak at this point or they may have supporting features that must be eliminated carefully. Eventually, pieces at this stage might be ready to use. Nevertheless, they might need further processing before they are deemed suitable for use. For example, they might need priming and painting to offer a satisfactory outermost layer's texture and finish. Treatments could be tedious and lengthy if the terminating standards are particularly exacting. They may also need to be joined together with other mechanical components to make a desired model or product [15] [16] [18] [19].

3. Classification of additive manufacturing primary categories

There are so many kinds of additive manufacturing approaches available in this contemporary era, which results in the classification of additive manufacturing methods in order to comprehend them better. There are a number of ways for classifying additive manufacturing processes, one of them proposed by the American Society for Testing and Materials (ASTM) F42 Committee, which divides additive manufacturing into seven broad categories: Powder Bed Fusion, Directed Energy Deposition, Material Extrusion, Vat Photopolymerization, Binder Jetting, Material Jetting, and Sheet Lamination [4] [16] [17] [18] [19] [20] [21] [22] [23]. In this article, the ASTM Committee's seven categories are described in the following subsections. Each subsection has three paragraphs: concept for the individual category; process parameters' relationship with fabricated parts; usable materials and techniques.

3.1 Powder Bed Fusion

Powder Bed Fusion techniques liquefy and bond material powder together [4] [15] [16]. In other words, thermal energy deliberately combines certain areas of powders by fusing [16]. To fuse powders, typically two types of heat sources are used: electron beam and laser. Whereas a laser employs a concentrated light beam to melt or sinter material, an electron beam uses a stream of high-energy electrons to do the same. Additionally, in many cases, the Powder Bed Fusion process needs a vacuum or an inert gas (e.g., Argon or Nitrogen) environment to prevent oxidation of the printed part during printing.

Many research papers have investigated the characteristics of Powder Bed Fusion fabricated parts. For instance, Morcos et al. showed that powder particle size affected the mechanical properties of the final parts [24]. In addition to this, Chu et al. depicted the greater strength of samples made with fine powder [25]. Another study by Song et al. upheld that particle size and scanning speed influenced density and surface roughness [26]. Buffa et al. discovered that a greater scanning speed resulted in a higher mechanical strength at the cost of ductility [27]. Another process parameter spot size — the diameter of a beam — was studied by Hung et al. and it was observed that the large spot-size pieces were more ductile due to their coarse grain structure. However, due to their finer grains, items manufactured with a tiny spot size had a higher yield strength [28]. Back to Morcos et al. also revealed that the existence of fine particles enhanced the densification of the produced parts [24]. The study of Spierings and Herres supported this point: fine particles improved the part density and surface finish [29]. Briefly summarize these studies in ***Table 1***. Notwithstanding the wide range of scholarly works carried out, issues including managing residual stresses, porosity, thermal fracture, and guaranteeing uniformity of material properties continue to be major areas of research and development in the sector.

Table 1 *Causing process factors of Powder Bed Fusion and their effects on fabricated samples*.

Causing process factors	***Effect on fabricated samples***	***Source***
Smaller powder size	Greater strength; improved densification; surface finish	[25] [29]
Greater scanning speed	Higher strength; lower ductility	[27]
Large spot-size	More ductile; poor grain structure	[28]
Tiny spot size	Finer grains; higher yield strength	[28]

To investigate the aforementioned properties, different powder materials and techniques were definitely used in this particular Powder Bed Fusion. Usable materials could be metals [4] [16], polymers [4] [16], ceramics [4], and composite [4]. But to conduct different powder materials, diverse Powder Bed Fusion additive manufacturing techniques are also required. One of the well-known Powder Bed Fusion techniques is Electron Beam Melting which employs electron beams to fuse metal powder particles layer by layer in a vacuum chamber, resulting in complicated components [30] [31]. Another method that only accepts metal alloys or mixed powder metals is Direct Metal Laser Sintering. It produces a high-density product by condensing metal powder without the need for binders using a laser beam [32]. Another kind of Powder Bed Fusion technique is Selective Laser Sintering which uses a laser to fuse powdered materials selectively, removing the need for support structures and enabling more design flexibility. Its capacity to build complex parts, its variety in material utilization, and its lack of requirement for support structures make it unique [32]. One type of Powder Bed Fusion technique that melts and fuses powder together in layers by either a laser or an electron beam is called Selective Laser Melting [33]. Lastly, one more Powder Bed Fusion technique is Selective Heat Sintering [4] [16]. Their characteristics are depicted in ***Table 2.*** This table may be helpful in choosing the best Powder Bed Fusion technique in light of suitable characteristics.

Table 2 *Characteristics of different types of Powder Bed Fusion additive manufacturing techniques.*

Technique types	***Energy source***	***Working conditions***	***Viable materials***
Electron Beam Melting	Electron beam [30] [34]	Vacuum [35] [34] [31]	Metal powders [30]
Direct Metal Laser Sintering	Laser [36] [37]	Inert gases	Combine metal powders [36] [32] [38]
Selective Laser Sintering	Laser [32] [39][40]	Inert gases [41]	Plastics, nylons, ceramics, and metals [42] [39] [40]
Selective Laser Melting	Laser [34] or electron beam [32]	Inert gases [43] [34]	Pure metal powders [32]
Selective Heat Sintering	Thermal printhead [44]	It may not require a vacuum or inert gases	Plastic powders [44]

3.2 Directed Energy Deposition

Directed Energy Deposition includes applying concentrated thermal energy — such as a laser, an electron beam, [16] or a plasma arc [32] — to fuse materials by melting them while they are being physically deposited. During the operation, a shielding gas — argon or nitrogen — is required to prevent oxidation [45]. This procedure provides for fine control over the deposition of materials, allowing complicated shapes to be created. The nozzle may travel in numerous directions and is not fixed to a certain axis [16]. Actually, this process needs relatively low cost and less time, but it has low accuracy, poor surface finish, and limitations for complex shape printing [46]. T

To begin with, some literature works could be seen to understand what has been done till now. For example, Salmi et al. noticed that the travel speed had less of an impact on porosity than powder mass flow rate and laser power [47]. In favor of this study, Kas et al. also found that increasing powder deposition density resulted in a decrease in porosity and an increase in strength. It was also observed that hardness variation was caused by different cooling rates at different height [48]. However, Zapata et al. found that the hardness of the produced pieces was unaffected by the varying deposition speeds [49]. Additionally, Guan et al. showed that the greater the laser scan speed, the more heterogeneous grain structure [50]. ***Table 3*** demonstrates the summary of their works.

Table 3 *Causing process factors of Directed Energy Deposition and their effects on fabricated samples.*

Causing process factors	***Effect on fabricated samples***	***Source***
Increasing powder deposition density	Decrease in porosity; increase in strength	[47] [48]
Different cooling rate	Hardness variation	[48]
Varying deposition speeds	Unaffected hardness	[49]
Greater the laser scan speed	More heterogeneous grain structure	[50]

Directed Energy Deposition may employ different material types [51] and some printing techniques. For materials, Directed Energy Deposition may be utilized with polymers and ceramics [52] [4] [16], but it is commonly employed with metals in the form of either powder or wire [4] [16]. While the powder is more exact owing to the nature of no preformed shape, wire is more material-efficient [15] [16]. Directed Energy Deposition can blend carbon fiber with polymer matrixes to produce composite materials that provide better strength-to-weight ratio products via reinforcement [53]. Apart from the ability to incorporate different materials, Directed Energy Deposition uses several additive manufacturing techniques. For instance, Laser Metal Deposition [16] uses laser radiation as an energy source, with argon and helium serving as inert gases to avoid oxidation. The method may successfully deposit materials such as stainless steel and possibly other highly reactive alloys [45]. Another technique is Laser Engineered Net Shape [16]. It uses a laser as an energy source, usually in an inert gas environment to avoid oxidation. It primarily processes metallic powders [54]. ***Table 4*** depicts their characteristics.

Table 4 *Characteristics of different types of Directed Energy Deposition additive manufacturing.*

Technique types	***Heat source***	***Working conditions***	***Materials***
Laser Metal Deposition	Laser [34] [45] [55]	Inert gases [34] [45]	Metal powders [55] or metal wires [56]
Laser Engineered Net Shape	Laser [34]	Inert gases [34]	Metal powders [54]

3.3 Material Extrusion

Material Extrusion involves purposefully distributing material via a nozzle or aperture to build up layers. In this technique, the material is introduced via a nozzle at constant pressure and in an uninterrupted flow. This pressure must be maintained stable and at a constant pace to ensure precise findings [15]. Material Extrusion is cost-effective and time-efficient while outcomes of finished parts have poor mechanical properties [46].

A great number of studies have been carried out on material extrusion. Lendvai et al. tried to determine the relationship between the extrusion multiplier — a process parameter that determines the volume of material pushed through the printer head/nozzle — and the different characteristics of fabricated parts. It was found that increasing the extrusion multiplier reduced porosity in 3D-printed parts. The association appeared to be linear in the investigation range. In addition to this, it was also observed that increasing the extrusion multiplier resulted in increased tensile strength of the fabricated parts. However, this relationship was not linear at all. Moreover, Thermal conductivity improved gradually as the extrusion multiplier increased [57]. Another two crucial process factors of Material Extrusion are built speed and layer height. Rafique et al. demonstrated that tensile strength and three-point bending strength improved as build speed and layer height decreased. But if the build speed was increased, it would result in a poor surface finish [58]. In addition to this, nozzle diameter has an impact on surface finish. Basak et al. showed that the smaller the nozzle diameter, the better the surface finish. However, it was also found that hardness and ductility were independent of nozzle diameter, layer thickness, and infill density [59]. Briefly summarize these studies in ***Table 5***.

Table 5 *Causing process factors of Material Extrusion and their effects on fabricated samples.*

Causing process factors	***Effect on fabricated samples***	***Source***
Increasing the extrusion multiplier	Reduced porosity; increased tensile strength; improved thermal conductivity	[57]
Decreased build speed and layer height	Improved tensile strength; enhanced three-point bending strength	[58]
Increased build speed	Poor surface finish	[58]
Smaller nozzle diameter	Better surface finish	[59]
Nozzle diameter, layer thickness, and infill density	No effect on hardness and ductility	[59]
Using waste thermoplastic	Lower durability	[60] [61]

Material Extrusion can incorporate a variety of materials and a few techniques. Materials could be polymers, composites, metals, and ceramic components [62]. To incorporate different materials kinds, many Material Extrusion techniques are needed such as Fused Deposition Modelling [16] [19] and Liquid Deposition Modelling [17]. Both are the most prevalent forms of Material Extrusion additive manufacturing. However, both are two independent techniques of Material Extrusion, each with its own set of properties and uses. Fused Deposition Modelling uses solid thermoplastic filaments that are melted and extruded to make three-dimensional structures [60], whereas Liquid Deposition Modelling employs a unique technology in which liquid ingredients are deposited, allowing for direct chemical alterations during the printing process [63]. While FDM is well-established and frequently used, Liquid Deposition Modelling offers intriguing potential for innovation in material science and customization. Fused Deposition Modelling, on the other hand, may remain the preferred choice for many industrial applications due to its maturity and reliability. ***Table 6*** represents the differences between these two techniques.

Table 6 *Characteristics of different types of Material Extrusion additive manufacturing.*

Technique types	***Material form***	***Solidification***	***Typical materials***	***Multi-color***
Fused Deposition Modelling	Solid filament [60] [64]	The molten substance is placed layer by layer and solidifies as it cools [60].	Use thermoplastic filaments [60] [64] which are melted and extruded through a nozzle.	Yes
Liquid Deposition Modelling	Liquid solution [64]	Layers of the paste are deposited via extrusion through a nozzle, followed by drying and curing.	Use a paste-like material composed of ceramics [65], woods [65], or photopolymers with a binder liquid.	Limited

3.4 Vat Photopolymerization

Vat photopolymerization is a process that uses ultraviolet (UV) light [15] [66] to create the chain of liquid light-curable resin molecules, and solidify the resin [67]. As the procedure employs liquid to construct items, there is no support for structure from the material throughout the process of building [16].

To commence with the literature, Valizadeh et al. noticed that process parameters influenced the mechanical and geometric properties of fabricated parts via Vat Photopolymerization [68]. In support of that proposition, Zhao et al. have proven that the incorporation of additives might enhance the mechanical properties of VPP-printed alumina ceramics. For instance, additives increased bending strength and fracture toughness in the study. Moreover, additives also mitigated the porosity, and improved crystalline quality [69]. Another study was carried out by Li et al. who demonstrated that higher curing depth ceramic samples showed better surface quality but less accuracy in shaping. Furthermore, the likelihood of cracks occurring increased as the cure depth increased [70]. Another crucial process parameter is temperature. Sameni et al. observed that by raising the process temperature, significantly lower viscosity of the photopolymer mixes was achieved. In the printing process, lower viscosity decreased separation forces and enhanced printability [71]. ***Table 7*** demonstrates the summary of their works.

Table 7 *Causing process factors of Vat Photopolymerization and their effects on fabricated samples.*

Causing process factors	***Effect on fabricated samples***	***Source***
Incorporating additives	Increased bending strength; better fracture toughness; reduced porosity; and improved crystalline quality.	[69]
Higher curing depth	Better surface quality; poor shaping; and increased crack likelihood	[70]
Raising the temperature	Lower viscosity; and enhanced printability	[71]

Only photopolymers materials [66] and limited techniques are suited for this Vat Photopolymerization. Although Vat Photopolymerization is unique for its high resolution and premium-quality results, very few materials can be employed for this process [46]. For techniques, both Stereo Lithography and Digital Light Processing are VAT photopolymerization sorts of additive manufacturing [16]. While Stereo Lithography uses laser beam to solidify the resin, Digital Light Processing employs a projector [72] [73]. In addition to this, Stereo Lithography creates objects point by point making the process slower [72]. In fillips Digital Light Processing builds the whole object at once, indicating that this process is faster [72]. ***Table 8*** shows the differences between them.

Table 8 *Characteristics of different types of VAT Photopolymerization additive manufacturing.*

Technique types	***Light source***	***Layer exposure***	***Build speed***	***Surface finish***
Stereo Lithography	Laser beam [72] [73]	Point-by-point [73]	Slower [72]	higher resolution and better surface finish [73]
Digital Light Processing	Projector [72] [73]	The entire layer at once [73]	Faster [72]	lower resolution and better surface finish [73]

3.5 Binder Jetting

The Binder Jetting technique involves two ingredients: a powder-based substance and a binder. The binder serves as the glue between powder layers. The binder is normally in liquid form, and the construction material is in powder form. A print head rotates horizontally along the x and y axes of the machine and deposits successive layers of the construction material and the binding substance. After each layer, the item being manufactured is lowered onto its construction platform [16]. It is a quick, simple, and cheap technique; nevertheless, resulted items can undergo shrinkage without infiltration [46].

Some researchers tried to identify some process-related insights for Binder Jetting. For example, Shahed and Manogharan observed that an increase in droplet velocity resulted in deeper penetration of the binder but reduced the area of spread. In addition, it was also noticed that an increase in droplet velocity resulted in a shorter spreading time [74]. Moreover, Suwanprateeb et al. and Zhang et al. found that bending and compressive strength were inversely proportional to layer thickness [75] [76]. Indirectly it relation was supported by another two studies. Enneti & Prough's study as well as Asadi et al. study obtained that decreasing layer thickness improved the precision and strength of manufactured components [77] [78]. On the other hand, increasing the number of printing layers led to longer printing times and higher manufacturing costs. Furthermore, Basalah et al concluded that a reduction in layer thickness significantly lowered the porosity [79]. Another important parameter is particle size. Miyanaji et al. highlighted that smaller particle sizes produced a superior surface quality and greater final densities following sintering. They also resulted in greater hardness in sintered components. In contrast, bigger particles increased surface roughness [80]. Another research by Wheat et al. pinpointed that printing with smaller particles improved density and reduced surface roughness, but increased shrinkage [81]. But shrinkage can be reduced by adding additives such as Nylon, according to Ziaee [82]. A summary of these scholarly works is illustrated in ***Table 9***.

Table 9 *Causing process factors of Binder Jetting and their effects on fabricated samples.*

Causing process factors	***Effect on fabricated samples***	***Source***
Increase in droplet velocity	Deeper penetration; reduced spread area; shorter spreading time	[74]
Increase layer thickness	Bending and compressive strength decreased	[75] [76] [83]
Decreasing layer thickness	Improved the precision and strength; lowered the porosity	[77] [78] [79] [83]
Smaller particles	Improved density; reduced surface roughness; increased shrinkage; greater greater density; greater hardness	[80] [81]
Adding additives	Reducing shrinkage	[82]

Binder Jetting can employ colorful materials but techniques are limited. This kind of additive manufacturing enables color printing and employs polymers, ceramics (foundry sand), and metals [16]. For techniques, both Powder Bed-Inkjet printing and Plaster-Based additive manufacturing are under this Blinder Jetting category [16]. PBIP uses an inkjet printhead to deposit a liquid binder onto a powder bed. The binder selectively binds powder particles together, forming a solid layer. This method is done layer by layer to produce a three-dimensional object [84] [85] [86]. On the opposite side of the coin, Plaster-Based printing is also a kind of Binder Jetting, it utilizes plaster materials, particularly for construction. But it does not require support materials, thus it is comparatively faster [87]. ***Table 10*** illustrates the differences between both techniques.

Table 10 *Characteristics of different types of Binder Jetting additive manufacturing.*

Technique types	***Material form***	***Build speed***	***Resolution***
Powder Bed-Inkjet printing	Powder	Relatively slower	Higher resolution and detail
Plaster-Based printing	Plaster powder	Relatively faster [87]	Lower resolution [87]

3.6 Material Jetting

In the Material Jetting category, material is jetted onto the construction surface or platform, where it hardens and the model is produced layer by layer. In other words, droplets are generated and positioned on the build surface in order to construct the item being printed, with subsequent droplets added to additional layers until the full thing has been built. In this style of additive manufacturing, the material is deposited from a nozzle that travels horizontally over the build platform. The material accumulations are then dried or solidified using ultraviolet radiation. Material Jetting is a quick additive manufacturing technique for colorful 3D creation; however, it suffers from exact color accuracy and uneven circumstances [88].

Some researchers already tried to find out relationships between process parameters and fabricated part's characteristics. To start with, Luna et al. found that drop spacing was the most significant factor controlling surface morphology [89]. Another study by Bezek et al. demonstrated that the ultimate tensile stress of components increased over time [90]. It was indirectly supported by the investigation of Puebla et al who depicted that the shortest time period resulted in the lowest ultimate tensile stresses [91]. However, elongation at break decreased significantly with time [90]. Adamczak and Bochnia noticed that ultimate tensile stress might not be affected by orientations [90] [92]. ***Table 11*** depicts the relationship between process parameters and specimen characteristics.

Table 11 *Causing process factors of Binder Jetting and their effects on fabricated samples.*

Causing process factors	*Effect on fabricated samples*	*Source*
Drop spacing	A significant factor in controlling surface morphology	[89]
Parts aging	Increased ultimate tensile stress; decreased elongation	[90] [91]
Orientations	Unaffected ultimate tensile stress	[90] [92]

In the Material Jetting technology, not only polymers are included but also waxes may be employed [16]. For techniques, Multi-Jet Modeling [16] and Drop on Demand [19] are instances of Material Jetting additive manufacturing. ***Table 12*** demonstrates the differences between them.

Table 12 *Characteristics of different types of Material Jetting additive manufacturing.*

Technique types	*Material deposition*	*Material types*	*Build speed*
Multi-Jet Modeling	Multiple printheads [93] simultaneously deposit multiple materials, including build material and support material.	Photopolymers, waxes, and other materials	Relatively faster due to simultaneous deposition
Drop on Demand	A single printhead [94] deposits material, often a wax-like substance, drop by drop.	Primarily wax-based materials	Slower due to sequential deposition of droplets

3.7 Sheet Lamination

When sheets of material are combined to make an item, such a method might be termed the Sheet Lamination process. In this procedure, two sheets are joined together constantly until the required object is constructed by either ultrasonic welding (for metals) or adhesive (for paper). Sheet Lamination provides opportunities for generating larger parts; however, it has low consistency of the surface and dimensional precision [46].

One study by Bhatt et al. noted that multi-material layers provided heterogeneous parts that may be adapted for individual purposes, increasing strength and usefulness [95]. Kanda et al. also wrote that the final product's mechanical qualities were affected by the materials used. For example, employing aluminum and polyurethane in laminated sheets could improve adhesion [96]. Moreover, Nyirenda et al. demonstrated that the total number of layers had a direct influence on the end product's mechanical strength and ductility. For instance, accumulative roll bonding of multilayer sheets had improved strength and microhardness due to smaller grain sizes [97].

Table 13 *Causing process factors of Binder Jetting and their effects on fabricated samples.*

Causing process factors	*Effect on fabricated samples*	*Source*
Multi-material layers	Heterogeneous properties of parts;	[95] [96]
Number of layers	strength and ductility	[97]

Both paper and metal are viable for this additive manufacturing category [16]. Laminated Object Manufacturing and Ultrasonic Additive Manufacturing are under the Sheet Lamination Process [4] [16]. ***Table 14*** presents the differences between them.

Table 14 *Characteristics of different types of Sheet Lamination additive manufacturing.*

Technique types	*Part strength*	*Material types*	*Surface finish*	*Bonding*
Laminated Object Manufacturing	Lower strength, suitable for prototypes and models	Paper [98]	Rougher surface finish	Glue [98]
Ultrasonic Additive Manufacturing	Higher strength, suitable for functional parts	Metal sheets or ribbons [98]	Smoother surface finish	Ultrasonic welding [98]

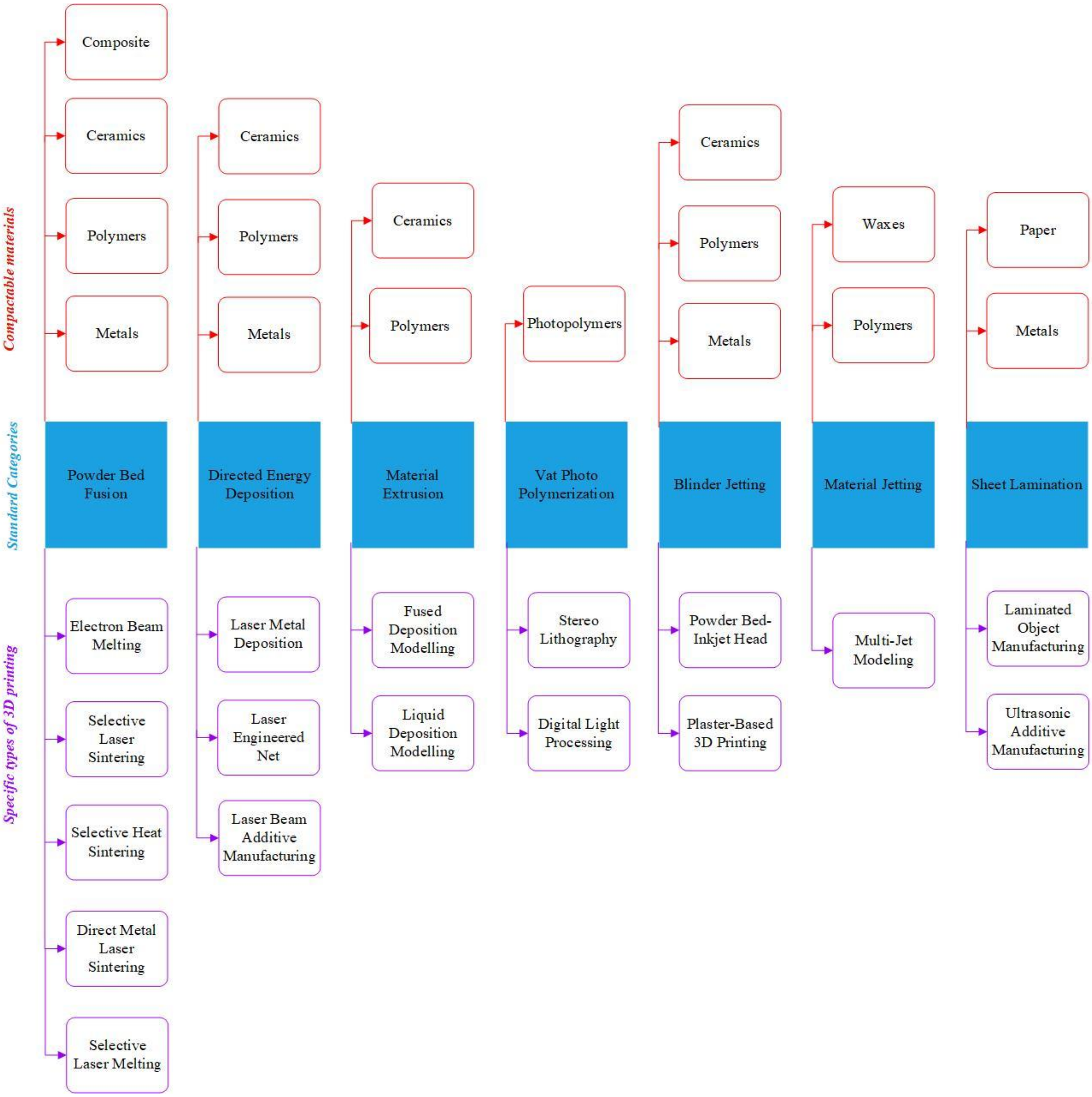

Fig. 2*: Seven categories of additive manufacturing, corresponding materials, and additive manufacturing types.*

Fig. 2 depicts all seven categories of additive manufacturing suggested by the ASTM F42 Committee. These seven categories are shown in indigo color in the figure. Additionally, corresponding usable materials for each broad group are shown in red color while the types of additive manufacturing under each major category are also demonstrated by the purple color.

4. Advantages and disadvantages of additive manufacturing technology

There are plenty of benefits and drawbacks to using additive manufacturing technology over conventional manufacturing.

There are several merits of additive manufacturing in comparison to traditional manufacturing. Generally, knotty geometrical shapes are difficult to fabricate by conventional manufacturing processes. However, the convoluted design components can be manufactured by means of 3D printers. Therefore, additive manufacturing gives the freedom of part design with full of complexity [99] [100] [101] [102] [103] [104]. Moreover, traditional manufacturing procedures would demand many iterative stages to be carried out like casting, rolling, forging, machining, drilling, welding, and so on, depending on the complexity of the objects. As you integrate more functions into a design, the number of these stages may expand rapidly. On the other hand, the number of processes and resources required might be greatly decreased when employing additive manufacturing [15]. Further, by being capable of printing a piece that is vacuous and has a thinner outer shell, which includes interior lattice structures instead of solid material all through, this drastically abates the quantity of material, weight, and build time [105]. So, additive manufacturing has the feature of building lightweighting parts [99]. Besides, even a very small adjustment in the design could result in a large increase in the time required to manufacture using conventional methods [106]. In contrast, it is also feasible to redesign parts utilizing component optimization approaches; this permits the structure to be improved with suitable durability to the cost ratio [105]. In addition, it has the potential to eliminate tolling [99].

Because it is an additive manufacturing process that does not require a cutting tool to subtract materials like a conventional manufacturing process. Additionally, the wastage of materials can be annihilated by the additive manufacturing method [107] because there is approximately no material waste during this process. Since there is nearly no waste production during the object creation, it is an eco-friendly approach [102] [103]. All of these benefits are illustrated in ***Fig. 3*** by a cause-and-effect diagram.

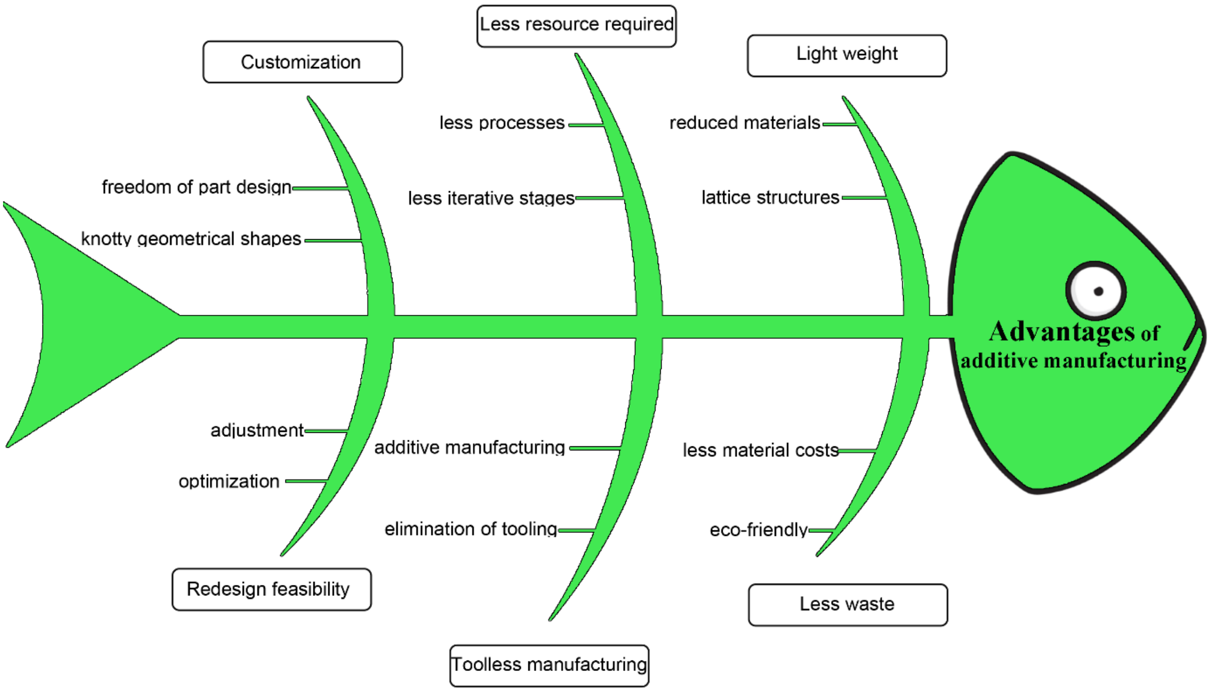

Fig. 3*: Demonstrating the merits of the additive manufacturing technology.*

By contrast, there are several demerits to the adoption of additive manufacturing technology in the manufacturing industry. These limitations hamper the use of additive manufacturing technology as a replacement for conventional manufacturing. Firstly, the use of additive manufacturing technology will lead to a decrease in the need for manual labor in manufacturing. This will have a significant impact on the economies of nations that heavily depend on a substantial workforce engaged in low-skilled employment [4]. Secondly, using additive manufacturing technology, individuals have the capability to fabricate a broad range of perilous objects [4] [108] including knives [4]. Hence, the utilization of additive manufacturing needs to be restricted exclusively to certain individuals in order to assuage undesirable actions [4]. Thirdly, anybody who gets a blueprint will have the ability to effortlessly produce counterfeit items. Because the simplicity of additive manufacturing technology lies in the process of drawing and inputting data into the machine, which then generates 3D things [4]. Fourthly, the capabilities of additive manufacturing technology are restricted in terms of the range of materials that can be used and the size of objects that can be built. Only a small number of materials can be processed and used to create the final goods [101] [103] [109] [110]. The 3D printer imposes significant constraints on the size of the object being built, such as limitations on the printing bed dimensions [103] [111] [112]. Fifthly, in some cases, certain components may require printing support during the additive manufacturing process, which necessitates cleaning after the printing operation has been completed [113]. Sixthly, it is viable for low-volume production compared to traditional manufacturing [103] [114]. Traditional manufacturing procedures, for instance, injection molding and compression molding, still dominate mass production [114]. It may be realized that the lack of repeatability [101] is one of the main challenges connected with additive manufacturing. Lastly, the quality of surface finishing on the 3D-printed items is not satisfactory enough due to layer-by-layer fabrication [115] [116]. This layer-by-layer production gives the components lower strength, precision, and gloss on the surface in some cases [58] [59]. All of these drawbacks are presented in ***Fig. 4*** by a cause-and-effect diagram.

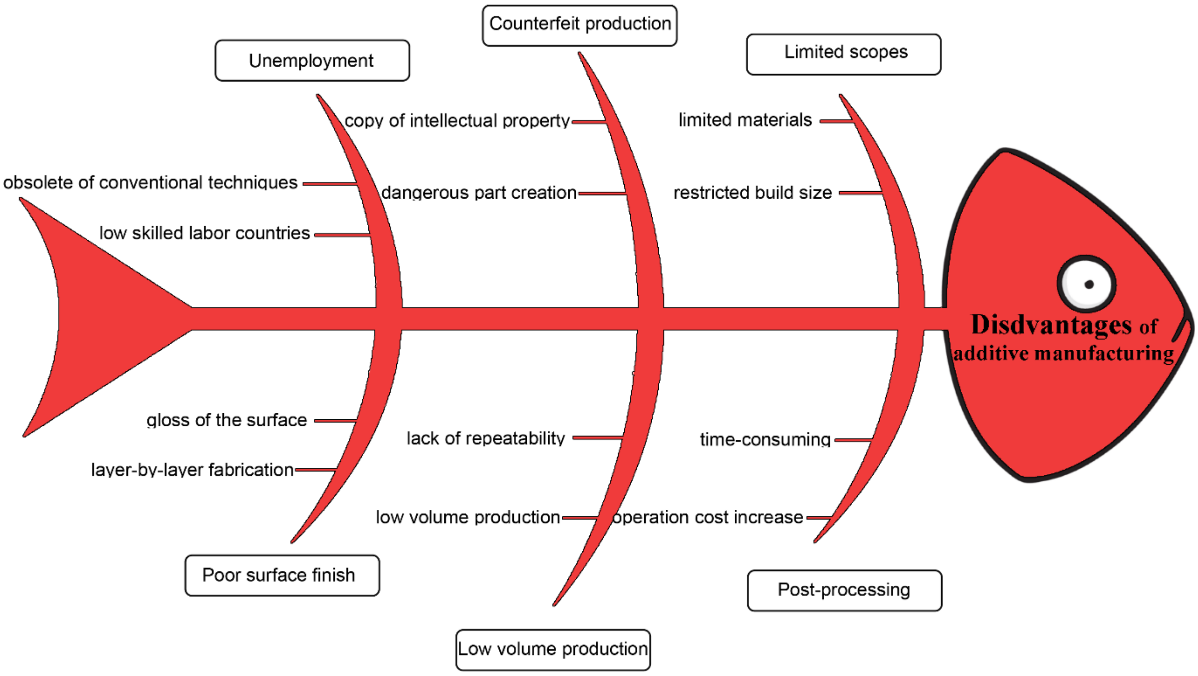

***Fig. 4**: Demonstrating demerits of the additive manufacturing technology.*

5. Application

There are many fields where additive manufacturing has been employed. Some of the fields are mentioned below:

5.1 Incorporating glass materials

One application of additive manufacturing is to use glass materials in order to build complex parts. From the literature review of glass-related works where additive manufacturing was conducted, it can be seen that there are some similarities and discrepancies among them. While Luo et al. [117] excluded the existence of air bubbles on the glass surface during numerical analysis, Fateri et al.'s [118] experimental study found some unexpected bubble-like spots on the created samples. However, Baudet et al. [119] depicted that air bubble-free specimens could be possible via additive manufacturing. Moreover, Luo et al. [117] assumed constant glass density with the changing temperature during numerical analysis whereas Fateri et al. [118] showed that fabricated samples had slightly less density than the raw materials — it is also supported by Baudet et al.'s investigation [119]. Fateri et al. [118] excellently explained the reason behind the low density of the fabricated parts was the presence of air bubbles, but there was no clarification from Baudet et al. [119] about how it was possible to get bubble-free components even though the parts had low density. Peters et al.'s work [120] could be a support to Baudet et al.'s study because bubble-free components were also produced by Peters et al.'s research [120] with an explanation — regulating the pool temperature was the key to eliminating porosities. Klein et al.'s [121] simulation result also indicated that controlling temperature was a primary factor for eliminating cracks. Additionally, Fateri et al. [118] concluded that fabricated components were comparable to traditional fused silica in light of findings of surface hardness although Datsiou et al.'s result [122] illustrated that additively manufactured components witnessed dramatically less flexural strength — the consequence of the existence of many porosities that triggered early fracture. Furthermore, Fateri et al.'s study [118] and Datsiou et al.'s investigation [122] both concluded that no crystallization occurred throughout the procedure and samples were amorphous. Samples' shape is related to energy absorption as shown by by Luo et al. in another study [123]. Besides these arguments, manufactured glass parts had pores and cracks that were noticed by Luo et al.'s work [117] and Datsiou et al.'s research [122]. It was reinforced by Baudet et al.'s conclusion [119] which depicted that optical polishing on the printed samples caused cracks. In contrast, Mader et al. [124] demonstrated that glass parts could be printed without cracks by the Material Extrusion technique, and good transparent glass components were also created. The same attempt — producing transparent glass parts — was made by two different works: Cooperstein et al. [125] could manufacture moderately translucent glass parts whilst Luo et al. [117] could not achieve it fairly see-through due to the presence of a lot of porosities inside the specimen. Luo et al. [123], however, wrote that a wire-fed additive manufacturing technique might produce glass items with an acceptable diaphanous optically and smooth surface was also noticed. Glass parts of Klein et al.'s exploration [121] could also fabricate transparent glass and smooth surfaces. In addition to attempting to produce transparent glass parts, both Mader et al. [124] and Klein et al. [121] demonstrated that multicolor glass components could be possible via additive manufacturing. Klein et al. [121]. Aside from this, gravity-fed glass parts creation was invented by Klein et al. [121] and further developed by Leung [126] for employing glass-like materials. Additionally, it should be mentioned that there were two kinds of computer-based simulation that could be applicable for robust analysis. One sort of simulation, the Finite Element Method, was utilized by Luo et al. [117] and by Datsiou & Ashcroft [127] whilst another type of simulation, Computational Fluid Dynamics, was conducted by Klein et al. [121]. Overall, it can be inferred that the factors behind all of these similarities and discrepancies are the tools and techniques that were selected for those studies. Therefore, tools should be chosen sanguinely when glass materials are supposed to be used in additive manufacturing.

5.2 Future space additive manufacturing

Another application of additive manufacturing is to advancement of future space manufacturing. To illustrate an example, Wang et al.'s work can be depicted where anti-gravitational additive manufacturing was undertaken to overcome the restrictions provided by gravity. It opened up new possibilities for additive manufacturing applications in settings where typical gravity-dependent technologies might not be possible, such as in outer space or moving vehicles. It was noteworthy to notice that magnetic force, when combined with a magnetic platform, allowed for the Fused Deposition Modeling additive manufacturing process to reach anti-gravity, suggesting the possibility of producing plastic parts through gravity independence [128]. In addition to the immediately stated study above, another work carried out by Gu et al. extended anti-gravitational additive manufacturing to the next stage. The study explored the impact of gravity and pressure on the Laser Metal Deposition process and the quality of metal components produced in space-like scenarios. Using Gambit and Ansys Fluent software, the research found that surface tension governed melt pool kinematics when gravity was lowered to empty or almost empty. The deposition anomaly became more noticeable as the gravity value declined. The study also explored the influence of pressure on deposition synthesis in a hypothetical space atmosphere with a lower pressure magnitude. It was found that lower laser power and higher scanning speeds could mitigate the impact of reduced pressure on deposition and reduce vapor generation [129]. Moreover, Huang et al. developed a Metal Droplet Deposition technology for space manufacturing, utilizing an anti-gravity electric field to regulate droplet trajectory for precision deposition. The technology used a droplet horizontal generator to produce and charge metal droplets, with computerized numerical control files for deposition routes and coordinate control. This droplet-based pioneer work paved the groundwork for an applicable additive manufacturing approach in space, as it allowed droplets to precisely form on vertical substrates and solidify into norm morphologies under the control of the anti-gravity electrical field [130]. Furthermore, Zocca et al. conducted research on microgravitation additive manufacturing using 316L stainless steel powder. They used a Laser Beam Melting system to melt the powder in a specific pattern for a wrench part. The microstructure of the final product showed complete melting with low porosity. The technique could produce parts with uniform quality independent of the gravitational environment [131]. In addition, Waddell et al. conducted a study on Computed Axial Lithography (CAL) as an In-Space Manufacturing (ISM) technology, testing its performance in various reduced-gravity environments, including simulated Lunar and Martian gravity and microgravity [132]. Now the question is: where may humans employ these additive manufacturing technologies in the near future? The moon might be that initial place since it is the Earth's only natural satellite. Therefore, additive manufacturing under lunar gravity seems to be very engrossing. While commercial manufacturing methods are already well-engineered under normative circumstances — gravity and atmosphere—on Earth, additive manufacturing under lunar gravitational settings has only been studied to a very limited extent. Thereby, Reitz et al. investigated the feasibility of additive manufacturing under lunar gravity and microgravity circumstances, specifically focusing on the selective melting of regolith simulants — these are synthetic lunar soils — using a laser-based process [133]. Additionally, Lotz et al. developed a methodology for conducting research on additive manufacturing processes under microgravity conditions using the Einstein-Elevator facility. The method allowed for quicker tests and improved the number of tests completed in a day compared to conventional drop towers. Initial tests focused on Laser Metal Deposition procedures, examining gas environment and substrate-free additive manufacturing. Results showed that layer bonding could be achieved with correct process changes, and efficiency was assessed in terms of speed and accuracy. The research emphasized the potential of substrate-free additive manufacturing for space-based component production [106].

5.3 Conducting biodegradable materials

One more impressive use of additive manufacturing is to conduct biodegradable materials. To begin with, Zeidler et al. demonstrated the use of renewable biobased materials in additive manufacturing, specifically for packaging delicate components. They used locally available waste materials like wood flour, miscanthus particles, fruit stone flour, rice husk, and seashell powder, which were converted into powder and stabilized with a binder. This study demonstrated the applicability of renewable resources in additive manufacturing [134]. In addition to this, Morales et al. created bio-composite filaments using recyclable polypropylene and rice husks, with varying fiber content ratios [135]. Moreover, McLaughlin et al. conducted research using polylactic acid as a competitor to petroleum-based materials. They combined polylactic acid with wood flour to evaluate particle species, size, and concentration in biopolymer and additive manufacturing performance. The results suggest wood floors could improve bioplastics and maintain sustainability [136]. Besides these scholarly works, Estakhrianhaghighi et al. conducted a study integrating cellulose-based compounds into a biobased polymer, polylactic acid, reinforced with waste wood fibers. The study enhanced mechanical properties, reduced composite coupon density, and introduced an excellent cellular composite for additive manufacturing [137]. Instead of wood fibers, Kariz et al. studied wood powder in adhesive combinations for additive manufacturing, determining optimal mixtures using extrusion forces and bending strength. However, wood-based bulk materials have weak mechanical characteristics, making them unsuitable for structural applications [138]. Additionally, Le Duigou et al. developed fine wood fill filament for Fused Deposition Modeling of wood fiber-reinforced biological composites. The study found that printing orientation and printing width significantly impact mechanical characteristics, including high porosity, water absorption, and swelling [139]. Further, Tao et al. developed a bio-composite filament using polylactic acid and wood flour, enhancing deformation resistance and lowering early thermal breakdown temperature, particularly for Fused Deposition Modeling [140]. Apart from employing biodegradable materials, optimization of process parameters was also needed to utilize the materials. Therefore, the study by Lyu et al. aimed to optimize additive manufacturing machine parameters for biodegradable materials, focusing on printing speed, nozzle temperature, platform temperature, and layer thickness. The research revealed ideal additive manufacturing products had the lowest porosity, best interlayer adhesion, and increased yield strength and elongation at break [141]. Moetazedian et al. conducted a study on the mechanical performance of additively manufactured polylactide specimens during degradation at different temperatures. They found no deterioration in mechanical or thermal properties after 8 months, with crystallinity being the most influential factor during early degradation [142].

6. Conclusion

This paper successfully shows eight common additive manufacturing processes: CAD model, STL conversion, file transfer to machine, machine setup, building the parts, removal of the parts, post-processing, and application. In addition to this, the classification of additive manufacturing proposed by the (ASTM) F42 Committee is also depicted. All seven categories are discussed and corresponding sub-categories are also compared in order to help future research to select them easily. Relevant materials and sub-groups are arranged under a graphical representation in a way that will allow readers to understand each category in a better way. Moreover, the advantages and disadvantages of additive manufacturing are also displayed in this article. Eventually, three impressive applications of additive manufacturing have been upheld from the literature: using glass materials, future space manufacturing, and conducting biodegradable materials in additive manufacturing.

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