Master Thesis

Marketing and potential application review of Large-Scale Additive Manufacturing

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Abstract

Since its advent, additive manufacturing (AM) has grown steadily and found applications across all types of sectors. While the great development of such technologies has improved the quality of prints and expanded the availability of materials, AM still has some limitations regarding its physical scaling. This work will present the state-of-the-art of large-scale additive manufacturing and subsequently greater attention will be given to extrusion-based 3D printing. Specifically, we will discuss about large scale additive manufacturing (LSAM) especially pellet extrusion.

The subject of this thesis is the presentation of innovations in the area of Fused Granulate Fabrication for Large-Scale Additive Manufacturing (LSAM), covering state-of-the-art multi-material printing combined with the use of sophisticated materials and embedded functionalities. The wide variety of covered materials comprises biodegradable plastics, bio-based thermoplastics, advanced thermoplastics, MIM granulates, ceramic-infused composites, and foamable granulates-all uniquely suited to different applications based on industrial needs. These materials now make it possible to create lightweight, high-performance, and sustainable construction, with the growing market demand for greener and functionally superior components in aerospace, automotive, and healthcare sectors.

Keywords Large scale additive manufacturing, Fused granulate fabrication, BAAM, LFAM, Pellet extrusion, Multi material printing

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Preface and acknowledgements

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Akhil Eldho

Acronyms and abbreviations

BAAM: Big area additive manufacturing

DED: Direct energy deposition

DLP: Digital light processing

FGF: Fused granulate fabrication

FFF: Fused filament fabrication

LFAM: Large format additive manufacturing

LSAM: Large scale additive manufacturing

MIM: Metal injection molding

MJ: Material Jetting

PBF: Powder bed fusion

SLS: Selective laser sintering

1 Introduction

Imagine a future where all it takes to replace a broken part is to download the file and choose "print". Because of the capabilities of additive manufacturing, this reality won't be far off. Often referred to as 3D printing, additive manufacturing, or AM for short, has revolutionized numerous industrial areas. Additive manufacturing is a manufacturing process used in the product development process. Commonly denoted as 3D printing, additive manufacturing (AM) is defined by the standard ISO-ASTM 52,900:2021 as “the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies [1].It can be used to manufacture prototypes, tools, and fully functional parts. Additive Manufacturing (AM) has the potential to completely reshape the manufacturing space by removing the geometrical constraints of commercial manufacturing and reducing component lead time, especially for large-scale parts. AM could be divided into seven process methods by the ISO/ASTM 52900-15 standard: binder jetting, direct energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization (ASTM 52900-15). In recent decades, additive manufacturing (AM) processes have grown enormously, allowing parts with excellent dimensional and surface finish qualities, paving the way to applications in aerospace, automotive, medical, and dental, electronics, military and defense, architecture, furniture, and construction. On the other hand, limitations still exist regarding production of large parts: commercial 3D printers have low print volumes, less than 1 m3 with low deposition rates [2]. Since 2012, it has become clear that low build speeds and technical limitations tend to limit additive manufacturing to produce exclusively small parts[3]

Beyond only plastics and metals, the fascinating discipline of additive manufacturing is redefining what's possible by embracing materials like food, concrete, and even living cells. This thesis explores a small segment of this topic: Combined market and potential application review for LSAM.

1.1 Emergence of Large-Scale Additive Manufacturing

Large-scale additive manufacturing (LSAM) is a significant leap in 3D printing technology. While traditional additive manufacturing has primarily been used for prototyping and the manufacture of smaller components, LSAM expands the technology's capacity to create far larger and more complicated structures. This trend towards LSAM has been fuelled by advances in both materials and technology, allowing for the manufacture of large-scale industrial components and even whole structures.

The capacity of LSAM to create items in dimensions that were previously thought to be unfeasible for 3D printing is one of its primary differentiators. By employing cutting-edge materials such as metals, composites, and high-performance polymers, LSAM systems may construct products with improved durability and structural integrity. Larger sizes and more complex designs are no match for these machines' capabilities, which enable highly customized industries including construction, automotive, and aerospace.

The adoption of LSAM grows very fast due to its efficiency and versatility. Compared to most traditional manufacturing processes involving a considerable amount of tooling and material wastage, LSAM can manufacture big parts directly from digital models, hence reducing waste by optimizing material usage. This becomes beneficial in sectors where sustainability and resource efficiency are increasingly critical. Besides drastically reducing waste, LSAM ensures lead time reduction and supply chain optimization through on-demand manufacturing. Large-format components could now be fabricated closer to the location of end-use in many industries, thus negating the need for extended logistics and storage arrangements.

1.2 Market Context of Large-Scale Additive Manufacturing (LSAM)

Large-scale additive manufacturing, or LSAM, is experiencing significant growth in the industry due to its potential to revolutionize industries like aerospace, automotive, construction, and energy. The global market for big, complex, and customized components is expected to increase significantly as more businesses use LSAM in their manufacturing processes.

Market estimates put the Additive Manufacturing market at an astonishing total of $18.5 billion in sales revenue by the year 2024 [4]. Such unprecedented growth is mainly driven by the growing need for functional parts in a variety of industries. While there are many advantages to AM, there are still significant challenges with scaling the technology efficiently to produce large-scale components. This issue remains one of the main barriers that must be overcome if the full potential of this new manufacturing process is to be fully realized. Among the greatest and most ascribable benefits of LSAM lies in the tremendous potential uptick in sustainability achieved by manufacturing processes. This advanced and innovative form of additive manufacturing, popularly referred to as AM, does not waste much material, since the layer-by-layer building technique it adopts optimizes the addition of material in a manner that is literally only in the place where it is needed. Despite such advantageous benefits derived from LSAM, significant challenges and obstacles regarding the effective application of this advanced manufacturing technology remain to be surmounted. The quality of product is supreme, as is the speed of manufacturing. Balancing these two paramount factors can be an intricate task. Besides, cost effectiveness is a crucial consideration. Even though AM saves significant amount of money by waste reducing and simplifying the assembly, these advantages must be weighed against the investment required for large-scale 3D printer. Small-scale AM is proven successful. But, for large-scale there is question whether the result can be replicate like small scale potentially involving more, advanced materials. LSAM's viability depend on scalability, repeatability, and reliability [5].

1.3 Project Scope and problem statement

The primary focus of this thesis is analysis of large-scale additive manufacturing technologies, with a particular emphasis on the significant commercial potential that these technologies provide, as well as their numerous applications across multiple industries. Such a review will help in highlighting not only its historical evolution over the years but also major technological developments that have taken place in this period of time. It will further delve into those key applications that have emerged within the industry as a direct result of these remarkable developments. Particular attention will be given to multi-material printing, from industrial plastics and composites to soft granulates such as silicone and TPU, to the newer class of materials such as MIM granulates. Besides, research will go deeper in technologies for printing foams currently under development in the VITAL EU project.

The thesis will also explain how such components will be integrated during printing, including but not limited to electronics, sensors, and positioning mechanisms. It will involve techniques like printing on conductive beds by applying materials capable of conducting electric current to the surface of an object, embedding components directly within printed structures for enhanced functionality, and placing elements on top of printed parts with precision with the intent of forming more complex assemblies. Further, several post-processing techniques will be evaluated in detail, such as chemical treatment, mechanical finishing, and coating. This is essential for full understanding of how these processes affect the quality and performance of the final product. Finally, this paper deals with research into advanced concepts related to future production line ideas, factory models that integrate LSAM technologies with state-of-the-art post-processing capabilities aimed at boosting efficiency and enhancing the quality of the manufactured products. This is the central challenge being tackled in the research: how to scale

LSAM for multi-material and functional componentry in an industrially efficient manner while ensuring quality, sustainability, and cost-effectiveness.

2 Literature review

2.1 Theoretical Background

The ISO/ASTM 52900-15 standard categorizes AM technology into two groups based on its application level: rapid manufacturing (RM) and rapid prototyping (RP), with seven process methods. RM technology relates to the manufacture of finished goods. RP technology involves creating prototypes, mock-ups, and models to evaluate product capabilities and create production processes. In the late 1980s, AM technology was referred to as RP owing to its limited use of materials and process methods, resulting in lower produced quality [6]. The history of AM technology developments and description of the seven process types are explained in the sections below.

2.1.1 History of Additive Manufacturing

Otto Munz's 1956 publication of "Photo-glyph recording" was a pioneering notion in AM. The process involved exposing produced objects to actinic radiation and immersing them in a vat of photoactive material to form solid layers at the air/liquid interface.

In 1986, patents for comparable concepts were filed in Japan, France, and the United States within weeks. Charles Hull's patent from the USA gained widespread recognition. This technology was "Stereolithography" (SLA), which is regarded as the father of AM. Charles commercialized the first AM equipment, the "Stereolithography apparatus 1" (SLA), utilizing SLA technology. (Hull 1986.) In 1987, the STL file format is introduced by the company where Charles was employed. This technology enables connection between the AM machine and CAD. Over the next decade, new additive manufacturing methods like "selective laser sintering" (SLS), "power bed style printer," "sheet lamination" (SL), "fused deposition modelling" (FDM), "material jetting," "binder jetting," and "direct energy deposition" (DED) were introduced to the market. Table 1 shows the precise year of invention and who developed each technology. In the 2000s the AM technology significantly improved with enhanced capability and widened processable materials of desktop printers of DLP, FDM, SLA, and SLS. This led to a 2018.) significant cost drop, reaching the public in 2011.

Table 1 History timeline of AM technologies (adapted from Hull 1986; Molitch-Hou 2018; Munz 1956; Pollack et al. 2019,1-2).

Year	Technology name	Developer
1956	Photo glyph recording	Otto Munz
	Stereolithography	Charles Hull
1986	Stereolithography apparatus - 1 stereolithography file format STL	Charles Hull from Ultraviolet
	Selective laser sintering	A patent from Carl Deckard and Joe Beaman. Cooperation of Helisys, Cubital, DTM
1988	Powder bed-style metal 3D print	A patent from Frank Arceclla
1989	3D printing process	A patent from the Massachusetts Institute of Technology (MIT) group
1991	Sheet lamination	Company Helisys first introduced to the market
1992	Fused deposition modelling	Scott crump patent
	Selective laser sintering	Introduced in the market
1993	Material Jetting	Commercialized and invented by Solid scape
	Ink Jetting	Sanders developed
	Binder Jetting	MIT invented
1996	Binder Jetting	Commercialized by Z corporation.
1997	Direct energy deposition	Frank developed at John Hopkins University
2011	Desktop machines began to reach public appeal	
2016	Rise of low-cost Stereolithography and Digital light processing	
2016	Wide variety filaments could be printed on a desktop machine	

2.2 Various AM techniques for Large-scale Additive Manufacturing

This section covers the common AM processes for large-format printing. The main three process we are focusing are vat photopolymerization, powder bed fusion, binder jetting, Direct energy deposition (DED) and material extrusion. This section will discuss the benefits and drawbacks of additive manufacturing techniques, including scalability, throughput, material selection, and pricing.

2.2.1 VAT Photopolymerization

Vat photopolymerization is an AM technique that required to use the liquid resin that contains photoactive polymers stored in vat or container. When a build platform is submerged in resin, the object being printed is progressively lifted out of the liquid.

Vat photopolymerization includes two major techniques: Stereolithography and Digital Light Processing. These cover a class of additive manufacturing that makes use of photopolymer resins to build objects layer by layer. SLA relies on a laser that, by curing with accuracy, solidifies liquid resin in a layer-by-layer fashion. On the other hand, DLP uses a digital projector; it can expose an entire layer of the object at once, thus fastening curing and production. The VAT Photopolymerization process initiates when the build platform is submerged in the VAT of liquid resin. The platform incrementally rises as printing proceeds, allowing additional layers of the resin to be set by light exposure. This solidifies each layer in precise conformance to the digital model, enabling the object to build incrementally.

The benefits of VAT photopolymerization include highly detailed, intricate precision, right down to fine finishes. It enables versatile materials with photo-active resins that can be tailored to specific uses. With efficient layer-by-layer curing, the process can exhibit higher productivity rates over most AM methods. Vat photopolymerization can be made in a large scale: it can be scaled from low volume to high-volume production. It allows geometrical complexity, which many other conventional methods struggle with, and it results in very minimal post-processing. A further important property is multi-material printing realization that combines different materials within one print. This versatility is therefore particularly important for use in manufacturing or prototyping in the aerospace, automotive, and medical industries.[7]

The main challenges faced by vat photopolymerization are heat management, which constrains print speed and size. There is fewer material options compared to other techniques. Proper curing depth is a must; under-curing impairs the adhesion of layers. Environmental factors such as sensitivity to light and temperature affect the results of printing. The operational cost is higher due to the setup and material costs. The equipment is expensive and challenging to handle. Health risks due to uncured resins demand strict safety measures.

Digital Light Processing (DLP) has become a common technique in large format printing, and this is the variation of vat photopolymerization which, instead of the scanning laser beam, uses a projection system. DLP entails using a digital micromirror device (DMD) to project a full digital image onto the resin vat, thereby polymerizing the entire layer at the same time, which means it is faster than laser-based methods [8]. However, the resolution of DLP printers and the possibility of larger build space are highly dependent on factors such as micromirror size, number, and lens quality. A large magnification can harm resolution and reduce UV light intensity, leading to an increase in resin curing time.

DLP is one of the problems faced by the manufacturers in that they need to take a peel step to release the print from the bottom of the vat, which is transparent and that brings the entire process to a slow. An alternative solution was CLIP (Continuous Liquid Interface Production) which was developed using an oxygen-permeable membrane through which a "dead zone" can be made where the rest of the part receives continuous exposure. Nonetheless, print speed is also limited by curing time and resin flow rate. To have resin in a steady supply and to prevent voids that might affect the print's integrity is the key to guaranteeing that a 3D Model will be printed successfully. This kind of constraint, pursuant to the printing parameters and the apparatus design requires close mediation with an emphasis on the matter of uniform resin dynamics, by which structure breakage in the final product is eliminated[9], [10]

Future research in vat photopolymerization has been looking into these challenges: how to provide increased printing speed, material variety, and scalability. Innovations such as nonreactive mobile liquid interfaces tackle heat management for efficient large prints with high complexity.
In conclusion, vat photopolymerization is a key additive manufacturing technology known for its precision and versatility, despite some operational and material challenges.

2.2.2 Powder bed fusion

Powder bed fusion includes Selective laser sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM). SLS is the most common one to fabricate polymer parts. These techniques operate on a common operating principle: a thin layer of powdered material-comprising but not limited to plastic, metal, and ceramic-is evenly spread on the build platform. Then, heat input by a laser or an electron beam normally scans the surface according to the cross-section of the part under printing. Powder particles are melted and fused together during this process. After that, the build platform drops, more powder is spread, and so on, layer by layer, until the portion is completed. The finished product is revealed by blowing off the unfused powder.

The PBF approach can be said to have several major advantages. Most compellingly, is the fact that it manages to make the part with an excellent surface quality and is well detailed enough to be aesthetically attracted and functional enough to perform the specific function required, thus, it becomes an ideal choice in a lot of precision, aesthetics and functional applications, which can be attributed to the truth of its producing parts with great surface quality and resolution that can be convenient for many different types of precision, aesthetics, and functionality. This is also due to the fact that the process is also able to be carried out on a broad collection of matter in many different places. One of the most salient strengths of PBF is its ability to fabricate parts with complex geometries and internal features, most of which may not require support structures. Hence, extensive post-processing for surface finish enhancement will be at a minimal. Further, parts made through PBF are usually strong and fully dense, making them ideal for demanding applications requiring high mechanical performance.[11]

There are currently limited numbers of large-format PBF printers with build volume exceeding 1 m3 in the market. In 2010, EOS launched EOS P 800, which offers a build size of 700 × 380 × 580 mm [34]. GE Additive came up with the in 2015, which has a build size of 800 × 400 × 500 mm. In 2019, Trumpf introduced the TruPrint 5000, providing a build size of 300 × 400 mm. Recently, in 2020, SLM Solutions released the NXG XII 600 with a build size of 600 × 600 × 600 mm

Considering everything and scaling up powder bed fusion (PBF), selective laser sintering (SLS), to be exact, as one of the problems is insufficient research on other ways it can possibly be done. One of the most significant difficulties is to get the laser beam to be uniform. The laser incident angle is the main factor to determine electrical energy density. Different energy densities across the laser spot nose from different incident angles [12]. It resulted in the wider and deeper melt-pool that could be taken by the scan direction versus the beam elongated path. Research has presented that when the incident angle is greater (18°), the elongated laser beam enlarges the interaction cross-section to the tune of +6.7%, meaning the energy density falls off by up to -6%. Lower energy density thus can result in a lack-of-fusion of the metal and surface roughness increase because of the small laser zone and almost no energy at a high angle of incidence to the laser beam.

Because the print bed size is larger for a build rate, and it is hard to reach the optimal incident angle when the light source is placed far from the bed. However, such a decision is no longer practical because additional vertical space is required which makes the achievement of the necessary precision in the vertically displaced Galvano mirrors more difficult. The above-mentioned factors are the reason the scaling of PBF systems is a complicated issue and emphasize the necessity for in-depth investigation in this field.

One of the main problems with selective laser sintering (SLS) at a large scale is related to material consumption, and most of it has to do with either using a high quantity of powder or the powder's limited reuse [13]. In SLS, the total layer must be filled with powder, if only a small portion is sintered, causing the material to be used inefficiently. It leads to the production of the huge amount of unused powder and thus the increase of both material waste and production costs. The reusability of the powder is also limited because of thermal degradation, which changes its properties; particle size and surface characteristics which have a negative impact on sintering and thus print quality.

Moreover, the technology of SLS expands energy management. Bigger powder beds need preheating, maintaining of temperatures throughout the process even for the unused powder, thus the energy consumption and operational complexity increase further. Despite these challenges, PBF remains one of the leading techniques in the field of additive manufacturing due to its ability to produce high-quality parts from a variety of materials. Continuous research and technological advancements are being pursued to improve the scalability and efficiency of PBF.

2.2.3 Material Jetting

Material jetting (MJ) is an additive manufacturing method that was initially based only on the selective polymerization of liquid photopolymers. While Material Jetting (MJ) has gained popularity in the large-scale additive manufacturing (LSAM) related niche, it is a technology that was used mainly for the quality selective polymerization of liquid photopolymers for finer and more detailed parts. The use of the MJ method within the framework of the LSAM context can help achieve ultimate precision along with high multi-material capacity. It, on the other hand, will make possible the production of very large forms that would not have otherwise been producible, as MMA could custom design very interesting visual aspects. The fact that MJ can be scaled up by the same method of jetting more colours at the same time, therefore, the product can be integrated with different functions and aesthetics within the sole build. Also, the key feature of MJ, the droplet deposition technique of inkjet printing, will ensure the uniform distribution of material in the same time promptness and high resolution even in larger parts. Challenges also exist in material turnout and post-processing, which include the detachment of support structures and the further curing of the model. These drawbacks get bigger as the size of the part grows as well. In addition, MJ's ability to combine different colours cannot be overlooked despite its requirement for a cured surface being a major cause of concern for designers[14].

Recently, Material Jetting (MJ) has been introduced also for the addition of metal, which is kind of a big step in the large-scale additive manufacturing business. This is the utmost advanced process where a controlled molten metal splash is placed directly at a heated printing platform, while the material solidifies and fuses with each other to produce metal parts. It is a strategic way of manufacturing the parts and, hence, it can give birth to components with mechanical properties that often perform better than their cast counterparts due to the droplets-controlled deposition and solidification. The possibility with MJ is getting the fine resolution and material density in metal parts gives the prospects for manufacturing in industries like aerospace, automotive, and heavy machinery, where precision and performance are critical. In addition to that, using this technology for large-scale applications is faced with the necessity of comfort related to the material throughput, and the heat management, and the integration of complex geometries. Nevertheless, the use of MJ in the processes of the creation of metallic parts remains the liking of Newcomer Industries as it brings into the venture the potential for the rapid production of intricately shaped molds which could help in saving a phase and reducing manual labor.[15]

Some examples of large-scale devices based on MJ technology are the “Massivit 1800” and “Massivit 1500” from Massivit 3D (Israel) Mimaki’s (Japan) “3DGD-1800¨ [16]. These use a technology called gel dispensing printing (GDP), a combination of FFF and SLA, in which a nozzle dispenses an acrylic photopolymer gel that is quickly hardened by ultraviolet light. The “TKF 9000” from Titomic (Australia) [102] uses the Titomic Kinetic Fusion® (TKF®) to manufacture metal parts. In the TKF® process, the metal particles are injected into a jet stream which accelerates them. The particles exit the spray nozzle and, upon colliding with the surface, they plastically deform, sticking to the surface and each other.

2.2.4 Binder Jetting

One of the first LSAM technologies to be developed was Enrico Dini’s D-Shape (2006). This technology is like the inkjet powder bed method, where a binder is selectively sprayed on the printing material. The binder and sand chemically react to form a sandstone material which creates 3D parts. Surplus powder that is not a part of the structure acts as a support to the structure and once the printing process is completed, it is removed.[17]

Nowadays the leaders of large format binder jetting printers are two companies: Voxeljet AG (Germany) and ExOne (United States), recently acquired by Desktop Metal. Both provide sand 3D printing equipment and are widely used for the production of industrial casting molds. Voxeljet AG has developed the “VX 4000, the largest industrial 3D printer for sand molding worldwide, with a build volume greater than 8 m2. The “S-Max Pro” from ExOne (Germany) has a lower build volume: 1.26 m3 and is compatible. with a variety of metal, ceramic and composite materials. The systems offered by the two companies are quite similar and differ only in terms of technical specifications, such as resolution, speed or the presence of more than one print chamber (as it is for ExOne) [17], [18].

2.2.5 Direct energy deposition (DED)

There are various examples of LSAM machines which use DED processes to produce metal 3D printed parts. There are three types of technologies that use Direct Energy Deposition (DED) which can be applied in LSAM:

- **Electron-beam additive manufacturing** (EBAM) is one in which the raw material fed is usually in wire form, and the electron beam, under a vacuum, is applied for welding the layers together. The fact that deposition is controlled by an electron beam ensures that the production of quality metal parts with superior mechanical properties is achieved. EBAM lending itself to large-area manufacture features faster build rates with less wastage of material compared to other traditional methods.

- In **Laser deposition welding** (LDW) the metal powder is fed through a nozzle onto the surface of the component where a laser creates a molten weld pool. Then, the powder is fused to the substrate to form a solid metal layer upon cooling. The accuracy with which material can be deposited makes the technique especially suited to repair work, coatings, and the making of complex geometries. LDW also allows the deposition of material onto existing components, a process which provides much flexibility in both part design and modification.
- **Wire arc additive manufacturing** (WAAM) works by melting metal wire using an electric arc as a heat source. The process is controlled by a robotic arm and the shape is built on a base plate from which the part is separated once the process is complete. The wire, when melted, is extruded in the form of beads on the substrate. As the beads stick together, they create a layer of metal material and the process is then repeated until the metal 3D part is complete. [17]

2.2.6 Material Extrusion

One of the best-known techniques for 3D printing, also known as fused deposition modelling (FDM) or fused filament fabrication (FFF), is material extrusion. The process involves the creation of three-dimensional objects by melting and depositing successive layers of molten material, mostly thermoplastics, through a nozzle. In the 3D printing of materials by extrusion, a solid filament of material is fed into the printer, which subsequently passes through a heated nozzle [19]. The filament then melts in the nozzle, making it mobile and is then used to build a layer of the build platform or a previously printed layer. The extruded material paves the way for quick cooling and solidifying formation of a strong bond between the layers. Using a layer-by-layer method, one can create complex geometries and a combination of designs.

One of the major advantages of material extrusion is its versatility. It is good to note that a wide variety of thermoplastic materials can be used in this process of material extrusion. Each has a unique property like strength, flexibility, and heat resistance offered by them. The very nature of the technology used by material extrusion makes it fit for the uses of applications with a wide range of diversity such as prototyping, product development, and even end-use part production. Besides, it is worth mentioning that material extrusion 3D printers are quite cheap and easy to find, so they are suitable for beginners, small businesses, and big companies. The procedure is very straightforward while the chance of using different technologies has made it a widely demanding and advantageous technology among the different sectors

- **FFF vs Fused Granulate Fabrication (FGF)**

Fused Filament Fabrication (FFF) process is the main method established and universally accepted as an industry standard due to its relatively low capital and material costs. Development of large-scale FFF 3D printers such as the WorkCenter 500 developed in cooperation with Oak Ridge National Laboratory (ORNL) and 3D Platform (3DP) keeps them at the cutting edge of the fabrication technology. The printer has a huge build volume of 1400 × 2800 × 700 mm [20]. It can produce very large parts and that is its advantage.
One of the drawbacks of traditional FFF is very low material deposition rates--a product of the head speed, acceleration, and extrusion diameter that are more or less within the range of 0.1 to 0.5 mm. This, in turn, limits the material deposition to less than 0.5 kg/h for smaller and less voluminous 3D printers. ORNL scientists decided to develop a high-throughput filament extruder with 6-mm filament and achieved an output rate of 3 kg/h. They have solved early filament melting and bridging issues by using a larger infeed, an extended barrel, and an air-cooling system, but more work still needs to be done on the torque at higher velocities.

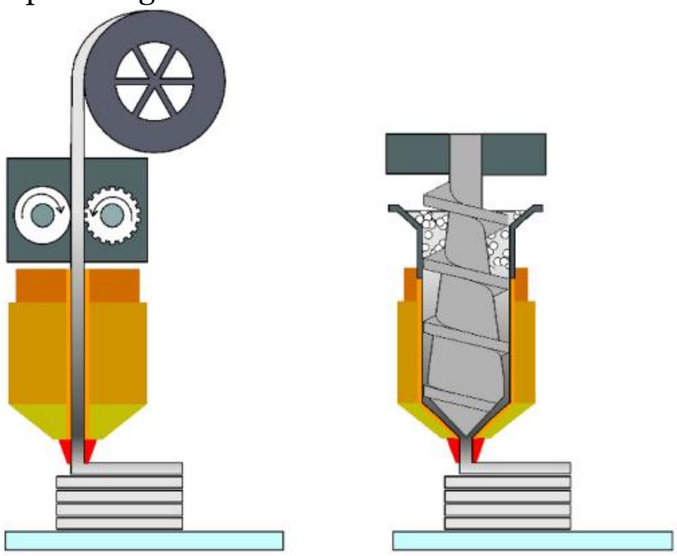

Figure 1 On the left, the FDM operating diagram, on the right, the pellet-based operating diagram

To maximize the throughput, the application of large-scale material extrusion in the production of pellets has become very popular. These systems speedup the deposition stage, thereby making the whole printing process more efficient as it is performed on a large scale. The combination of Fused Granulate Fabrication (FGF) and 3D printing has brought development to the surface, which can be done with flow rates up to 200 times faster than traditional filament materials. Some studies have concentrated on the use of plastic pellets for 3D printing, with Venkataraman building a screw extruder 3D printer that is compatible with polypropylene (PP), polyethylene (PE), and polystyrene (PS) as the materials [21]. In another piece of work, they carried out the investigation of plunger 3D printers for polymer pellets. This entailed the analysis of various topics like material degradation, fuse continuity, product scale, and surface precision. Table 2 shows some of the commercially available extruders with their respective specifications on material throughput.

Different types of extruders have been created for varied scales of production wherein most people prefer single-screw extruders because they possess size and weight advantages which increase their agility while printing, yet twin-screw extruders afford better mixing as well as compounding particularly for fiber-reinforced polymers despite limited scope to 3D printing. According to researchers at ORNL, “twin screw extruders are usually designed for powdered thermoplastics instead of pellets leading towards increased operational costs with complicated conveying processes”. Also, another drawback is that these devices require a melt pump to ensure precise regulation thus adding mass, expense plus intricacy into it. Also, conveying systems become more elaborate; thus, making them less cost effective due higher costs associated with them like transportation cost among others. For instance, researchers based at ORNL warned us that twin-screw extruders generally utilized in powdered thermoplastics but not in pellets driving operational expenses higher than normal [22]. Besides this, additional burdens of weight and price as well as increased intricacy come from twin screws’ necessarily attached melt pumps. The horizontal installation of twin-screw extruders may diminish X/Y area used in printing while vibrations during printing may misalign or break screws. The flow rates range from 1 to 80 kg/h and the temperatures can go beyond 450 °C for these ones which make them suitable for big-sized prints particularly if we are talking about such fine manufacturing materials as PEEK. So, they are well-suited for large-scale operations that require efficiency alongside productivity.

Table 2 Commercially available extruders for LSAM

	Model	Weight (Kg)	Max temperature (◦c)	Available nozzle sizes (mm)	Max flow (kg/h)
Dyze Rev3rd	Pulsar RD-	7	500	1.0,3.0,5.0	3
	M10	18	500	2.5-10.0	12
	RD-M25	40	500	3.0-12.0	25
	RD-M40	90	500	2.0-20.0	50
Massive Dimension	MDPE 2	8.4	450	.4-4.0	0.9
	MDPE 10	14	450	1.5	5.7
	MDPE 50	59	450	-	22.7
Extrudinaire		1.2	500	0.2–4.2	0.3
Weber	AE16	-	450	-	2
	AE20	-	450	-	4.5
	AE30D	-	450	-	20
CEAD	E25	<29	450	2-18	12
	E40	<70	450	4-24	40
	E50	165	450	8-20	84

3D printing through pellets not only allows mixing of material during the printing process but also the possibility of printing functionally graded materials (FGMs). FGM materials utilize less expensive material that has lower mechanical performance throughout most of the printed part and then designs in higher performance materials in specific areas which optimize cost, weight, and mechanical performance overall. Sudbury conducted research themselves on analyzing material transitions within the extruder using Thermogravimetric Analysis (TGA). They found that at 100 RPM, the extruder required 32 seconds or 2.43 meters of material to initiate extrusion, and a further 1.52 meters before the extrusion material was in a steady state condition with the second material. Brackett J presented their own dual-hopper system (Figure 2) for multi-material printing using a rocker that allowed for easy material transitions [23], [24] . Their system switched between hoppers by closing off the material feed tube feeding the first hopper and opening the feed tube for the second hopper. While this system has controlled material composition for the transitions initially, transitions between carbon fiber reinforced ABS and neat ABS showed visible differences between Layers 1 and Layer 20, which proved to be irreversible for each layer. They also asserted the direction of the material transitions would prove to be useful for predicting behavior. Additional work is required to improve the control over material composition within the transitions. Table 3 provides a list of materials that have been used in FGF LSAM.

Figure 2 dual-hopper system on the MDF's BAAM-B

Table 3 List of available materials in FGF LSAM

Materials	Suppliers
CF/ABS	Techmer Engineered solutions, INEOS
PLA, PP, ABS and PET	Nature Works LLC, McDonnough Plastics, Northwest Polymers and CiorC
PEEK 90G and PEEK 450G	Victrex®
TPU (Shore hardness 25A- 65A)	Kraiburg TPE (Waldkraiburg, Germany)

Pellet printing also faces several challenges: unstable material transfer leads to problems such as "bridging", air entrapment during plasticization, and uncontrolled oozing out from the nozzle. All these reduce product quality. While using shredded recycled plastics, it has been observed that the mass flow rate decreases with an increase in the printing speed. They also noted that, at low temperatures, extruder interruptions and stalling occurred, leading to failures in printing. Engineers proposed a double-stage screw extrusion mechanism for these purposes [25]. Here, the larger first-stage screw is used to melt, convey, and pressurize the material, while the smaller second-stage screw acts to provide additional plasticization and melt control. Meanwhile, pressure control is conducted in real time by pressure monitoring and adjusting the first-stage screw speed through a pressure sensor. It also has a vent hole to release entrapped gases to avoid bubble entrapment.

However, due to the first extruder being placed horizontally, the available print area reduces. The issue with material retraction that leads to oozing or stringing during printing is tackled by systems like the retraction mechanism from Extrudinaire, which allows for quick lifting and lowering of the screw. This offers a high level of precision and control. Overall, pellet-based extruders provide a very high deposition rate, cost-effectiveness, material versatility, and support of sustainable practices by using plastic waste as feedstock.
Pellet-based extrusion allows for significant material cost savings in comparison with filament extrusion, including avoiding many common problems such as filament runout. The pellet-based extrusion technology is also said to be capable of more than two orders of magnitude improvement in production speed and reduces the energy consumption per kilogram of material by about the same margin compared to filament-based extrusion. This makes pellet extrusion an overall better and more cost-effective solution for large-scale additive manufacturing from both throughput and energy efficiency standpoints.

3 Process parameters development for LSAM

Material extrusion is based on a few core technologies: the most common is Fused Filament Fabrication, mainly for applications requiring small build volumes, but the larger-scale printing has been dominated by pellet-based extrusion technologies. While FFF had been a mature and well-understood process, pellet-based technologies are of relatively recent origin and come with a different set of challenges and opportunities that merit further exploration.

Pellet-based 3D printing doesn't use preformed filaments, it uses raw plastic pellets. It boasts advantages such as lower material costs and increased production rates, rendering them ideal for large-format parts. This technology, however, is still up-and-coming; hence, in-depth research is needed in order to improve the existing challenges and stabilize the process. Material deformations, along with layer delamination, may come along with printing process issues, mainly in large-format applications. Such defects have compromised both structural integrity and aesthetic quality. Further development of the material formulation and processing techniques is needed. Similarly, pellet-based extrusion requires deep knowledge of the thermal and rheological behaviour of materials to achieve a reliable, quality print. Optimization of printing parameters, including temperature of extrusion, rate of deposition, and bonding between layers, must be conducted in research studies toward further improvement in mechanical properties with minimal defects. With these challenges, there is tremendous scope expansion open in pellet-based extrusion technologies for material extrusion technologies in industrial and architectural applications [26].

3.1 Rheological behaviour

Understanding the rheological behaviour of materials is important to define the optimal process parameters in material extrusion, including extrusion temperature, screw speed, and fibre composition. Indeed, a lot of research has been performed to characterize the rheological properties for different types of printing materials, such as acrylonitrile-butadiene-styrene (ABS), polyphenylene sulfone (PPSU), polyetherimide (PEI/ULTEM), polyether sulfone (PES), polyphenylene sulphide (PPS), polyetherketoneketone (PEKK), and polymers like polyester and vinyl ester[27] .

All these studies were concerned with the addition of reinforcing fillers, such as carbon fibres and glass fibres, to investigate their effect on the rheological properties and Tg of the materials [28]. In fact, by adding these fibres, researchers try to improve the mechanical properties of materials while understanding their influence on the flow and behaviour under heat and shear conditions.

In addition, most of such studies have focused on the determination of extrusion temperature limits beyond which polymer degradation may occur-a factor important for material integrity considerations. The effects of temperature variation and different shear rates on rheological behavior were also examined in order to determine appropriate conditions for the process. These will be very useful in developing better and more reliable material extrusion processes, especially those related to applications requiring advanced composite materials.

3.2 Mechanical properties

The poor mechanical properties and anisotropy of 3D-printed parts in industrial applications are some of the major challenges to wider adaptation. This anisotropic behaviour may be identified by the variation of tensile and compressive strengths along the horizontal and vertical directions, respectively. It is related to the microstructure inside the layers of deposited material and at its boundaries. Traditionally, low-temperature thermoplastics have been used in material extrusion processes, such as polylactic acid, acrylonitrile–butadiene–styrene, and polycarbonate. While these materials are sufficient for prototyping, parts printed with them show limited strength and elongation; therefore, their application in functional usages has been restricted [29].

In recent years, along with the development in materials science, new 3D printing materials have been developed, among which include nanomaterials, composites, biomaterials, smart materials, and even fast-drying concrete. High-performance technical polymers such as ULTEM, polyphenylene sulphide (PPSF), nylon, polyether ether ketone (PEEK), and polyetherketoneketone (PEKK) have been developed, offering superior mechanical, physical, and thermal properties compared to conventional extrusion materials.

Research has also shown that adding fibres to polymer pellets significantly improves mechanical properties, while this method heightens anisotropy, as noted by ORNL and TES. Specific studies comparing BAAM extruded materials with injection-moulded material samples, and research involving carbon fibre-reinforced PPS for LFAM, show this to be the case.

Original solutions to anisotropy include the use of a "Z-Tamping" system. This process system compacts every deposited bead to minimize the formation of voids and increase interlayer cohesion, which reduces porosity and increases mechanical strength. The Z-Tamping system incorporates an air-cooled platen vibrating at about 20 Hz which serves to flatten deposited layers. The effectiveness is increased further when this is used in conjunction with IR lamps that warm deposited layers to just above their Tg before the deposition of subsequent material, as shown in Figure 3. This thermal optimization further enhances layer adhesion and overall integrity of the part [30].

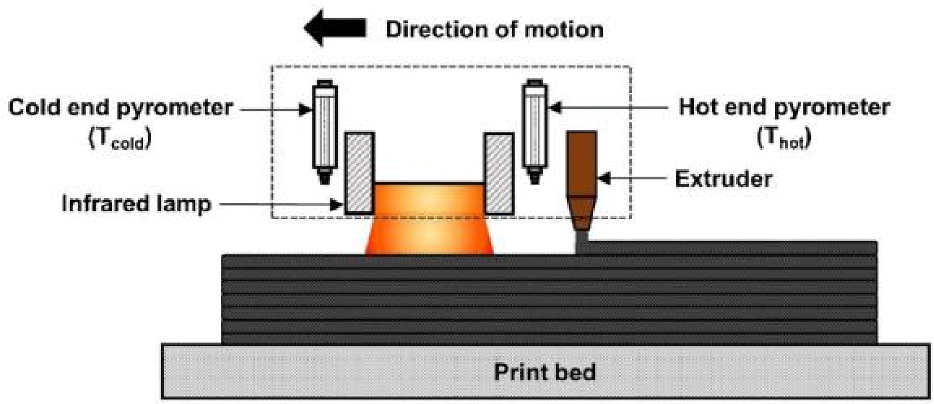

Figure 3 Scheme of the experimental setup including IR lamps

3.3 Delamination and distortion control

In the case of thermoplastic 3D printing, material is deposited layer by layer, and each layer is placed upon the previously cooled one. As the extruded material cools below its glass transition temperature, it naturally contracts. However, this contraction is impeded by the underlying cooled layer, causing interlayer stresses that might build up with each consecutive layer, leading to deformation and delamination [31].

Among the most influential factors are those referring to deposition time per layer and maximum horizontal dimensions of the part. The complications above are especially critical for large-format additive manufacturing (LFAM) processes. Different computational modelling techniques have been proposed for predicting residual stresses, deformation, and damage or delamination, allowing the possibility for process optimization.

One method of minimizing delamination is to heat the print bed to at least Tg and perform the process in a closed chamber. This is quite normal for smaller systems, but larger systems are much more difficult to adapt this technology to. Large, heated chambers have also been known to compromise system flexibility and/or involve complicated temperature uniformity control. Substrate temperature also needs to remain below a certain value to avoid substrate deformation as new layers are deposited.

Adding carbon fibres to the polymer pellets has developed as an effective strategy for the reduction of distortion. CF reinforces thermal retention in deposited layers, thereby eliminating the stringent requirement for a heated chamber and reducing stresses that may induce cooling. Thermal analyses have indicated that CF enhances the extrusion temperature, maintaining the layers warm for extended periods and ensuring better layer adhesion.

Another consequence of reducing the layer deposition times is a mitigation of thermal distortions. This can be attained by increasing the extrusion rates or employing continuous toolpath algorithms for minimizing interruptions in extrusions. One alternative approach is real-time optimization of deposition time based on predictions of surface temperatures of the parts printed to maintain thermal stability and minimize any deformation.

3.4 Porosity control

Porosity affects both FFF technology and, on a larger scale, pellet-based technology: the deposition of oval beads involves the formation of triangular voids between adjacent beads, this phenomenon can significantly degrade the mechanical bond and reduce overall performance of the printed part.

Furthermore, as previously highlighted, the addition of fibers has several advantages but increases internal porosity. This may be because, contrary to what happens in FFF where the fibers align with the direction of the tool path, this does not happen in the pellet-based process, in which the fibers maintain a random orientation in the deposited material.

As mentioned, a “Z-Tamping” system has been used on LFAM devices to reduce the porosity. This system forces the deposited beads into nearby pores while it is still warm and pliable, resulting in a more uniform deposit surface [17].

3.5 Geometric and surface qualities

Various challenges are related to surface quality and dimensional accuracy in large-format additive manufacturing. In particular, single extruder dependence leads to the complication of support structure removal and generally poor surface finishes due to the significant bead size and high layer height used in these processes.

Improvement in surface quality and dimensional precision depends on a painstaking optimization of process parameters. Key factors include layer thickness, printing speed, melt flow, and the pressure inside the extrusion cylinder. While adjusting parameters improves matters, post-processing is often required to achieve a good enough surface finish: "Milling or more elaborate processes, as was done in the case of the 3D-printed Shelby Cobra". The actual post-processing in this case involved machining and sanding the vehicle body, followed by filling, polishing, and painting to refined finish.

One such solution for these challenges would be the use of a nozzle that can print at two resolutions. Along with this concept, a mechanism known as a "Positiverter" can further refine the accuracy of extrusion by reducing the error in start-stop during printing; hence, defects are minimized as shown in Fig. 4.

The other factor causing surface roughness is the "sharkskin" phenomenon, which results in a matte or uneven finish. It is associated with conditions related to the structure of the polymer matrix, flow rate, and temperature. This phenomenon in most research findings is linked closely with the onset of viscous-elastic transition at larger shear rates, necessitating stringent process conditions in order to reduce its effects.

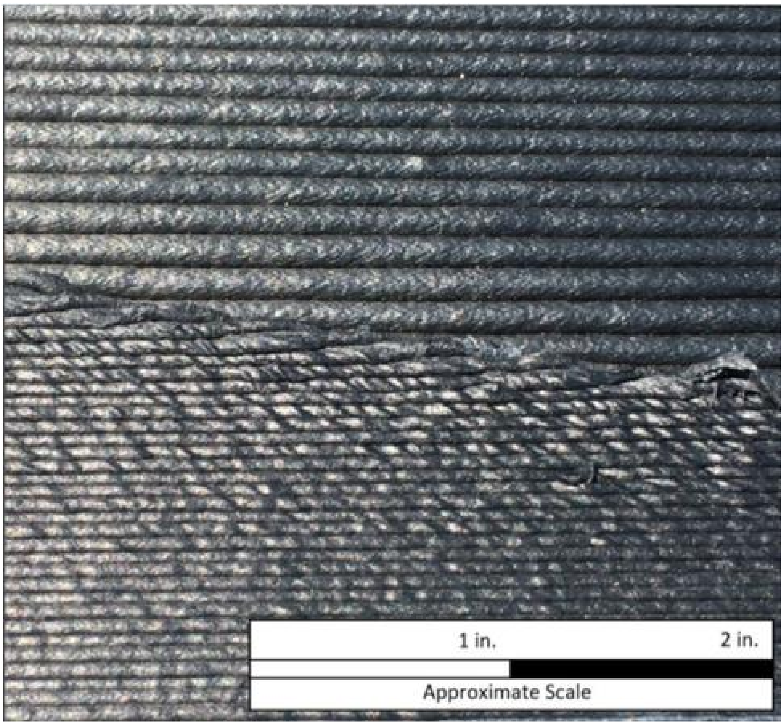

Figure 4 Print with different resolution [32]

4 Materials used in LSAM

Large Scale Additive Manufacturing (LSAM) using Fused Granulate Fabrication (FGF) technology can utilize a wide range of materials, offering versatility and customization options for various applications. The material spectrum in LSAM by FGF is wide and serves various industrial needs. Among these, industrial granule includes ABS, PLA, and PC, which are some of the widely used materials for their strength and good processability. Soft granules, like thermoplastic elastomers and TPU, have been applied for functional parts, requiring flexibility and resistance to impacts. These have granules of Metal Injection Molding (MIM)-mainly composed of polymer-bonded metal powders that allow the creation of complex, high-strength metal parts after debinding and sintering. The composite granules reinforced by carbon or glass fibers enhance strength and thermal properties, while specialty materials such as recycled plastics contribute to the sustainability of the FGF process.

4.1 Industrial Plastic and composite hard granules

In LSAM, industrial plastic granules and composite hard granules form the basis of the manufacturing process for the mechanical, thermal, and structural properties of printed components. The selection of materials is performed in view of their processability, performance characteristics, and application-specific requirements.

- **Industrial plastic granules**

Industrial plastic granules like **ABS, polycarbonate, and polyetherimide (PEI/ULTEM)**, are also common in LSAM because of their strength and ease of processing. The thermal stability, accuracy in dimension, and mechanical strength make these thermoplastics suitable for tooling, prototyping, and functional end-use parts. High-performance polymers, for example, **PEEK** and PEKK, are usually used in aerospace and automotive industries owing to their great strength-to-weight ratio and resistance against high temperature and chemical agents.

Industrial plastic granules are finding their essential place in the FGF process owing to their easy availability, economic viability, and diverse material properties in LSAM systems. Granules based on different thermoplastics like ABS, PC, PA, and PEEK are prepared to fulfil specific application needs. Due to these properties, the mechanical strength, thermal resistance, and durability of these granules have made them very important in the manufacturing of large format, high-performance components.

In the process of multi-material LSAM, industrial plastic granules enable the fabrication of components with material properties that vary in space. Such a possibility makes it realistic to combine high impact-resistant materials like ABS with such ones as PC, providing better thermal behaviour, thus accomplishing functionality related to a set of operating conditions. Equally, high-temperature thermoplastics, such as PEEK or polyetherimide (PEI), are also usually combined with other polymers, thus generating lightweight strong components for aerospace and automotive tooling.

With the Fused granulate fabrication, many advantages are accrued through this granule-based approach: significantly reduced material cost and supportive of faster deposition rates for higher flow rates in pellet extrusion systems. This enables multi-material deposition-manufacturing with gradients, wherein a component transitions from property to property in stiffness, flexibility, or thermal conductivity smoothly over its course within a structure.

Yet, the challenges have remained concerning the uniform adhesion between layers and the material shrinkage/warpage. Large differences in thermal and rheological properties may result in a poor bonding or accumulation of residual stresses that can reduce mechanical integrity of the final part. In-situ thermal control, robotic deposition, and adaptive extrusion are under investigation for the resolution of these problems. Overall, industrial plastic granules are essential for the development of multi-material FGF LSAM and hold enormous innovative possibilities for the fabrication of complex shapes of high-performance components.

- **Composite granules**

Composite granules are different classes of plastics whose primary reinforcement **includes carbon fibres and glass fibres**. These reinforcements substantially raise the tensile strength, stiffness, and thermal conductivity of the material. Carbon fibre-reinforced composites will be applied to realize lightweight and high-strength materials, while glass fibre composites provide a balance of strength, impact resistance, and cost-effectiveness.

Composite hard granules represent one of the advanced material developments for large-scale additive manufacturing using a recently developed class of FGF-based processes. These granulates, made from a basic composite matrix of thermoplastic matrices such as polypropylene, polyamide, and polyether ether ketone, are combined in various ways with carbon fibres, glass fibres, and ceramic particles. After reinforcing, these composites obtained great strength, stiffness, and durability, and proved excellent for structural applications including, but not limited to aerospace, automotive, and even general industrial tooling. The resulting composites exhibit outstanding strength, stiffness, and durability, hence finding applications as structural material in aerospace, automotive, and industrial tooling.

In multi-material LSAM, composite granules make possible the building of parts with tailored material properties. For instance, carbon fibre-reinforced PEEK provides great thermal stability along with lightweight for aerospace tooling, while glass fibre-reinforced PA gives toughness and wear resistance to automotive parts. With these granules, softer or more flexible materials can be combined in one build to create functionally graded structures, like rigid outer shells with interiors that are flexible.

Unique challenges exist regarding deposition of composite hard granules. Mechanical performance could be altered through anisotropy provided by the alignment of fibre during the processing, in addition to abrasive wear associated with extrusion systems. Indeed, ensuring high interlayer adhesion for composites, along with multi-material prints from other material sets, often requires well-matched control of the processing parameters along with in-situ thermal management. Considering all the present challenges, composite hard granules play a cardinal role in extending the possibilities of the LSAM manufacturing concept to high-performance components offering multi-functionality and having superior mechanical and thermal properties.

4.2 Soft Granules

Soft granules, due to their flexibility, elasticity, and impact absorption capability, are one of the most important material classes in FGF and LSAM. Soft granules are indispensable for all applications that require material pliability, cushioning, or energy dissipation. Thermoplastic polyurethanes are among the commonly used soft granules owing to their excellent elasticity, abrasion resistance, and durability.

Examples of these applications include important components like seals, gaskets, shock absorbers, and protective coverings used extensively in different fields. Thermoplastic elastomers, better known as TPEs, are valued above all for their unique capability of associating rubber-like flexibility with the ease and efficiency of thermoplastic processing. This great characteristic allows them to be used in different applications, such as soft-touch grips, medical devices that require comfort and functionality, and flexible joints that have important functions in many industrial applications. Other soft granules, like

LDPE and EVA, absorb impact and have found uses largely in the footwear industry, erosion controls, ergonomic products, and packaging.

Moreover, silicone-based thermoplastics, although less common, find use in high-heat resistance and biocompatible applications such as medical-grade components and soft robotics. These materials are particularly advantageous in multi-material printing, where they complement rigid materials like carbon-fiber-reinforced polymers. This combination allows for hybrid structures, such as automotive parts with flexible zones that absorb shocks or tooling with regions of damping, furthering functional design capabilities. However, soft granules are tricky to process in FGF. Their lower melting points and tendencies to deform require that temperature, speed, and cooling rates of extrusion are carefully controlled. Optimized nozzle designs and tailored print paths are required to preserve the mechanical integrity and surface quality of the printed components. As soft granules find more and more applications in multi-material printing, they allow for the realization of innovative designs combining flexibility with rigidity and will further extend the boundaries of large-scale additive manufacturing applications.

4.3 Foams

Foaming of thermoplastics results in more sustainable, lighter, and less expensive components for a variety of commodity and engineering applications. This is while the foamed structures encounter less shrinkage and better dimensional stability due to the lower material input.[1] On the other hand, foamed products have better weight-related properties, such as specific impact strength and toughness, compared to their solid counterparts. Foaming could also offer significant thermal and acoustic insulation properties. Noticeable improvements in the specific properties can be achieved by controlling the cellular structure.

Due to their lightweight and cost-effectiveness, cellular thermoplastic foams are considered as important engineering materials. On the other hand, additive manufacturing or 3D printing is one of the emerging and fastest growing manufacturing technologies due to its advantages such as design freedom and tool-less production. Nowadays, 3D printing of polymer compounds is mostly limited to manufacturing solid parts. In this context, a merged foaming and printing technology can introduce a great alternative for the currently used foam manufacturing technologies such as foam injection molding

- **Classification of Polymer Foams**

Thermoplastic foams can be classified based on their cell size, foam density, and cell structure. Based on the cell size and cell population density, the thermoplastic polymer foams are divided into conventional, fine-celled, microcellular, and nano cellular foams.

Figure 5 shows the classification of polymer foams based on their cell size and cell population density over time. Microcellular polymer foams, that is, foams with cell size less than 30 µm and cell density in the range of 109–1012 cells/cm3, have been widely commercialized in industry to manufacture products for various commodity and engineering applications.

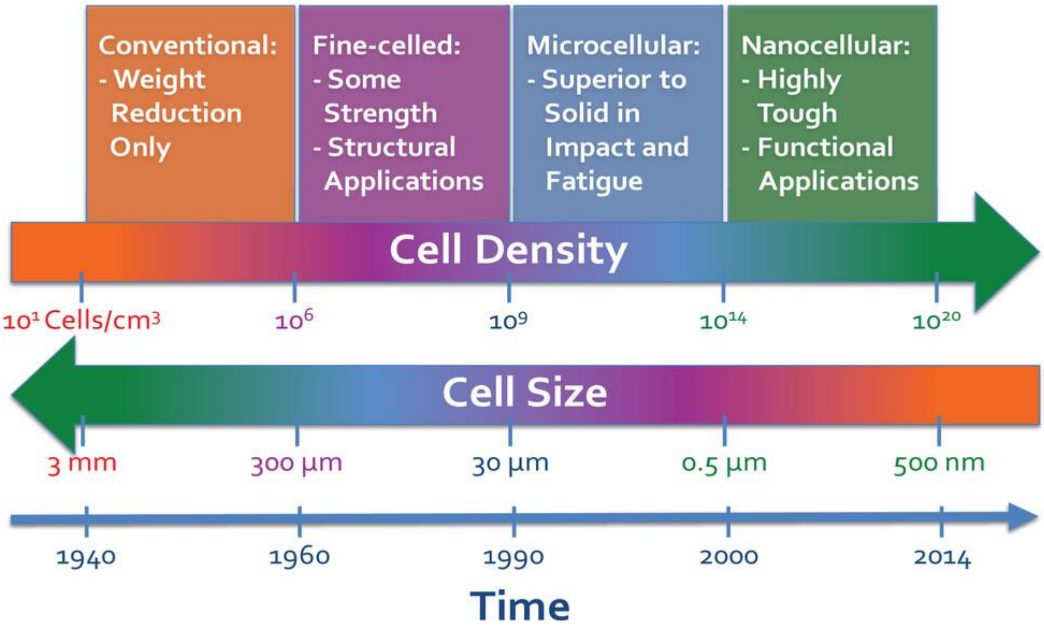

Figure 5 Classification of polymer foams based on their cell density and cell size over time.

Thermoplastic polymer foams can also be categorized based on their cell structure whether they are open-cell or closed-cell. Open-cell foams are interconnected structures, while closed-cell foams contain no openings between their cell walls. Since each of these structures provides different properties, they can be incorporated in various applications. For instance, open-cell foams are utilized in sound insulation or filtering applications whereas closed-cell foams are used for structural applications or heat insulation.

FGF additive manufacturing from foam material has been the key to a game change for the design principles of lightweight parts, optimizing material usage while integrating functionality into the parts. These foams are prepared either with the help of granulate additives or gas-generation methods to obtain structures that reduce material weight with maintained strength. In this regard, such innovation holds particular importance in multi-material printing, where hybrid functionalities are crucial for many uses across industries such as aerospace, automotive, and construction.

In FGF, the usual foam materials are thermoplastics like polypropylene, polyethylene, polystyrene, and thermoplastic polyurethane. Materials are normally foamed in a controlled way during the extrusion process with the help of either chemical foaming agents or physical foaming agents. The CFAs decompose at a particular temperature, releasing gases such as nitrogen or carbon dioxide and thus initiating foam. Conversely, in PFAs, inert gases like nitrogen or supercritical carbon dioxide are directly introduced into the polymer melt for a foamed structure. Both techniques have very tight control over density, cell size, and mechanical properties in the final product. Granulate additives play an important role in improving foam qualities in the FGF process.

Nucleating agents in the granules bring improvement in the homogeneity of bubbles, which ensures uniformity in the cellular structure throughout the whole printed component. Further, composite granules with reinforcements, like carbon or glass fibres, enhance mechanical properties of foam materials quite substantially. These advanced foams have especial relevance in multi-material printing, where they can be combined with solid polymers to produce lightweight cores with load-carrying shells, as is already shown in both aerospace and automotive applications. The use of gas-generated foams adds another dimension to the capability of FGF: the ability to dynamically modulate gas infusion during extrusion to achieve gradient structures with different densities in one component. This is especially useful in multi-material configurations, where it is now more feasible to integrate areas of different properties into a single, cohesive unit. In a given case, foam sections can be used for insulation or cushioning, while rigid polymer sections become the structural supports. The addition of foam materials to FGF has not been without its challenges, however. The important technical challenges are to maintain consistent cell size, minimize defects, and ensure good layer adhesion in foam-rich areas. Scaling up LSAM processing of foam would, therefore, require advanced nozzle designs and tight process control. Segmented heating, fine-grained extrusion parameters, and in-situ measurement techniques are some of the strategies being developed to address these issues.

In addition to the above, foams in FGF manufacturing offer huge sustainability benefits by reduced raw material consumption and providing ways for energy-efficient design. Multi-material printing of foams further expands this capability to make components combining strength, lightweight properties, and multifunctionality. As research continues to innovate both in material science and process technologies, the role of foam materials in FGF will be further extended and may transform industries relying on high-performance lightweight components.

4.4 Metal injection moulding (MIM) Granulates

MIM granulates, otherwise known as feedstock, play a very important role in the whole Metal Injection Molding process. These granulates are made by mixing fine metal powders with thermoplastic binders and additives.
Within the context of FGF Additive Manufacturing, MIM granulates allow for fabricating metal-based parts by using the same extrusion techniques as traditionally reserved for polymers. After printing, the parts undergo a process of debinding and sintering in which the binder material is removed and the metal powder consolidated, yielding fully metallic components.

Figure 6 MIM granulates used for 3D printing

MIM granulates are becoming increasingly popular in the new FGF due to the possibility of manufacturing complex and high-performance metallic parts in an additive way. Such MIM granulates consist of hybrid materials that can contain fine metal powders and a polymer or wax-based binder. This gives these particles excellent flowability and good processability for applications requiring extrusion-based technologies such as FGF. It provides a temporary matrix for holding together the metal particles during the printing process; afterwards, it undergoes post-processing, such as debinding and sintering, which transforms it into an entirely metallic part with very impressive mechanical characteristics.

In FGF, MIM granulates are extruded through a heated nozzle. The binder melts during this process and supports the uniform deposition of the layers. The high-volume fraction of metal contained in FGF—60-70% (volume)—

will allow the final component to reach desired density and strength after sintering. This may be quite advantageous for large-format additive manufacturing, as these granular feedstocks do provide scalability and cost-effectiveness. The MIM granulates' capability of multi-material printing has also opened functional application avenues. By mixing metallic granulates with either polymers or composites, one gets hybrid parts with unmatched mechanical and thermal properties. For example, the metallic regions can be embedded within lightweight polymeric structures to realize custom applications within aerospace, automotive, and medical sectors.

MIM granulate components need critical post-processing. The binder material is usually removed by the debinding process, which may involve chemical solvents or thermal treatment. This is followed by sintering, where the metal powders are heated to nearly their melting point, which leads to densification and a monolithic metallic structure. While these steps may introduce challenges such as shrinkage or porosity, tight control over the process assures dimensional accuracy and mechanical integrity. These properties of resulting parts are the same as conventionally made components in every respect: strength, resistance to wear and corrosion. Besides, these granulates have the potential to allow FGF systems to combine the geometric freedom of additive manufacturing with the robust properties of metals. The said versatility makes it possible in aerospace brackets, automotive engine components, and custom medical implants. Despite challenges with regard to debinding and sintering, the scalability, cost efficiency, and material versatility afforded to MIM granulates in FGF provide the impetus for innovation and position the technology at the cornerstone in large-format additive manufacturing of high-performance applications.

- **Multi material consideration of MIM granules**

MIM granulates are currently changing the field of multi-material printing in the context of FGF, particularly in LSAM. A finely powdered metal combined with a polymeric or wax-based binder, MIM granulates enable the additive production of complex metallic parts. Even more application possibilities are opened up by being able to integrate further materials like polymers or composites within a single component in order to achieve an advanced functionality by the multi-material printability of MIM granulates.

With multi-material printing, MIM granulates can be combined with other types of granulates in the same printing process, such as polymer-based or ceramic-loaded materials. Such a route enables the fabrication of hybrid structures where the metallic regions contribute strength, conductivity, or wear resistance, and the polymeric or composite regions contribute low weight or insulating properties. A typical example could be a structural part having metallic load-bearing elements and polymeric shock-absorbing regions, tailored for aerospace or automotive applications. Such designs, which are difficult to attain with traditional manufacturing methods, become feasible using multi-material FGF.

The challenges in multi-material printing using MIM granulates lie in the compatibility of materials used during deposition and post-processing process. Different thermal properties, such as melting points and thermal expansion coefficients, demand very precise control over printing parameters to avoid defects like delamination or warping. The MIM granulates must be coordinated very carefully in the processes of debinding and sintering with the characteristics of other materials in the component. Gradient interfaces or transitional material layers are alleviating such challenges, improving cohesion and performance of the resultant part.

Multi-material FGF with MIM granulates allows for the creation of custom functionality. For example, conductive metallic traces can be printed along with insulating polymers for electronic applications, or wear-resistant metal inserts can be embedded within polymeric tooling for manufacturing. This also allows the repair or edition of components already manufactured by selective deposition of MIM granulates where reinforcement is needed. In short, the addition of MIM granulates to multilateral FGF extends LSAM's design possibilities by the fabrication of parts with superior mechanical, thermal, and functional properties. Overcoming these challenges, such as material compatibility and post-processing issues, will greatly unleash its potential for industries in highly customized, high-performance parts.

4.5 Future Materials

Progress within FGF in the growth area of LSAM requires perpetual advancement within material development to meet evolving industrial requirements. Future material developments will be focused on achieving improved mechanical properties, sustainable functionality, and multiple functionalities, which will result in an expansion in their application areas and give scope for solving new challenging demands. This section highlights recent and future developments within FGF materials.

- **Biopolymer Alternatives**

Biopolymers are emerging as one of the most important categories of materials in FGF because of their renewability and versatility. Sourced from renewable biological feedstock materials such as starch, cellulose, and polylactic acid, these biomaterials can meet the increasing demand for green alternatives to traditional materials in LSAM. This class of materials has immense potential in multilateral printing applications, whereby their incorporation into other classes of materials would enhance functionality and sustainability.

Biopolymer blends, frequently reinforced with natural fibres like bamboo or hemp, offer enhanced mechanical strength and thermal stability of the final product, hence finding a broader scope of application in packaging, consumer goods, and even in the automotive sector.

New biopolymer formulations have demonstrated improved thermal and rheological properties, suitable for high-throughput and large-scale applications of FGF. For example, optimized PLA blends have been developed that can maintain stability at higher temperatures and shear forces in the extrusion process, thus assuring consistent quality in large-scale manufacturing. FGF employs biopolymers, including PLA, PHA, and Bio-PE, as main feedstocks. All these materials possess excellent mechanical properties and are biodegradable, hence finding a suitable position in applications where environmental concerns are an issue. Blending of biopolymers, usually with natural fibres such as bamboo or hemp, may enhance the mechanical strength and thermal stability of the final product, which extends its application fields to packaging, consumer goods, and even automotive parts.

Advances in the formulation of biopolymers have enhanced their thermal and rheological properties, thus making them suitable for high-throughput, large-scale applications of FGF. For example, optimized PLA blends have been developed to maintain stability under the higher temperatures and shear forces of the extrusion process, ensuring consistent quality in large-scale manufacturing. Biopolymers significantly aid the process of multi-material printing in FGF because they combine well with other types of materials, such as engineering plastics and elastomers. Biopolymers might be used as the main matrix material or as functional layers, given that they confer properties such as biodegradability, flexibility, or aesthetics.

The biopolymer example can include PLA combined with a carbon fibre composite in developing lightweight, tough parts in those industries needing this class of part, ranging from aerospace to consumer electronics. Development functionalized biopolymers now include UV resistance, anti-microbial, and even electrical conduction, thus further enhancing their roles within multi-material systems. Such properties further allow the fabrication of parts featuring functionalities such as self-sterilizing medical tools or sustainable electronic casings. Besides this, the thermal and mechanical compatibility of the biopolymers with other materials guarantees defect-free bonding during multi-material builds by avoiding defects like delamination.

- **Advanced Thermoplastics and Thermoplastic composites**

In Additive Manufacture, the introduction of Fused Granulate Fabrication has provided this groundbreaking technology a complete change. Advanced thermoplastics, like its cousin thermoplastic-based composites, are basic constituents and play major roles in achieving success regarding LSAM processes for components with extremely good mechanical, thermal, and chemical properties. Advanced polymers like PEEK, PEI, PSU, and PPS have already been developed with much superior property profiles that this class has become one of the fundamentals in the realm of FGF materials, mainly owing to superior mechanical properties in addition to flexibility.

Advanced thermoplastics have outstanding resistance to any form of degradation, temperature, chemicals, and wear, which places them ideally for demanding applications in the aerospace, automotive, and industrial tooling sectors. In fact, PEEK and PEI are common in the aerospace industry, particularly where lightweight applications demand high thermal and structural performance under highly adverse conditions. PPS is highly prized due to its high crystallinity and ability to withstand aggressive chemical environments—ideal in chemical processing equipment and electrical insulation.

Thermoplastic composites, reinforced with fibres such as carbon, glass, or aramid, greatly expand the capabilities of fused filament fabrication (FGF). Of these, carbon fibre-reinforced thermoplastics (CFRPs) have been notable for light weight coupled with high stiffness and strength. These are in use for structural applications requiring extraordinary load-carrying capacity, as in automotive frames and aerospace structures. Glass fibre reinforcements are much less stiff than carbon fibres but provide a much lower-cost alternative with better resistance to impact and are therefore widely used in construction and consumer products.

Advanced thermoplastics and composites are compatible with multi-material printing strategies, enabling integration of properties within one component. The example shows a part combining high strength of CFRPs and flexibility of unreinforced thermoplastics, resulting in a multifunctional structure designed according to specific application requirements. The capability not only widens the design freedom but also helps to produce complex, high-performance components.

- **Smart Materials**

Smart material, within the new field of Fused Granulate Fabrication (FGF) for large-scale additive manufacturing (LSAM), are characterized by being dynamic in their properties due to environmental stimuli such as temperature, pressure, humidity, and electrical fields. These materials surpass the static properties commonly found in traditional polymers and open up new applications in a variety of sectors including aerospace, medical devices, robotics, and energy. Their ability to change due to external conditions makes them especially suitable for applications needing accuracy, longevity, and flexibility.

An important class of smart materials used in FGF refers to a class of polymers known as **shape memory polymers**. Under the action of suitable stimuli-most provided as heat input-these can transform into a pre-set geometric shape. This property finds wide applications in space for making parts capable of changing shapes or self-deploying/deploying themselves in response to altering environmental conditions. In medicine, SMPs enable self-fitting implants or devices that adapt to the human body, increasing the improvement in patient outcomes. It is the combination of structural functionality and adaptability that makes these polymers indispensable in complex use cases.

Another class of innovation is represented by **self-healing polymers**, which are capable of autonomous repair of microcracks and damages. In such materials, active incorporation of healing agents or mechanisms inside the polymer matrix repairs the wear and tear without any need for manual intervention. This becomes very important in very extreme conditions or in areas inaccessible for repair, for example, deep-sea applications or aerospace structures. Self-healing polymers improve not only the component's service life but also reduce maintenance costs and shutdown times, thus guaranteeing reliability for longer periods of time.

Piezoelectric polymers are another class of smart material that is finding increasing applications in FGF. These classes of materials produce an electrical charge upon mechanical stress, or vice versa, and will be of great interest to sensors, actuators, and energy harvesting devices. Their integration into multilateral systems allows the creation of parts with integrated sensing or actuation capability, targeting markets such as advanced robotics or wearable technology. Piezoelectric materials, therefore, close the gap between structural function and active response.

Thermochromic and photochromic materials are those that extend the use of smart materials in FGF. These polymers will change color based on changes in temperature or light, allowing aesthetic and functional applications dynamically. For example, thermochromic materials can be used on car parts or architectural elements that change color with changing conditions, while photochromatic materials can be applied with eyewear or coatings to adapt to changing conditions. What's more, these materials further make parts highly customizable fitting into the increased demand currently for customized solutions within manufacturing. The integration of smart material in FGF enables the printing of multiple materials and, hence, the smooth integration of conventional polymers with smart functionalities. Such a synergy can enable the fabrication of multifunctional components possessing both structural and dynamic properties to meet the ever-increasing complexity of industrial demands. On the other hand, the application of smart material in FGF is not without challenges. Compatibility with the existing thermal and rheological processes will need precise control and optimization. Besides, cost and scalability remain major concerns for smart materials in their wide industrial use.

These, though, are not insurmountable problems, and the outlook for smart materials in additive manufacturing is good. Current research is focused on scaling the process and reducing costs to improve the material properties for better integration into multi-material systems. As the technology matures, smart materials stand to revolutionize LSAM as it enables innovation in adaptive, responsive, and high-performance manufacturing. The capability for the transformation of industries through added functionality and durability underlines the status of smart materials as one of the main areas of development in AM.

- **Biodegradable and sustainable materials**

Biodegradable plastic pellets are the small, granular forms of biodegradable plastic that will form into various plastic products. The raw material used in these pellets comes from renewable sources, including plant starches, polylactic acid, or polyhydroxyalkanoates, all of which break down over a period, provided appropriate environmental conditions exist, including heat, moisture, and microbes. Whereas traditional plastics are manufactured from petroleum-based resources, biodegradable plastics are supposed to degrade into non-toxic byproducts such as water, carbon dioxide, and biomass. This makes them an eco-friendly alternative to producing items that would otherwise contribute to environmental pollution.

Biodegradable plastic pellets are typically produced through processes such as extrusion or compounding, where bio-based materials are melted and formed into small, uniform pellets. The raw materials undergo chemical processes that allow them to degrade more easily compared to traditional petroleum-based plastics. Some of the most common materials used for creating biodegradable plastic pellets include:

- **Polylactic Acid (PLA)**: Derived from renewable resources like corn starch or sugarcane, PLA is one of the most widely used biodegradable plastics. PLA pellets can be moulded into a variety of products, including packaging, disposable cutlery, and food containers.
- **Polyhydroxyalkanoates (PHA)**: These bioplastics are produced by bacteria that feed on organic materials. PHA is biodegradable in both soil and marine environments, making it a promising solution for reducing plastic waste in oceans and landfills.
- **Starch-Based Polymers**: Starch-based biodegradable plastics are produced by blending plant-based starch with biodegradable additives to create products like bags, packaging materials, and agricultural films.

Biodegradable pellets are therefore used in considerable amounts in FGF, attracting emerging sustainability aspects in manufacturing. These materials, derived from renewable resources such as starch, polylactic acid, and polyhydroxyalkanoates, offer an excellent environmental alternative to conventional petroleum-based polymers. Biodegradable pellets break down naturally under specific industrial composting or natural environmental conditions, minimizing the problem of waste and related environmental impacts when parts are thrown away.

Biodegradable materials in FGF have appropriate mechanical strength and thermal stability for LSAM. For example, PLA is one of the most important biodegradable polymers that can be easily processed with great rigidity. However, the disadvantages related to low thermal resistance and brittleness require modification either by blending with other polymers or by reinforcement with natural fibers, such as hemp or bamboo. In fact, the properties of such biodegradable materials are further enhanced with these composites granulates, hence making them more viable industrially.

Biodegradable pellets provide the ability to fabricate complex structures and functionally graded structures with tailored properties in multi-material printing. The multi-material capability of FGF enables fabrication in a single part biodegradable region with non-biodegradable or specialty materials. This allows for innovative designs, such as components where structural sections are reinforced with durable polymers while disposable or eco-friendly parts are made from biodegradable materials.

Besides that, multi-material printing allows the processing of biodegradable pellets with foaming agents or bioactive compounds for lightweight or functionalized parts, respectively. All these features render biodegradable pellets suitable for applications in packaging, medical devices, and disposable tools. The switching between materials during printing is allowed to ensure compatibility and no-jump transitions between zones at different material properties. Biodegradable pellets in multi-material FGF manufacturing indicate a step towards sustainability and versatility. Their combination-both biodegradability and multi-material capability-pursuing circular economy principles would lead to reduced waste with extended uses of FGF in various industries: automotive, consumer goods, and healthcare. Additional material formulation research and process optimization will improve the feasibility and functionality of the biodegradable pellets in FGF applications.

- **Ceramic Infused Granules**

Ceramic-infused granules represent a new class of materials that raise the performance and versatility of FGF to a qualitatively new level of large-scale additive manufacturing. In these granules, a combination of thermoplastics with ceramic particles brings about their unique properties such as high thermal stability, wear resistance, and very good insulation; therefore, such material is sought after in the aerospace and automotive industries and in power engineering

Ceramic-infused granules represent a new class of materials that raise the performance and versatility of FGF to a qualitatively new level of large-scale additive manufacturing. In these granules, a combination of thermoplastics with ceramic particles brings about their unique properties such as high thermal stability, wear resistance, and very good insulation; therefore, such material is sought after in the aerospace and automotive industries and in power engineering. In addition, the integration of ceramic additives into polymer matrices significantly improves the general mechanical and thermal performance of the material, enabling the manufacturing of complex, durable components for extreme environments.

Among all the ceramics, zirconia (ZrO_2) is one of the most used due to its excellent thermal stability, wear resistance, and high ionic conductivity. Zirconia-infused granules are of particular benefit in FGF, where the material has to go through elevated temperatures and mechanical stresses during printing. Its inherent toughness, achieved through its special phase transformation mechanism, significantly enhances the resistance to impact and fracture toughness of the parts printed with it. In this way, zirconia-infused granules can be used in high-performance applications such as heat exchangers, moulds, and parts that are subjected to steep thermal gradients. In the polymer-ceramic hybrid approach for FGF, specific properties can be adjusted. For example, the incorporation of zirconia into high-temperature-resistant polymers such as polyetheretherketone or polyetherimide leads to the generation of materials for extreme applications without loss of structural strength. The presence of ceramics increases the rigidity and resistance to wear and tear for the material and opens up applications such as sliding mechanisms or cutting edges. Zirconia-filled granules can also provide very good electrical insulation; therefore, there is a potential application area in electronic and electrical applications.

Other benefits of ceramic-infused granules in FGF are related to the advantages of multi-material printing capability. Combining ceramic-based polymers with other metals, elastomers, and conductive polymers, for instance, in a single part will extend a functional design space. Such a part could have thermal-resistant zones, for instance, made of zirconia-based granules with other regions of the parts being flexible or conductive using other types of materials. Thus, it allows the production of functionally graded parts and can be optimized for local mechanical, thermal, or electrical requirements. Main difficulties in the processing of FGF with ceramic-infused granules concern the homogeneous distribution of ceramic particles within the polymer matrix. Ineffective distributions within the context of additive manufacturing can result in the emergence of vulnerabilities and structural imperfections in the printed constructs. Addressing these challenges, advancements in material formulation and mixing methodologies are being pursued to ensure uniformity and reproducibility in the functional attributes of the produced materials. Furthermore, the incorporation of ceramic elements can be optimized through post-processing techniques such as sintering and annealing, thereby enhancing the intrinsic properties of the composite materials and mitigating potential defects.

Zirconia and other ceramic-infused granules are the forerunners for advanced capabilities in manufacturing with FGF LSAM. Given their unique combination of mechanical robustness, thermal stability, and multi-material compatibility, they hold a niche as a key material that will play a leading role in future developments. Further materials formulation and process optimization research will widen their application areas towards high-performance, multifunctional components in the most demanding industrial sectors.

4.6 Foam Printing

Because they are lightweight and inexpensive, cellular thermoplastic foams are considered as important engineering materials. On the other hand,

Additive manufacturing, better known as 3D printing, is a new and fast-growing technology.
Growing manufacturing technologies due to its advantages such as design Freedom and manufacturing without tools. Today, 3D printing of plastic Compounds are primarily used to produce solid components. In this case, A combined foaming and printing technology can offer a good alternative. for the foam manufacturing methods that are used today like foam Injection Molding.

Foaming of thermoplastics results in greener, lighter, and cheaper elements applies to an array of commodities and Foamed structures provide an advantage to engineering applications since they shrink less and have better dimensional stability because of the reduced input of material. Conversely, Foamed products have improved weight-related features. characteristics, such as particular impact resistance and durability, as opposed to their solid counterparts. Foaming could also provide essential thermal and acoustic insulation characteristics. Operational Characteristics may also be elicited in foamed. Elements, for instance, by using electrically conductive nanoparticles such as carbon nanotubes or graphene, for example as barrier-forming nano clay or cellulose nanocrystals.

- **Foam Printing of Bio-based thermoplastic**

Biobased thermoplastics are a class of novel materials, which are wholly or partly derived from renewable biological sources, offering a greener alternative to conventional petroleum-based plastics. Those bioplastics have very similar properties and processing behaviour to traditional thermoplastics, allowing them in many fields to be applied with great ease. Biobased thermoplastics: defined as macromolecules derived from biological sources, for use in thermoplastic applications. The major raw materials are carbohydrates—starch, sugars and cellulose; natural oils—palm, castor and soy; proteins; lignin; animal-derived components, such as chitin. These biobased substances exhibit a thermoplastic character of softening or melting under heat, thereby allowing thermal processing to be carried out.

The two main types in this category are drop-in bioplastics and novel bioplastics. Drop-in bioplastics are chemically identical to the conventional, petroleum-based plastics; the difference lies in the fact that renewable raw materials are used for their production—for example, bio-polyethylene (Bio-PE), bio-polypropylene (Bio-PP), and bio-polyethylene terephthalate (Bio-PET). Novel bioplastics include polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and thermoplastic starch (TPS); their chemical structure differs from that of the conventional plastics.

Biobased thermoplastics offer significant sustainability advantages, including reduced carbon footprints, decreased reliance on fossil resources, and, in some cases, biodegradability. It is expected that all these industries will find their uses for biobased thermoplastics. Contrasting with their promise, the biobased thermoplastics face multiple challenges in feedstock sourcing in a sustainable manner, reconciling performance and biodegradability, and developing effective recycling and composting systems. Therefore, further research and development in this field is essential to drive the transition towards a circular economy and to firmly establish biobased thermoplastics as part of the new stream of sustainable materials.

Extrusion foaming, foam injection Molding, and bead foaming are three commonly employed technologies for processing thermoplastic foam. In extrusion foaming, one of the main advantages is the production of low-density polymer foams with continuous profile and simple 2D geometries. In contrast to foam extrusion, foam injection moulding is usually used to manufacture high-density foam structures with complex 3D geometries. The final foam injection moulded part results in a product with lower material cost, high dimensional stability, lower energy consumption, and a shorter cycle time. Bead foaming is another common alternative to produce low-density foam products with 3D geometries. This method involves the manufacturing of low-density bead foams followed by steam chest moulding into the desired final shape. Fused Granulate Fabrication, a technique using innovative technologies of additive manufacturing like foam printing with bio-based thermoplastics, allows materials of bio-based origin to become lightweight and functional thanks to cellular structures. Bio-based thermoplastics result from renewable feedstock resources like starch, cellulose, or natural oils, characterizing these material sources as rather harmless towards the environment in comparison with petroleum-based material sources. Furthermore, the integration of foam structures in bio-based thermoplastics enhances their utility by reducing material consumption, improving thermal insulation, and maintaining structural integrity.

In principle, there are two methods able to bring about foaming in biobased thermoplastics: chemical and physical foaming. The former is simply a granule with specific blowing agents that, in heating, liberate gases responsible for creating a cellular structure, while the latter is made by introducing inert gases such as CO_2 or nitrogen inside the material during the extrusion.

Vital EU project

Bio-based Thermoplastics (b-bTPs) are not currently being adopted as a part of “circular by design” business models to replace fossil-based solutions across thermoplastic processing value chains This situation will only change when the price and processability of b-bTPs become commercially viable. Foamed polymer products are a critical part of the modern global economy, with the global foam plastics market estimated at $102.0(€87.0) Bn in 2019, predicted to increase to $123.7(€105.5) Bn by 2027.

VITAL will develop innovative thermoplastic processing solutions for foamed thermoplastics, based on three b-bTP processing value chains: 3D printing process based on granulated feedstocks; Bead foaming process and a Foam Injection Molding (FIM) process.

In the chain value of processing foamed thermoplastics, it is critical that these limitations are overcome for a transition into sustainable, circular economy bio-based solutions. VITAL represents an important step along this journey since, for the first time, it will be providing innovative high-efficiency and low-cost processing solutions along with key enabling knowledge toward the realization of commercially viable "Sustainable by Design" approaches using b-bTPs. The adoption of VITAL outputs across the polymer processing sector will, with the vocational training programme, facilitate the commercial use of b-bTPs by manufacturers for an attained paradigm shift into using bio-based alternatives in line with cleaner, more climate-neutral industrial value chains. VITAL will stimulate the uptake of sustainable-by-design advanced materials and processes, not just by overcoming technical limitations but by achieving "buy-in" from processors, OEMs, and customers, all of whom are represented in the consortium [33].

5 Integration of Electronics, Sensors, and Positioning Mechanisms

Integration of parts, such as electronics, sensors, and positioning tools, within the Fused Granulate Fabrication (FGF) process of large-scale additive manufacturing (LSAM) is a novel capability that reconfigures conventional manufacturing practices. The new process eliminates additional steps of assembly, reduces production time, and enables multifunctional and smart structures to be designed. Inserting parts right into the printing process allows us to add functions and customize better, helping industries such as aerospace, automotive, healthcare, and consumer goods, where smart components increasingly become more relevant.

One of the biggest issues in attempting to put these parts together is in controlling how heat-sensitive they are. Thermoplastics are melted and set in place by FGF using high temperatures, which might damage fragile electronics or sensitive sensors. This requires careful timing between the putting down of materials and the placing of components, using heat-resistant encapsulation materials. In addition, strong sticking between the embedded components and the base is important for strength and lasting quality. If things are not lined up right or do not stick well, it can cause problems in performance or part failure.

Various methods have been developed to aid component placement in the FGF process. The pause-and-insert approach is the act of stopping printing at some layers to insert manually or robotically parts such as RFID chips, sensors, or actuators. The process is quite simple but needs workers and often disrupts production. More advanced systems have robots attached to the printing head, which helps mix parts better while printing. That makes things not only more precise but also allows combining more complex shapes and features. Also, printing with multiple materials has become a strong way to include parts. By using different materials that have different qualities, like flexible plastics for covering and hard plastics for support, FGF allows safely enclosing delicate parts without hurting the part's use or strength.

The uses of component integration in FGF are multifold. For instance, the integration of electronics like circuit boards, antennas, and RFID chips into printed parts facilitates wireless communication and tracking; this is particularly useful in IoT devices and aerospace parts. Sensors that monitor stress, temperature, humidity, or other environmental factors can also be integrated directly into structures. For example, strain gauges built into big construction parts allow for real-time checking of structural health. Also, tools like actuators, hinges, or alignment devices can be added during printing to allow for movement or exact assembly, which is very useful for robots and machines.

In the coming years, FGF LSAM will probably benefit greatly from the improvement in hybrid manufacturing, robotics, and material science. Hybrid systems that mix adding and removing methods can place components more precisely, while better robotics can make automated placement more accurate and flexible. Smart materials, like conductive or shape-memory plastics, can lessen the need for outside electronic parts. This makes it possible to have fully integrated systems with fewer steps. Also, using digital twin technology in manufacturing could give immediate feedback. This allows for quick changes to where parts are placed and how they are embedded. In the last analysis, integrating electronics, sensors, and positioning mechanisms directly within FGF LSAM parts truly marks significant progress within the domain of manufacturing innovation. It is going to enable the creation of smart multifunctional systems, for which there are increasing requests from advanced industry sectors. As technology matures, component placement inside FGF LSAM would be among the most essential elements towards intelligent, high-performance customized manufacturing solutions.

5.1 Printing on top of an electronic conductive bed

Within the realms of Fused Granulate Fabrication applied to Large-Scale Additive Manufacturing, the integration of electronic components, sensors, and positioning systems into the printing process is taking up promising grounds toward technological advancement. One approach that has proved effective has been direct printing on an electrically conductive substrate; this provides easy and seamless integration of electronic capabilities within fabricated components, heralding immense progress toward intelligent and multifunctional structures.

Use of an electronic conductive bed in printing allows for a more precise placement of the conductive pathways, sensor arrays, or integrated electronic circuits within the finished part. The conductive bed provides a two-purpose substrate, acting as a base integration of components whereby the thermoplastic materials could be applied around the pre-positioned electronics without their losing operable integrity. The approach is particularly beneficial in applications in such industries as aerospace, automotive, and the production of IoT devices, where there is an increasing need for intelligent systems with integrated electronics. The electronic conductive bed is mostly composed of materials such as flexible PCBs, conductive inks, or metallic meshes. In most cases, the substrate is designed specifically to withstand the thermal and mechanical stresses developed from the process of FGF. The conductive bed is placed on the build platform while printing and coated with layers of thermoplastic material. The conductive paths found within the substrate can be aligned with specific features of the printed component and so provide direct connections to integrated sensors, actuators, or power supplies. Because manufacturers can insert these parts while the product is being printed, it grants them increased efficiency in their production and assembly, minimizes error rates in an assembly context, and further allows complexity in design.

Sensors integrated onto a printed part, for example, can be bonded to the conductive substrate, providing real-time data acquisition and communication. Actuators or positioning mechanisms similarly can be fed and controlled by the embedded conductive network. However, printing onto an electronic conductive substrate faces some challenges. The main conditions are strong adhesion of the thermoplastic material onto the conductive substrate to ensure structural integrity; and the sensitive nature of electronic components to heat requires an efficient controlling system since it will easily damage sensitive circuits or conducting traces on the substrate by exposing them to high temperature during FGF. Actually, developing new material formulations for low-temperature thermoplastics and encapsulation materials arises to overcome these disadvantages.

Another factor is the accuracy of the printing process: misalignment between the printed layers and conductive paths leads to either a non-functioning or less than optimal functioning of it. Advanced alignment and monitoring systems are adapted in such cases for correct placement of the layers for high performance. In any case, the application of an electronic conductive bed inside the FGF LSAM holds enormous promise for the development of clever manufacturing. Such an approach would help integrate electronic elements and sensors into large-size parts effortlessly, opening prospects for building complex, highly efficient systems with minimal or no post-processing. This will see the importance of conductive bed printing in FGF increase in time as material advancement in science and printing methodologies are made, driving innovation on different levels.

- **Methods for printing on electronic bed**

Printing on an electronically conductive bed in the FGF LSAM technique involves advanced methods to precisely integrate thermoplastic materials with an electronic substrate. The various methods are designed so as not to affect the functionality of the embedded electronics while ensuring strong adhesion and high structural integrity. Several ways have been developed to effectively facilitate printing on electronic beds, including:
Direct Deposition on Conductive Substrates: The technique involves the direct extrusion of thermoplastic granulates onto an electronically conductive bed, such as a flexible PCB or conductive ink layer. Pre-processing is necessary for the conductive bed to ensure thermal and mechanical compatibility with the extruded material. Surface treatments like plasma cleaning or priming are usually conducted to enhance adhesion between the electronic bed and the deposited polymer layers.
Thermoplastic Encapsulation: This includes the process of depositing a protective layer of thermoplastic material over sensitive electronic components that are laid on a conductive bed. Encapsulation ensures the components are guarded against thermal and mechanical stresses during printing. For that, control of the extrusion parameters, like temperature and flow rate, becomes critical in order not to damage the electronics while maintaining the structural integrity of the printed layers.
Hybrid layered printing: This approach represents the electronic conductive bed as an intermediate layer within a multi-material printing process. Thermoplastic layers are interchanged with conductive or insulating materials; thus, complex structures could be fabricated with embedded circuits. This approach enables perfect integration of electronics, while thermal and mechanical isolation could be maintained where required.

5.2 Placing components inside the printed objects with the same machine

The main approaches to embedding components include the creation of cavities or recesses during the additive process. While depositing material layer by layer, the FGF system leaves voids at some specified positions in the digital model. These voids accommodate components like sensors, electronic modules, or actuators. After the cavities have been created, components are set in place. This can be done by hand, but more advanced systems use a robotic arm integrated into the FGF machine for an automated placement process. Such robotic systems move in concert with the printing head and therefore align components precisely without interrupting the build process.

The process for sensitive components involves further protection. For instance, thermal considerations are very important because the high temperatures of FGF may damage embedded electronics. To avoid this, low-temperature thermoplastics can be deposited around sensitive areas, or heat shielding can be used. The mechanical properties of the surrounding structure also have to be such that they provide enough support to the embedded components without causing excessive stress or interfering with their functionality. The rise of multi-material FGF systems has boosted this ability even more. These setups let users switch between different materials on the fly making it possible to cover parts with protective or insulating layers. For example, conductive polymers can create electrical paths, while insulating thermoplastics protect the electronics inside from outside forces or physical stress. This flexibility with materials is key in cases where keeping parts intact is crucial.

Keeping an eye on things as they happen is vital to place components. Sensors built into the FGF system track how cavities and parts line up and where they sit in real time. This constant feedback helps stop mistakes making sure the parts inside match exact design plans.

Embedding components right into printed structures has many uses across different fields. In the aerospace industry, sensors built into structures that carry weight can keep an eye on stress in real time. For consumer products, devices with built-in electronics that connect to the Internet of Things can be made with fewer steps. Medical gear gets better with built-in sensors that track health stats while staying light and small. This method cuts down on how complex production is, makes things more reliable by having fewer parts to put together, and paves the way for new tailored designs that do many jobs at once.

5.3 Placing components on top of the printed objects

Putting elements like electronics, sensors, or positioning mechanisms on top of printed objects is seen as the main part of Fused Granulate Fabrication for Large-Scale Additive Manufacturing. This step plays a key role in making a smart structure that covers many fields. The process of adding these parts during or after building the main structure aims to boost how well it works how it's made, and how much it can be changed to fit different needs.

First comes the designing of the printed object to have external components, which normally includes planar surfaces, specific mounting features, or embedded channels for wiring. Then, during printing, FGF equipment with robotic arms or tool changers can be used to apply a certain layer or coating at picked places on the object's surface to provide a stable foundation supportive of adhesion. The base layers can be made up of either conductive or thermally insulating materials, depending on the particular use, thus ensuring reliable bonding and operation of the components.

The FGF LSAM system features robotic arms for the post-print placement of components. These robotic appendages are designed to pick up, position, and fix components such as sensors, RFID chips, or electronic modules onto the printed structure with a high degree of accuracy in alignment. Adhesives, thermal-bonding processes, or mechanical fasteners can also be used in an automated manner to provide secure attachment. Advanced alignment technologies, like machine vision and laser-guided systems, are required in achieving proper placement, specifically in the case of products with large or irregular shapes.

The major feature of multi-material FGF LSAM systems—that of printing functional interfaces or conductive pathways directly on the surface of the printed object prior to the placement of components—enables significant benefits. For example, it enables the deposition of conductive polymers to obtain seamless circuits connected with external components. It then enables the overlay of insulating materials to protect the circuits and enhance the durability of the electronic integration.

This methodology is especially important in applications where access to components post-printing is needed for maintenance or upgrade. For example, externally attached sensors to aerospace or automotive components allow for real-time monitoring and are easily replaceable, thereby enhancing the lifespan and safety of the product. In consumer products, the exposure of electronic components such as touch sensors or LED displays maintains the user experience while safeguarding the structural integrity of the underlying 3D-printed material.

The challenges involved in placing components on top of printed objects are mainly related to the creation of strong adhesion, thermal compatibility, and precise alignment. Advances in adhesive technologies, surface preparation methods, and robotic control systems are successfully addressing these challenges, therefore enabling the reliable integration of components while preserving the performance integrity of the printed structure. By seamlessly integrating components onto printed material surfaces, FGF LSAM systems dramatically increase the flexibility of additive manufacturing. This feature permits intelligent, multifunctional products tailored specifically to meet the high-volume, specific needs in the fields of aerospace, automotive, healthcare, and consumer electronics. As such, R&D continues and the FGF process reveals new integrations of outside components to show possibilities from large-scale manufacturing where innovation and efficiency are leveraged in the design.

6 Applications of Large-scale additive manufacturing

Large-scale 3D printing is considered one of the most renowned fabrication methods that have changed traditional ways of fabrication in many industries. In this section, we are going to look at some significant examples where latest technology confronted conventional practices. These include aerospace, marine engineering, and automobiles, among many more. These practical applications will bring out the flexibility, cost-effectiveness, and sustainability that large-format polymer 3D printing has to offer to industries that are not only into increasing efficiency but also innovative. Here we are mainly discussing applications with polymers.

Several industries are now starting to exploit the established advantages of polymer-based additive manufacturing. Among these are renewable energy, aerospace, shipbuilding, moulding, and defence industries, which are highly delving into large-scale AM with the main idea of reducing production costs and speeding up development timelines. This could be highly beneficial for industries in which the integration of big-scale AM will make a real difference in their manufacturing processes.

6.1 Automotive

AM provides the ability to reduce weight or volume with the freedom of a more optimal design. By applying topology optimization and working with lattice structures, part weight and cost can be reduced. The automotive industry is constantly trying to reduce the overall weight of its components and design. The main applications of LSAM in the automotive industry are related to components for cars, electric vehicles, prototypes, molds and tooling.

First announced in 2013, Urbee is being labelled as the first "3D printed car," a three-wheeled, two-seater compact hybrid. Major components of the vehicle body and bumper were all 3D printed in ABS on a large-format additive manufacturing system (figure 7). This system creates an entire vehicle roughly 3 meters in length in about 2500 hours. It is expected that LSAM technologies would be apt for electric vehicles, allowing the manufacturing of lightweight polymer components that would aid in efficiency [34].

Figure 7 Urbee First 3D printer car

One of the early users of pellet-based extrusion technologies was the US-based company Local Motors. The significant reduction in cost and manufacturing time with the pellet-based method motivated LM to start the production of vehicles using pellet-based extrusion. They introduced "Olli," an electric self-driving shuttle, in 2016 that had about 80% of its structure 3D printed (figure 8). LSAM technologies also have the added advantage of rapid prototyping of vehicles for their testing and development. An example of this is when a certain BAAM system was coupled with a hardware-in-the-loop system in which powertrain and vehicle control models were created in the HIL environment and were integrated into the CAD model, which was then printed using the BAAM system. Historically, automotive moulds and tooling have been made using non-AM processes. During the past ten years, this has begun to change, and several examples illustrate how LSAM is being used in the production of moulds and tools. First, there was Polimotor, which produced an automotive engine with many polymer components; the company is currently working with Ford on a composite engine prototype. In collaboration with ORNL, Polimotor examined the feasibility of the LSAM processes to fabricate an injection mould for the composite engine oil pan [35].

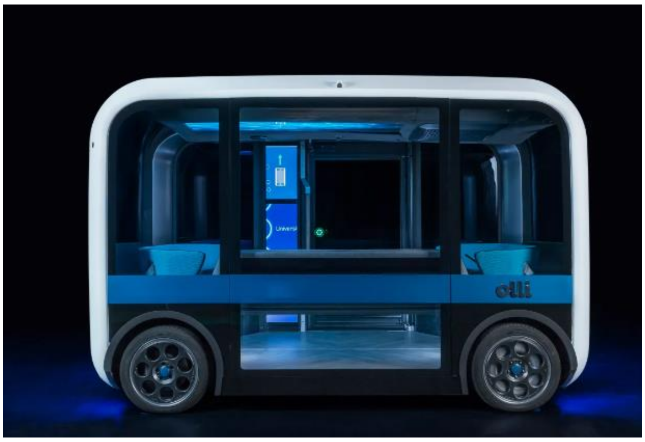

Figure 8 3D printed vehicle “Olli”, Local Motors

6.2 Naval Industry

This is attributed to the annual expenditure of some $13 billion, which the industry spends on spare parts-a driver for seeking more efficient solutions. Additive manufacturing has emerged as the transformative approach in improving the productivity of low-volume production. Compared to conventional techniques, additive manufacturing offers shorter lead times, enabling the manufacturing of components in near-net-shape. Large-format polymer 3D printing has already made an impact in the maritime sector, enhancing spare part availability.

In 2017, the U.S. Navy, in collaboration with ORNL produced a composite submarine hull (Fig. 9) made of ABS/CF in a LSAM system. The built hull is a sea, air, and land (SEAL) delivery vehicle. The use of LSAM methods allowed to reduce the production time and achieve a cost reduction up to 90% [35]. One of the other most popular applications of LSAM is the University of Maine 3D-printed boat called “3Dirigo” [36]which in 2019 received three Guinness World Records for the world’s largest prototype polymer 3D printer, largest solid 3D-printed object and largest 3D-printed boat (Fig. 10)

Figure 9 Submarine Hull

Figure 10 3Dirigo by University of Maine

Al Seer Marine also unveiled the HYDRA (Figure 11), the first 3D-printed drone boat in the world, manufactured from a 36-meter-long composite-based pellet extrusion system from CEAD [37]. The innovative vessel is five meters in length and weighs 345 kg. Production took just five days. At the same time, the company Caracol 3D printed with the assistance of a robotic arm the hull of a sailboat made of recycled polymers. Besides, another interesting application is that of the Swedish company Pelle Stafshede, which produces 3D-printed kayaks with corn and wood pellet [38].

Figure 11 Al Seer´s 3D printed drone boat

6.3 Aerospace

The aerospace industry is highly dependent on extensive supply chains and must bear severe problems in maintaining extensive inventories of spare parts. This always results in the high costs of storage. Adoption of 3D printing as an emerging technology will offer much relief to these manufacturers, enabling them to make replacement parts according to demand. This could cut lead times and costs drastically compared to traditional channels of supply. 3D printing further helps in tailoring the demand for parts and hence making inventory management quite efficient; the need for large storage facilities can thus be minimized. Further, engineers can redesign hard-to-source or obsolete components for printing with this technology, which has resulted in savings on time, cost, and labour.

Similar to other industries, there is an added value of the use of LSAM technologies for mold and tool manufacturing, even in the aerospace sector. For example, in 2016, ORNL manufactured a trim and-drill tool by 3D printing for the fabrication of a part in the wing of the Boeing 777x aircraft [39] shown in figure 12. Besides, LSAM was used by CNE Engineering in fabricating molds of engine exhaust covers for Scandinavian Airlines during the COVID-19 pandemic, saving them from supply chain delays and several grounded flights. Since the old methods were not an option, 3D printing allowed CNE to meet urgent needs of SAS, as tooling was printed in days, not weeks, and castings were completed in hours [40]. Similarly, SFM Technology re-engineered restraint cradles for Royal Navy helicopters and, with 3D printing, increased production yield four times higher than that achieved with conventional manufacturing techniques (Figure 13).

Figure 12 The 3D printed trim tool co-developed by Oak Ridge National

Figure 13 Main rotor blade restraint cradle for AgustaWestland AW101

Large-format 3D printing has also demonstrated clear benefits in the production of low-cost rapid tooling, jigs, and fixtures. For example, the Chair of Carbon Composites at the Technical University of Munich utilized LSAM to produce a mould for a composite flaperon in less than eight hours. Examples like this show how efficiently and quickly LSAM can produce and simplify the manufacturing process [41].

LSAM represents one of the critical enabling technologies for future space missions. This is because it enables the direct fabrication of large structures in space, therefore reducing the dependency on materials that would be supplied from Earth, and overall transportation costs. The main advantages of LSAM are that it enables habitat building and all other primary infrastructures using in-situ resources, like lunar regolith or Martian soil, making the process fundamental in long-term space colonization [42]. Yet, there are also considerable challenges the technology faces: a 3D printer would have to work in super-low or super-high space temperatures, high levels of radiation, and microgravity-conditions which all require material resistance against each element. As an example, studies were done to enhance the thermal properties of 3D-printed polymer composites by investigating the effects of composite geometry and print direction on thermal anisotropy; furthermore, composite geometries are considered with respect to print quality and mechanical property assessments. Precision and reliability during remote operation are critical to successful deployment in space. Overcoming these challenges might just open a whole new frontier in space travel where infrastructure development could take place off the planet [5].

6.4 Construction Sector

In construction, much of the application of AM has been in the development of mock-ups and scale models, enabling architects to have the liberty and space to experiment with designs and test concepts, trying out new functionalities. Initial developments in additive manufacturing for construction made use of properties of cementitious materials, made possible by the advance development of contour crafting and 3D concrete printing techniques. While cement-based AM materials are by far the most common, there are some exciting aesthetic and structural possibilities for polymers in the sector, too. Camacho et al. reviewed general additive manufacturing applications in construction. Through a literature review, they underlined that the main uses of LSAM for architectural models, residential structures, windows, furniture, decorative components, and Mold components in off-site construction.

For the first time, Nowlab has developed the BANYAN ECO WALL, a highly advanced irrigated green wall that has been fully fabricated using BigRep's large-format FFF 3D printing technology [43]. This innovative structure, drawing inspiration from natural plant systems, serves both as a supporting element for plants and as an integrated irrigation system. Supported by sophisticated CAD software and additive manufacturing, this design has become representative of the new degree of functional complexity made possible by digital fabrication processes while demonstrating capabilities well beyond the possibilities offered by traditional construction techniques. ORNL, in collaboration with SOM, designed and fabricated a single room building module of about 20 m². Using BAAM technology, about 80% of the structure was built using carbon fibre-reinforced ABS. This was part of the Additive Manufacturing Integrated Energy (AMIE) project [44] that was intended to demonstrate the integration of a hybrid vehicle with a photovoltaic energy system. The photovoltaic system supplies the energy needs of the building and recharges the vehicle's battery during sunny days. On the other hand, nighttime or overcast conditions will make the system draw energy from a secondary-use battery storage or, when necessary, from the electrical grid (figure 14)

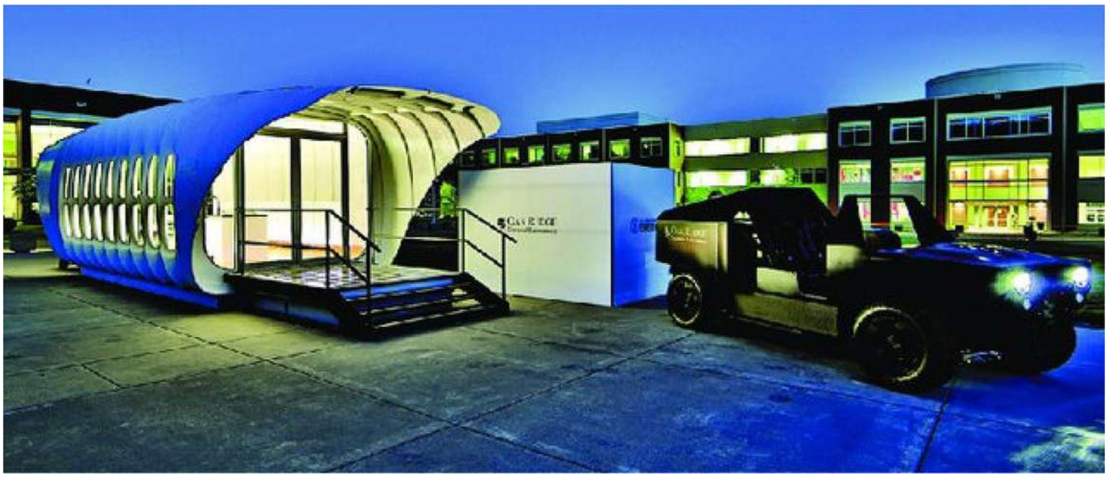

Figure 14 Additive manufacturing integrated energy demonstration

LSAM technologies were used to manufacture a facade shading system for an overlay pavilion at Expo 2020 in Dubai. To select a printing material that met the aesthetic and performance requirements (especially in terms of resistance to high temperatures), tests were conducted in a climatic chamber of the Politecnico di Milano. A high temperature (HT) PLA with 5% of wood fibres was chosen. Other potential significant applications include the fabrication of Molds for precast concrete, typically made from wood in labour-intensive and expensive processes. Carbon Fiber-reinforced ABS moulds were developed by ORNL in collaboration with Gate Precast. Advanced moulds demonstrated a service life about ten times longer compared to those created through traditional methods.

6.5 Wind energy systems

Additive manufacturing can further improve the wind turbines' performance, bringing it even greater advantage to the fast-growing wind energy industry. In 2020, the U.S. saw a 24 percent year-over-year growth in its offshore wind pipeline, and the EU installed 17.4 GW of new wind capacity-although growing delays for permits, and global supply chain disruptions have slowed progress. Currently, the tooling and molds required to produce wind turbine blades can exceed $10 million in costs alone and take 16–20 months before they are market-ready. To reduce this challenge, the University of Maine is utilizing 3D printing technology with bio-based feedstock to fabricate molds of the blades. Therein, the cost of blade development could be reduced by 25%–50%, reducing at least six months from current production timelines [45]. Besides that, molds can be recycled by grinding and reusing the material in the next molds, therefore contributing to better sustainability. Importantly, the mechanical properties of the bio-based materials are comparable to those of aluminum (figure 15)

Figure 15 A 3D printed wind blade mould. Image courtesy of UMaine

In partnership with ORNL, the company Hover was able to 3D print parts for a revolutionary vertical axis wind turbine designed to capture more energy than traditional turbines. These technologies have distinct advantages for this application, as each can be scaled economically to meet the operational environment. Another key application was the manufacturing of a mould for a wind turbine blade using BAAM technology. After printing, the mould was treated with a layer of fiberglass and then used to produce a set of three blades with no visible wear. This was further enabled by additive manufacturing, which allowed for the inclusion of a heating system in the mould itself-the heat would distribute uniformly through internal channels[46] (figure 16)

Figure 16 3D printed wind turbine mould by ORNL

6.6 Magnets

It must be considered that permanent magnets are composed of rare elements; therefore, it is important to limit their waste as much as possible during the manufacturing processes. Additive manufacturing technologies can play an important role in this field. The large-scale additive manufacturing printed magnet is proving to be one of the most promising energy-related innovations, especially because of its established interest in direct-drive wind turbines that use very large permanent magnets. The advantages of these direct-drive turbines are that gearboxes, one of the heaviest components, also require much maintenance. At ORNL, LSAM printed magnets were fabricated with BAAM technology using NdFeB and NdFeB combined with SmFeN powders embedded in a Nylon 12 matrix [47]. These prototypes include a cylindrical magnet of 15 cm in length and one with a horseshoe shape with dimensions of 5 cm², illustrating the potential of this technology in wind turbine efficiency (figure 17).

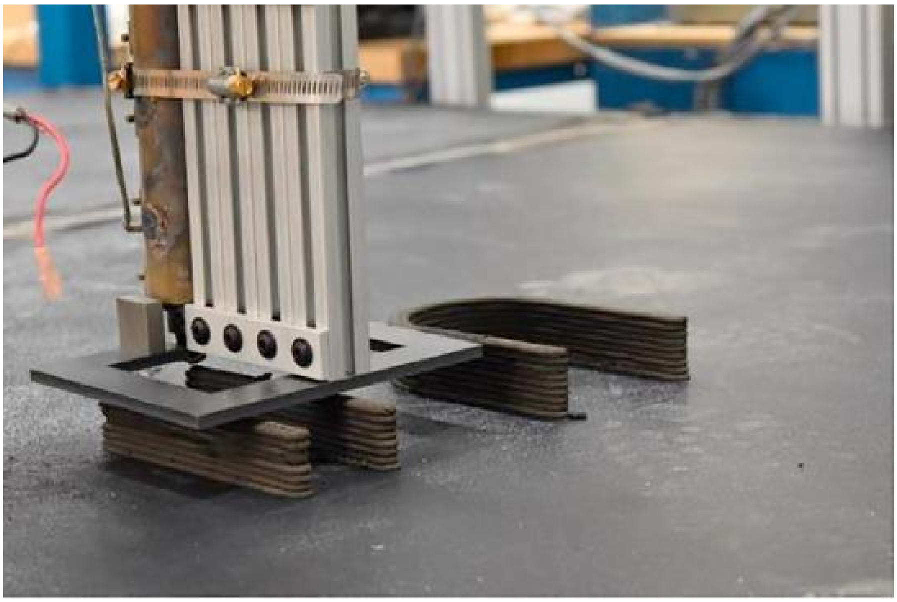

Figure 17 Two Nd-Fe-B sintered magnets

It is important to note that the load fraction of the Nd-Fe-B powder in the magnet significantly affects its properties, and these can be improved by optimizing the temperature and magnetic field for post-print alignment [48]. Table 1 in appendix summarizes the applications of LSAM technologies in the different activity sectors that were mentioned above.

7 Challenges, Opportunities and Potential

Some of the main challenges to additive manufacturing extrusion systems include the development of advanced modelling tools, nonoil-dependent sustainable materials, establishment of specifications and standards, and intellectual property issues. Specific, very critical challenges to the LSPED process are those related to process control, inspection criteria, and cost-effective production strategies.

The review of issues and solutions concerning LSAM, along with its applications across various sectors, underlines both the challenges and opportunities that lie ahead. These challenges encompass all layers of the AM value chain, from part modelling to process control, material selection, and therefore offer remarkable research opportunities in view of driving innovation for both academia and industry. Designing future systems for scalability and improving the production rate, while maintaining competitive costs by integrating multiple processing steps-additive and subtractive manufacturing-must be met. Integrating multi-material platforms that can create parts with functionally graded properties will therefore present exciting opportunities. Material reduction by advanced infill strategies should be one of these innovations, improving weight reduction for non-structural parts, whereas most of the critical, multidisciplinary requirements require LSAM to meet those of multifunctional and structural applications.

One of the few remaining gaps in the coverage by this work involves the possibilities of LSAM for maintenance, repair, and operations. Recent research has pointed out the high potential of AM for industrial maintenance, especially for on-demand manufacturing of spare parts. AM technologies offer tool-free production and a wide design freedom, thus improving the efficiency and effectiveness of maintenance, especially in the manufacturing of spare parts on demand.

This section evaluates the challenges and potential aspects across five key areas: material selection, innovative manufacturing processes, enhancement of interlayer bonding, the compromise between surface quality and production speed, and quality assurance with process control. The objective is to provide an encompassing view of the current landscape and potential progression of large-scale additive manufacturing.

7.1 Material selection and development

Materials development is the key factor in solving the challenges of LFAM, especially when polymers are used. The main drawbacks include thermal shrinkage, which is related to the tendency of the polymers to shrink while cooling down. The dimensional accuracy and integrity of the structure are major concerns in the printed parts. The degree of the thermal shrinkage is given by the coefficient of thermal expansion of the polymer. For example, ABS and PC have CTE values of 60–70 µm/m°C and 70–110 µm/m°C, respectively [49]. When large formats are targeted, these shrinkage problems become much more severe as more material volume needs to be considered. High-performance polymers like PEEK are under increasing interest for LFAM because of their superior mechanical properties and thermal resistance. On the other hand, PEEK poses additional challenges regarding the high melting point and a high risk of developing thermal stresses during cooling, which can lead to warping and delamination. Warping rates as high as 20.3% have been reported in studies for PEEK, hence showing the need for solutions that can mitigate these effects.

Various methods have been developed to tackle shrinkage and warping. Optimizing the printing environment by manipulating factors such as temperature, humidity, and cooling rates has shown promising results. Adjusting the temperature of the nozzle and print speed, for example, was found to minimize warping in PLA. Innovative techniques, such as using heat collectors to preheat deposited layers in printed PEEK, have reduced warping from 20.3% to 5%. Other functional methods include the addition of additives to alter the CTE of the polymers. The physical barriers provided by fillers and reinforcements, such as fibers or particles, can restrict polymer chain movement, hence reducing shrinkage and enhancing dimensional stability. These additives do not only alleviate thermal stresses but also enhance functionality for printed parts. For instance, they may provide specific electrical or magnetic properties, thus further enlarging the area of application for polymer composites [50].

Nevertheless, adding fibers and other reinforcements brings about new challenges in the process of extrusion. High fiber content is likely to alter the viscosity, flow behavior, and melt strength, which may lead to nozzle clogging or poor dispersion. Generally, fiber-reinforced filaments experience clogging at fiber loadings higher than 40–50%. In vat photopolymerization techniques, sedimentation and fiber entanglement can compromise the homogeneity and bonding within the composite.

Further research in various aspects of material behavior is, therefore, needed for enhancing the printability of high-fiber loading filaments. The knowledge about the effect of fiber characteristics such as length, diameter, and aspect ratio on rheological properties and extrusion behavior will help in the optimization of the formulations. Investigations on the role that can be played by additives such as coupling agents and compatibilizers in optimizing fiber dispersion and interfacial interactions can reduce agglomeration and enhance processing results.

In summary, while LSAM opens perspectives for more advanced applications, the resolution of material issues, especially in high-performance and fiber-reinforced polymers, is needed. In fact, optimizing environmental control, functional additive incorporation, and refining material formulations will boost printability, reducing defects and furthering applications for LSAM technology.

7.2 Interlayer Bonding

One of the key challenges in 3D printing relates to anisotropy in mechanical properties, which is due to layer-by-layer deposition. In conventional additive manufacturing, material deposition is conducted in the x-y plane, while subsequent layers are added in the z-direction. Often, this results in relatively weaker inter-layer bonds compared to continuous material in the x-y plane, which commonly contributes to much lower mechanical strength in the z-axis direction. Tensile tests showed that reduction in strength in the z-direction can be as large as 78% for ABS and PLA, while carbon-fibre-reinforced ABS shows an even stronger dependence, with strength varying by a factor of 8 depending on orientation [51]. Continuous carbon fibre-reinforced nylon, on the other hand, can have its strength along the fibre direction 150 times bigger compared to across layers. While anisotropy in 3D printing techniques other than powder bed fusion or vat photopolymerization is observed, the extent of anisotropy is different. Parts produced with SLS show a 10% drop in tensile strength on the z-axis compared to the x-axis, while minimal anisotropy is seen in SLA, with only about 1% difference. However, DLP techniques indicate noteworthy changes in directional stiffness due to the differences in tensile testing and print orientation.

The mitigation of anisotropy requires critical improvement in inter-layer bonding. One of the major factors is thermal history at the boundary between deposited layers. A good temperature, well above the Tg of the deposited material, is very useful for encouraging interdiffusion of molecular chains and providing a strong bond. Interlaminar fracture toughness has been found to increase considerably by maintaining optimal thermal conditions during printing, such as higher nozzle and bed temperatures. With reduced printing speed, the inter-layer bonding is enhanced by slow cooling and longer chain mobility. Advanced anisotropy approaches modify material properties and optimize printing processes. For example, ionizing radiation exposition induces cross-linking between layers, reducing anisotropy by 20-50%.

Target microwave heating of carbon nanotube-filled polymer composites, on the other hand, has succeeded in enhancing their bond strength by up to 275% [52]. For large components, IR preheating has been quite effective, with enhancements such as 500% in fracture energy and 80% in tensile strength. Excessive preheating, however, especially above 220°C, degrades the properties of the polymer. Optimizing IR energy transfer is thus crucial to find the most appropriate combination. There have also been some promising mechanical interventions. The addition of a tamper-a quickly oscillating platen located around the extruder nozzle-has improved the compressive forces and given a 52% gain in z-direction strength. Curiously, when the tamper was positioned under the nozzle to provide extra compression, strength was reduced, probably due to excessive cooling preventing layer bonding. Again, this illustrates further work is required to optimize both the tamper design and operational parameters. Other methods, such as laser-assisted bonding, have been much more successful. In fact, laser systems have demonstrated increases of up to 195% in tensile strength and 50% in interlayer bond strength, which positions this tool favourably for the problem of anisotropy in AM. Such combined efforts indicate that anisotropic mechanical properties have an important role in the development of 3D printing. The enhancement of interlayer bonding, accompanied by the optimization of thermal and mechanical procedures, permits researchers to produce components with improved structural robustness and reliability. These contributions are especially important for applications requiring high mechanical performance and dimensional stability, particularly in the context of large-scale additive manufacturing [53].

7.3 Process control and quality assurance

Large-format 3D printing needs robust process control and quality assurance due to the huge consumption of materials and energy involved in the process. To achieve consistent quality, defect-free production is very important to establish the technology as a reliable cost-effective manufacturing solution.

Material extrusion presents challenges in maintaining uniform material deposition, especially during transitional operations such as starting, stopping, and navigating corners. The delayed response in material flow during these transitions often results in defects like under extrusion at the start and oozing at the end, leading to visible seam inconsistencies. These issues are more pronounced when larger nozzle sizes are used. In turn, scientists from ORNL have come up with the *Posiverter*, a machine regulating the material feeding to prevent delays, therefore improving seam quality [54]. Corner bulging and narrowing due to mismatched material feed rates in deceleration and acceleration, respectively, have also been minimized by feedforward control mechanisms, which anticipate any variation in flow to adjust to smoother transitional changes to guarantee better deposition quality. Another critical aspect of process control is temperature management. Larger extruded filaments have a higher mass and thus cool down more slowly-about 0.5°C/s-and require extra wait time to solidify before depositing subsequent layers. In the case of shorter toolpaths, such delays are especially relevant to give the material time to sufficiently solidify and support the subsequent layers in maintaining structural integrity while avoiding deformation.

The main problem with vat-photopolymerization is shrinkage during and after printing, which severely causes geometric distortions and impairments in functionality. Studies have shown that variations in parameters like laser exposure time, concentration of photo initiator, and UV-curing time can result in a significant reduction of shrinkage. Among all, post-print UV curing was more effective, with areal shrinkage rates as low as 1%. It must be underlined that increased layer spacing and structure height amplify the effects of shrinkage, and thus only carefully optimized process parameters are necessary [55]. Generally, besides the proper choice of process parameters, effective monitoring is mandatory to ensure the quality of printed parts. While manual inspection for each layer would be time-intensive and laborious, correlating sensor data with possible defects remains a complex task.

To overcome the limitations described above, machine learning algorithms were integrated into automated monitoring systems. Real-time sensor data analysis is possible with such systems for the detection of deviation from normal conditions that can indicate potential defects. In this way, dependency on manual inspection will be drastically reduced and proactive quality control through in-process closed-loop feedback mechanisms is possible. Machine learning-driven monitoring can bring about potential transformation in solving various quality issues. Such systems analyse real-time sensor data for the detection of seam anomalies, inconsistent material flow, and thermal fluctuations. This will help in the reduction of material wastage, energy consumption, and enhance the efficiency level in production. Moreover, it reduces the requirements for post-processing or rework by a great amount with its incorporation, hence enhancing the reliability of the processes. Advanced process control and quality assurance strategies include, among others, the development of the *, Posiverter*, feedforward mechanisms, and machine learning-based monitoring, which represent a further critical step toward large-format 3D printing. These newer innovations, apart from improving mechanical and structural properties of printed parts, will ensure consistent quality to maintain the technology as a sustainable and economically viable solution for industrial-scale applications.

7.4 Trade-off between production speed and surface finishing

Production speed is one of the primary factors in material extrusion that generally influences the throughput of the 3D printing process. Throughput, defined as the rate of depositing material, depends directly on the maximum volumetric speed, being a function of print speed, layer height, and extrusion width. While increasing these parameters can enhance throughput, there are inherent limitations to achieving higher speeds due to constraints in the moving mechanism of the printer. Furthermore, faster print speeds typically result in compromised surface quality, leading to rougher and less aesthetically pleasing surfaces on printed objects.

This is all closely related to nozzle size: the larger the nozzle, the more material that can be deposited, increasing throughput. But this usually comes at the cost of a worse surface finish, since the increased thickness of the layers makes the 'stair-stepping' effect more pronounced on the surface of the printed object. This is one of the most important trade-offs between production speed and surface quality in material extrusion and drives the development of novel nozzle designs that try to find an appropriate balance.

Examples for such solutions include adaptive nozzle systems, which can change between larger and smaller nozzle dimensions depending on the geometry to be printed. Such systems, designed to optimize both throughput and surface quality, deploy smaller nozzles in detailed or angled regions to enhance surface finish without sacrificing the overall production speed by a great magnitude (figure 18). This active method reduces the adverse effects of larger nozzles on surface quality while achieving faster depositions in areas where a high degree of finesse is not needed [56].

The development of such a multi-resolution approach for printing large composite parts with a robotic 3D printer with dual six degrees of freedom manipulators by Batt represents another advance toward optimizing both the speed at which a part can be printed and the quality of its surface. This system enables one manipulator to use a large nozzle to rapidly print part interiors, while the second manipulator utilizes a smaller nozzle to create high-quality surface finishes on the outside. This multiscale approach significantly reduces build times without sacrificing surface quality and frees up the printing possibilities for non-planar surfaces as well, rather than strictly along horizontal planes.

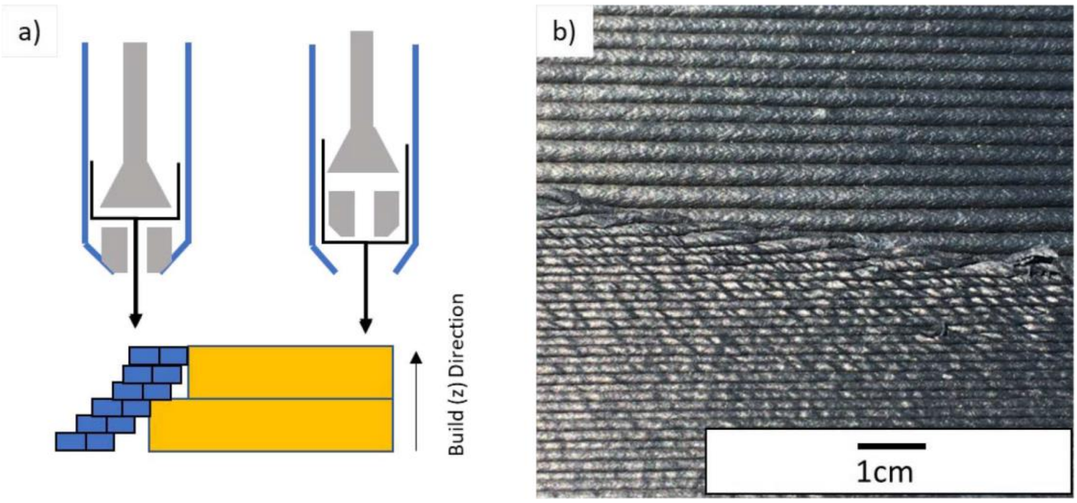

Figure 18 Variable size nozzle to improve surface quality without significantly sacrificing print time. (a) Mechanism of variable size nozzle and (b) the difference in surface finish using different nozzle size[32]

Other developments related to multi-nozzle setups have also improved deposition rates. Mhatre et al. presented a multi-nozzle printhead design with an extra rotational axis to achieve higher deposition rates by allowing more material flow. This, on the other hand, demands 4-axis toolpath planning with special considerations toward deposition accuracy. A new toolpath planning strategy was also proposed for gantry-based systems with multiple independent extrusion heads, following a static priority approach wherein one extruder has priority over the others. This approach greatly reduces the printing time with no compromise on part quality and allows better exploitation of multiple extrusion heads toward higher printing efficiency.

Collaborative robotics also finds its role in improving material extrusion speed. Shen et al. presented a large-scale 3D printing system with multiple collaborative robots. In that work, an optimization algorithm for task scheduling improved the printing efficiency by 73% compared to traditional methods. Collaborative robots avoided interference and optimized printing sequences, which showed a significant speed increase. They have pointed out, however, that sophisticated segmentation algorithms that can cope with complex geometries in 3D models are needed for the wider applicability of such an approach [57].

Another promising method for optimizing print scheduling was introduced by Poudel, who proposed a generative approach to automatically generate various printing schedules for objects segmented into parts. The approach searches over a wide solution space and allows collision-free printing of even complex geometries. While this process indeed has the potential for great gains in efficiency, its limitation again lies in the fact that, although the generated schedules are valid, they may still not be optimal. Future work needs to be done on integrating optimization layers into this system to find the most efficient and collision-free printing schedules.

These new nozzle designs, multi-nozzle systems, collaborative robots, and generative scheduling signify the balancing act between production speed and surface quality that has so far characterized material extrusion. It is quite possible to increase throughput without sacrificing surface finish by optimizing print parameters and using innovative technologies, hence making material extrusion a rather efficient and high-quality manufacturing technique. This can include everything from rapid prototyping to the production of functional parts, each requiring a balance of speed and aesthetics.

7.5 Complexity in toolpath generation for higher degree of freedom 3D printing

Despite the increasing application of robotic arm systems to 3D printing, which offers greater manufacturing flexibility through multi-axis printing, several limitations yet remain which require more research and development. One of the main challenges to be addressed with robotic 3D printing is the difficulty in achieving sharp corners, since these involve sudden changes in nozzle velocity. This will often introduce infinite acceleration, but most robotic systems are bound by the maximum acceleration that can be achieved, which is usually dependent on the type of actuators in use. During printing operations, the robot may also approach what is called a "singular configuration" in which there are extremely high joint oscillations. This seriously lowers the quality of the layers being printed. To avoid this problem, Apis Cor has implemented an algorithm that relies on the pseudo-inverse of the Jacobian matrix, so that smooth trajectory generation is guaranteed, especially when the robot approaches singular configurations [58].

Articulated robotic systems are another approach in large-scale 3D printing. Robotic arms are space-effective alternatives to gantry systems, which can be mounted on transportable platforms and thus are suited for on-site construction. Articulated robots generally have a much more restricted workspace than gantry systems. This is because of the large moments generated at the base of a robot when extended to maximum reach. For example, a "cylindrical robot" design, which features a first joint for vertical translation, a second joint with revolute motion, and a third joint with telescopic translational movement, can be space-efficient but faces difficulties when printing sharp corners, often resulting in circular toolpaths [59]. In this configuration, only three degrees of freedom (DoF) are utilized. More complex geometries demand higher numbers of DoFs for changing the orientation of the nozzle and allowing for complicated 2D movements that come with sharp corners. However, in practice, most 3D printing is done on a layer-by-layer basis, so more than four DoFs are not typically required, where the fourth DoF can be used to rotate the print head around the vertical axis.

The additional DoFs require specialized slicer software to create proper toolpaths for robotic arms. Although a few commercially available software's for robotic 3D printing exist, they are still in their relative infancy and have much room for improvement. For example, Lim et al. used Grasshopper, a plugin for Rhinoceros®, to generate curved layered FDM toolpaths within a single scripting environment. However, the generated toolpaths must still be checked for collisions via a post-processor, an often-multi-software process. The interoperability and integration of the necessary functions related to robotic 3D printing should be better for future software solutions so that different teams working with the same digital design representation can collaborate seamlessly [60]. Considering that all the processes in 3D printing are digitized, interoperability among architectural design, structural analysis, and printing should be guaranteed.

In addition, to minimize manual involvement, the translation of the digital model into a format compatible with the 3D printing process should be done to make the building process easier and faster. This verification should be automated. Moreover, the creation of digital models for 3D printing is still a time-consuming process; thus, software and process optimization developments are still necessary for further improvements in efficiency in robotic 3D printing.

7.6 Recyclability of materials

Additive manufacturing (AM) parts typically require post-processing steps, such as machining to smooth surfaces, which generates a significant amount of waste. This waste, often composed of plastic that may contain carbon fibres or other fillers used to stabilize the print, complicates recycling efforts. Recycling composite materials, while offering considerable potential, is a complex process fraught with challenges. The biggest challenge with these materials, however, is how to separate the different components since each of these components needs to be segregated into their pure forms that can easily be recycled effectively.

Traditional methods of recycling are ill-prepared to deal with such complexities that composites pose. For example, thermoplastics can be melted and then remoulded, but the resulting temperatures often lead to deterioration of both the thermoplastic and reinforcing fibres, which nullifies it as an approach for composite materials. Further development of sophisticated recycling methods is required, including chemical and mechanical recycling. Chemical recycling especially breaking down the composite to its chemical base-is highly essential since most of the photopolymer resins are thermosets, and hence, cannot be re-melted as in the case of thermoplastics. This aspect has made the recycling of photosensitive resins even more cumbersome. These chemical recycling processes degrade the cured resin into its chemical components by using different types of chemical treatment, which can then presumably be recovered for the synthesis of new resin. This is complicated and still largely in development [61].

One of the major problems of composite recycling is that the quality of the material always remains worse than that of the virgin materials, since during recycling processes, the material characteristics are degraded. An example here would be that recycling thermoplastic materials leads to a reduction in molar mass and thus reduces tensile strength. Ongoing research is important in the enhancement of the qualities of recycled composites by improved techniques of processing and using advanced additives.

Other challenges include the economic viability of recycling composite materials. Collection and transportation costs are high, as well as the processing cost. The market for the so-called recycled composites is still at an emerging stage. Any technological developments in reducing the cost of recycling with value-added recycled products could make the process more viable economically. Despite these, recycling composite materials allows for considerable environmental benefits. Reducing waste even from such industries as 3D printing may considerably reduce the acute negative impact on the environment. New recycling methods can turn waste into a resource of high value, thus stimulating the circular use of materials where it is reused and not wasted.

Research and development provide a key to the future of composite material recycling. Research to develop new recycling methods is under way, including "design for recyclability," which includes designing composites that are easier to recycle in the first place. Another very promising area of research involves bio-based composites, which might be simpler to decompose and recycle. Furthermore, the establishment of industry standards and regulations would even further stimulate composite material recycling. Policies that require responsible product end-of-life management would encourage manufacturers to design products that are more recyclable.

8 Post processing

Post-processing of parts built on most AM machines is highly dependent on the preparation of a part for its intended form, fit, and function. Depending on the AM process, the reason for the post-processing will vary. Focusing on the post-process techniques, this chapter are those used to enhance a component or to overcome limitations due to AM.

- Post-processing to improve surface quality
- Support Material Removal
- Surface Texture Improvement
- Aesthetic Improvement
- Post-processing to improve dimensional deviations
- Accuracy Improvement
- Post-processing to improve mechanical properties
- Property Enhancement Using Nonthermal Techniques
- Property Enhancement Using Thermal Techniques
- Preparation for Use as a Pattern

Post-processing techniques for Fused Granulate Fabrication can be very important in enhancing surface finish, dimensional accuracy, and the mechanical properties of printed parts. Due to its large bead size and layer height, FGF will generally require post-processing if a part is to meet industrial standards for functional or aesthetic applications. Below are listed the main post-processing techniques used in FGF.

8.1 Mechanical post-processing

Mechanical post-processing comprises a set of methodologies to enhance surface quality, improve dimensional accuracy, and develop better mechanical properties in the 3D-printed parts through physical alteration of their surface or internal geometry. They include manual or machine-executed processes involving application of forces, abrasion, or cutting actions to achieve a given finish and functional characteristics. Mechanical post-processing is applied at a large scale in additive manufacturing, especially in Fused Granulate Fabrication (FGF), in order to reduce surface roughness problems, dimensional defects, and structural issues.

- **Machining**

Techniques such as milling, turning, and drilling can further be used to refine the shape, dimensions, or surface of printed parts. This is especially good at achieving tight tolerances or adding features that can't be created during printing.

Material removal is also called machining, and the selection of a proper strategy is very important for finishing AM parts and tools. Many machining processes have been shown to be useful for AM post-processing, depending upon the complexity of the component and the material being removed. When the cause of material removal is mechanical force, the process is called conventional machining. If the metal cutting process is carried out without mechanical forces, the process is stated as advanced machining.

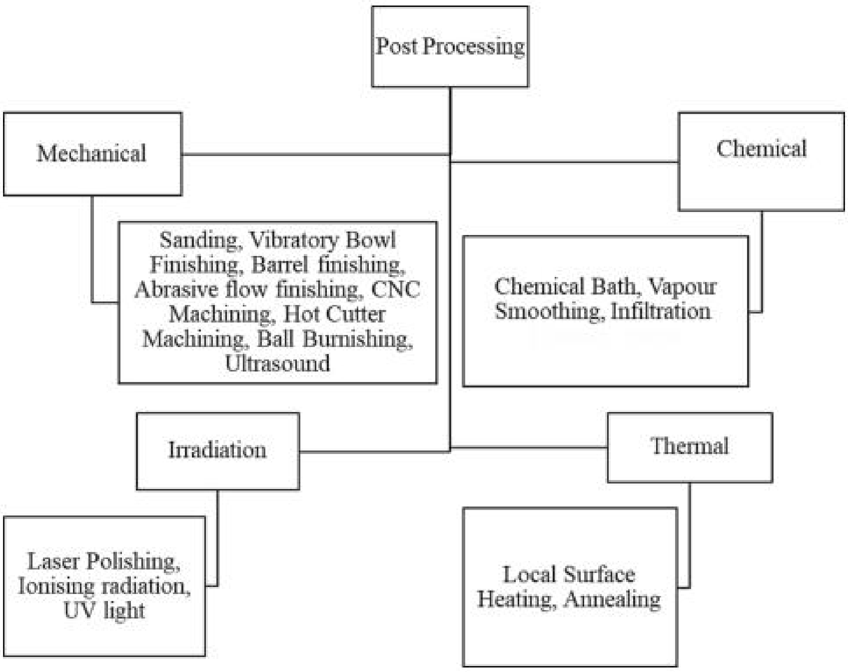

Figure 19 Post processing categories [62]

- **Sanding/Polishing**

Abrasive materials are used to smooth rough surfaces or to obtain a glossy finish. Sanding may be done manually or by automated means; polishing may be done with the aid of rotary tools or special compounds. Grinding is the most common abrasive machining method and provides high surface quality and dimensional accuracy. AM can produce very hard materials, such as those used in drill and milling bits, and to post-process these hard materials, CNC form-grinding is useful. Grinding is highly used for achieving a very smooth surface on an AM-produced part, such as when sample preparation of AM parts for various material characterizations such as scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) is needed. Grinding has limitations for complex parts, which limits the usage in the AM field.

Lapping and cleaning/polishing pads using rotary devices are also commonly used to remove rough surfaces of AM parts. Due to high speed and soft abrasive materials, these grinding processes are useful for finishing. Lapping and cleaning/polishing are normally performed with simple rotary movement (single axis), so they are not suitable to improve dimensional accuracy in complex geometries.

- **Shot peening/blasting**

Shot peening or blasting represents one of the common methods of mechanical post-processing for the enhancement of surface properties and performances of 3D-printed parts, mainly for additive manufacturing techniques on a large scale, such as FGF. The process involves bombarding the surface of a part with high-velocity media in the form of steel, glass, or ceramic beads. The impact will cause small indentations that plastically deform the surface, thus inducing compressive residual stresses. These stresses drastically improve the fatigue strength, cracking resistance, and life of the component.

Shot peening is a method that induces residual compressive stress by bombarding surface with very hard spherical media in a controlled operation. The media is generally steel, ceramic, or glass, but can be any powder with equal or greater hardness than the workpiece. Shot peening acts like a tiny peening hammer producing a small indentation on the surface. In thermal-based AM techniques such as Material extrusion, PBF, and DED, periodic heating and cooling create high residual on the surface of the workpiece. Shot peening can enhance the states of surface stress by causing beneficial residual compressive stress. Proven results under controlled shot peening present a dramatic benefit on the strength and life of components that makes the material more resistant to fatigue, fretting, and stress corrosion cracking. Shot peening improves the surface characteristics of metals, composites, and polymers. By using small media, the process can be applied for intricate and lattice shapes. By using media that is identical to the powder used to create the AM part, the powder can be recycled and placed into the AM machine for further use. 3D printing of Turbine blades and gears are very demanding areas in AM where surface treatment like multi-axis shot peening is required. Figure 19 shows a schematic of shot peening.

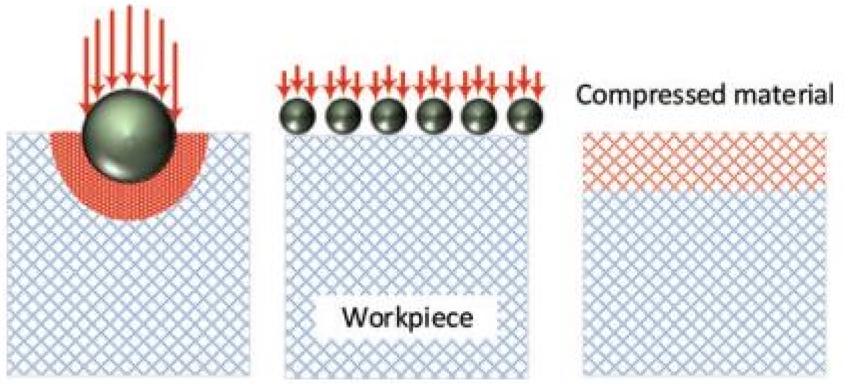

Figure 20 Schematic of shot peening

The table 1 in appendix describes analysis of the mechanical post processing treatments

8.2 Chemical post-processing

Chemical post-processing involves treatments using chemicals to enhance surface quality, functionality, and aesthetics in 3D-printed parts. This technique turns out to be very effective in smoothing surfaces, removing defects, and preparing parts for further applications such as coating or bonding. It can be widely applied with FGF and other additive manufacturing techniques where surface roughness or structural imperfections can arise during the printing process.

Vapour smoothing is one of the general methods in chemical post-processing. The parts are subjected to a certain chemical vapor-for instance, ABS with acetone and polycarbonate with dichloromethane-which partially dissolves the very top layer, creating a smooth, shining surface finish. This technique is notably helpful for attaining superior aesthetics or a reduction in friction in functional parts.

Chemical etching is performed with the treatment of acids or alkali solutions onto the surface to remove layers that are rough or unwanted. This process is generally done with metals or composites when tight tolerances in dimension are required or when certain surfaces need preparation for a coating or adhesive application.

Cleaning by a solvent is one of the common post-processing techniques for removal of contaminations, oils, or residual materials from the printed part. For example, polymer-based parts can be swabbed with alcohol or other cleaning agents to prepare the component for improved adhesion or to ready it for painting.

Chemical treatments may also encompass surface modification processes such as plasma treatment or chemical priming that enhance hydrophobicity, corrosion resistance, or paint adhesion. Chemical post-processing has its merits, but great caution should be exercised in concentration, exposure time, and environmental factors since over-treatment can lead to material degradation or changes in the surface that are not desired. Chemical post-processing has great enhancements in quality and performance; hence, it is considered an important step in the realization of precision, durability, and functionality in advanced 3D-printed components.

Chemical-Based Advanced Machining Processes

Chemical Machining (ChM) ChM employs corrosive solutions or baths of temperature-regulated etching chemicals to remove material. Inert materials known as maskants are used to protect specific areas that shouldn't be removed. ChM is suitable for complex materials that can be damaged by cutting forces in conventional machining. ChM is used to remove the materials from the surface of the workpiece and material removal rate is uniform making it suitable for thin walled and lattice structures. ChM can be used for etching samples for microstructural characterization. It achieves accurate dimensional tolerances and therefore can be used as post-process method for jewellery and aerospace parts. The disadvantages of ChM are the generated gas from corrosive substances and low material removal rate. The material range for ChM is limited, and finding a suitable maskant for different materials is problematic.

The Austrian company Hirtenberger founded the method ChM to remove supports and smooth AM-produced metal parts later sold to Rena which is providing commercial services now. Using a combination of hydrodynamic flow, electrochemical pulsing, particle-assisted removal and surface cleaning, a multistep automated technique removes supports and performs rough and fine material removal processes. Supports must be printed in unique ways so that they are removed by ChM, without substantially removing material from the part. This system is applicable for most metals and alloys regardless of hardness. Hirtenberger claims a surface quality of Ra = 0.5 µm, which is suitable for many applications. Table 5 gives the overall summary of the chemical post-processing treatment. Due to the large size of AM parts in LSAM, some methods have constraints and limitations.

Table 4 Chemical post-processing treatment: Analysis

Post Processing Method	Principal	Main Process Parameters	Merits	Demerits
Chemical Bath	To determine CBF. a part is submerged in a chemical bath that includes solvents such as dichloroethane, dimethyl ketone, or ester, as well as solvents that include chlorides.	Nature of chemical agents, immersion time, temperature	Fast and low cost technique, complex geometries can be created	Large amount of chemical solution required; small features can be eroded
Vapour Smoothing	The Vapour Smoothing finishing technique reflows the material by creating a controlled reaction between chemical vapours and the outer surface of the manufactured product.	Number and duration of smoothing cycles, temperature, nature of chemical agents	Short processing time, negligible dimensional deviation	Non uniform finishing, low process control
Infiltration Coating	The entry of a low-viscosity liquid substance into porous components is known as infiltration. Coating comprises smearing an outer surface of the component with a thin layer of a coating substance.	Infiltrate viscosity, immersion time, temperature Immersion time, withdrawal speed, no. of dipping cycles, temperature, viscosity	Low cost, internal volumes can be treated Fast processing time, complex geometries can be created	Limited to porous parts, removal of excess infiltrate Impurity complications, non- uniform surface finishing

Plating	Plating effectively transforms a conductive substance into a non conducting material by adding a thin coating of conductivity to its surface.	Current density, solution flow rate and temperature, solution chemical composition, processing time	Durability and thermal resistance are improved	Suitable only for prototypes, surface preparation required, non- uniform surface finishing

8.3 Irradiation post-processing treatments

Irradiation is a method applied after the creation of 3D parts, to enhance their properties by means of different kinds of electromagnetic radiation: ultraviolet light, electron beams, and gamma rays. This method can also improve polymers and composite materials by making them stronger, more stable at high temperatures, among other things. It often involves crosslinking or polymerization, where radiation changes the molecular structure for better performance of the material.

UV light is usually how photopolymer resins are hardened quickly. It helps make it more resistant to scratching and just overall improves the finish of the surface. Electron beam treatments guarantee deeper penetration and allow for fine control, making them much more suitable for industrial or medical applications where structural enhancements are required. Similarly, gamma radiation promotes crosslinking throughout thick materials, increasing wear resistance and enabling simultaneous sterilization.
While irradiation treatments have significant advantages, they must be carefully controlled to avoid material degradation. It is a key part of modern additive manufacturing, which enables functional and durable parts for high-performance applications.

Laser polishing can be applicable to Large-Scale Additive Manufacturing (LSAM) parts under specific conditions, but its effectiveness depends on the material used and the scale of the application. large-scale application remains limited by the size and cost-effectiveness of the process. It is best suited for high-value applications where superior surface finish is critical.

Post Processing Method	Principal	Main Process Parameters	Merits	Demerits
Laser Polishing	During laser polishing, a laser beam is utilised to scan the component's surface	Laser speed and power, scanning path	Very high repeatability, finishing of parts having small dimensions	Time consuming suitable for planar surfaces
Ionising radiation	It improves polymer properties by generating high amount of interlayer crosslinking for Thermoplastic polymer	Radiation dose, temperature radiation sensitizers	Excellent potential to enhance polymer properties, internal volumes can be treated	High cost, safety issues, specialized operators required
UV light	Use of UV light for increasing crosslinking of photosynthesis polymer	UV Wavelength, exposure time	Low cost treatment, independent processing time	Applicable only for photopolymers, blind parts cannot be treated

8.4 Coating and Aesthetic Post-processing

Coating and aesthetic post-processing are some of the most important techniques in additive manufacturing for improving the appearance, durability, and functional properties of 3D-printed parts. These processes are particularly relevant for applications where the parts must meet high standards of appearance, weather resistance, or mechanical protection. This is the use of any paint or resin formulation available which would improve the aesthetic of the print. Painting may be done manually by using an air spray or brush. Two types of coating polymers were used, namely, polyurethane elastomer and liquid silicone. The details are provided in the reference. Both these products are commonly used in outdoor waterproofing.

Polymer Coating: While coating is usually done using spray paints and other formulations for aesthetic purposes, direct polymer coating, on the other hand, is found to increase the adhesion of 3D printing materials on textile fabrics by initially coating the latter with a soluble polymer layer (dissolved or melt polymer). One of its advantages is that adhesion can be substantially enhanced without significantly changing the haptic properties and the bending stiffness of a fabric. Plastisols are polymers which require solvent evaporation after coating. Epoxy resins are thermoset polymer coatings that involve curing.

8.5 Thermal post-processing treatments

Thermal post-processing is one of the most critical methods to enhance Fused Granulate Fabrication (FGF) and Large-Scale Additive Manufacturing (LSAM) parts. This involves developing controlled heating processes, including annealing, to relieve internal stresses and increase mechanical properties. Warping resulting from thermal gradients formed during printing can also be reduced by such treatments. Moreover, heat treatments increase the crystallinity of semi-crystalline thermoplastics and, therefore, improve their thermal and chemical resistance. In large-scale applications, heating chambers or localized heating devices are adopted for uniform treatment in massive components. In addition, processes like hot isostatic pressing (HIP) are adopted to densify these parts to reduce porosity and increase strength, ensuring functional and structural reliability.

Post Processing Method	Principal	Main Process Parameters	Merits	Demerits
Local Surface Heating	Local heating with light projector	Air jet velocity, temperature, nozzle speed	Low cost, flexible tool	Local Overheating, internal channel cannot be treated
Annealing	A component is heated to a certain temperature, held at that temperature for a predetermined amount of time, and then slowly cooled to room temperature.	Temperature, time	Low cost, internal volumes can be treated	Warping issues, high processing time, dependent upon polymer properties

8.6 Challenges in post-processing

Post-processing in 3D printing is very important because it improves the mechanical properties, surface finish, and dimensional accuracy of printed parts, especially in large-format printing. Kumar and Velmurugan reviewed different surface treatment and surface modification techniques for 3D printed materials in general, touching on Operations such as machining, blasting, polishing, and texturing. oxidation, coating, and deposition. However, the post-processing in LSAM poses distinct challenges: overseeing the microstructural heterogeneity that affects mechanical properties and navigating complex surface the finishing and metrology of large and complex components. Those challenges require innovative solutions to ensure the excellence and effectiveness of large-format 3D Printed parts.

- **Managing microstructural heterogeneity that affects mechanical properties**

In polymer 3D printing, control of microstructural heterogeneity is important to obtain the homogeneity of mechanical properties in printed parts. Further, changes in printing parameters such as temperature, printing speed, and layer adhesion could lead to changes in material density and strength, remarkably affecting the durability and resistance of the final product when subjected to stress.

For such challenges, precise control of printing parameters and further post-printing treatments homogenize the microstructure. Scaling up 3D printing processes complicates post-processing owing to the greater volume and surface area, whereby uniformity in treatments becomes difficult. Heat treatment, especially isothermal annealing, has been found to enhance the mechanical properties in 3D printed parts. For example, isothermal annealing at 250°C for 18 hours enhanced the mechanical properties of carbon fiber-reinforced polyphenylene sulfide (PPS) parts through increased crystallinity and storage modulus. However, there are still difficulties in applying uniform heat to large parts, which has driven innovation in approaches such as segmented heating and infrared treatments to achieve better heat distribution [63].

- **Navigating complex surface finishing and metrology for large and intricate parts**

Surface finishes and dimensional measurement accuracies are tough to realize in large-format 3D printing of complex parts. The larger the size and geometry of the parts, the more challenging the task becomes, requiring advanced surface smoothing, polishing techniques, and precision metrology. These will help in fulfilling the functional and esthetic requirements of precision-intensive industries, such as aerospace, automotive, and medical. Integration of post-processing with robotic machining can be one of the major solutions for achieving precision and efficient surface finishing; this, however, involves very complex programming of robots since geometries may vary, and a trade-off is needed between efficiency and precision. Systems most used in geometrical metrology within additive manufacturing include tactile coordinate measurement machines (CMM), optical methods, and X-ray computed tomography. XCT is particularly useful for measuring internal features of highly complex components, and hence, the method of choice for quality inspection. However, large size and material thickness in large AM parts reduce the effectiveness of XCT, while some devices are unable to measure components beyond specific size and weight limits [64][65].

9 Conclusion

AM is touching the lives in many walks of industry and is fast becoming another or an auxiliary option opposite to the traditional formative and subtractive methods. By now, different industrial sectors have explored the benefits of using AM in their processes and, as highlighted, the build size enlargement of these technologies is of paramount importance for their further applications in this field.

This master thesis explores the general review of large-scale additive manufacturing, with focus on pellet based LSAM systems. Case studies in various industries have shown the benefits that pellet-based LSAM technologies bring in these areas and should encourage researchers and companies to do more work in this field. The use of the technology significantly reduces manufacturing time and costs, but it must be kept in mind that this started a few years ago, and parts of the technology can still be better. During the setup phase, one has to take proper care in the factors of part orientation, infill density, layer height, and support positioning, taking into consideration the main characteristics and requirements of the component. If the production timeline is the critical constraint, and mechanical strength or surface finish is less important, then the process parameters should be set to maximize print speed. In contrast, should mechanical strength be the foremost consideration, it is imperative to modify the parameters appropriately to enhance the structural integrity of the fabricated component.

Parts with high heights may be subject to dimensional inaccuracies due to the vibrations produced by the printer or may have problems of curling if there is no constant temperature control of the printing chamber. Other work is needed to investigate the possibility of printing with multiple materials or to combine AM with other processes, like hybrid techniques. The studies presented in this review testify to these needs and demonstrate the great interest from the scientific community in this technology.

This innovative leap in LSAM enables the fabrication of complex industrial needs through multi-material printing, adding significantly to the growth of FGF. It also facilitates the building of parts that can have a variety of different materials within a single build for enhanced functionalities and properties toward specific applications. Biodegradable plastics, bio-based thermoplastics, and high-performance thermoplastics together with MIM granulates and ceramic composites continue to extend the realm of FGF LSAM possibilities. Significant developments, like the creation of foamable granulates, conductive polymers, and functionalizing materials with properties of being antimicrobial and UV-resistant, have helped enhance this capability for adaptability. In doing so, the manufacturing of lightweight, high-performance, and sustainable structures has found suitable applications in industries dealing with high stress uses aerospace, automotive, and medical devices.

Beyond material innovations alone, the integration of electronics, sensors, and positioning mechanisms has redefined component functionality manufactured by FGF LSAM. Techniques printing on conductive beds, embedding components within printed structures, and placing elements onto completed parts further streamline a production process and enable smart, interactive systems to be fabricated. These advances offer a reduction in assembly times with improvements in the performance of end-use components and provide the pathway to enabling embedded sensing, actuation, and multifunctional design. While significant challenges related to material compatibility and the precise control of thermal and rheological properties remain, research and development will doubtless continue to overcome such barriers. With technology in development, multi-material printing in FGF LSAM will be the future of sustainable and versatile manufacturing-a robust platform for future industrial applications.

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Appendix

Table 1

Post Processing Method	Principal	Main Process Parameters	Merits	Demerits
Manual finishing or Sanding	It is done with sandpapers of various grit sizes	Paper grit type and size, applied pressure and velocity	Suitable for prototypes	High processing time, low repeatability
Vibratory Bowl finishing	Use of abrasives with custom shaped pallets a bulk finishing process	Cycle time, Vibratory frequency, abrasive media size and shape	High degree of automation, good repeatability	Complex equipment, non-uniform finishing small holes and cavities can be an issue
Barrel finishing	It is like vibratory bowl	Cycle time, abrasive media size and shape, adopted compound	High degree of automation, good repeatability, low cost of equipment	Non uniform finishing long processing time, small holes and cavities can be an issue
Abrasive flow finishing	A complex method for micro- and nano scale edge contouring, deburring and surface finishing	Extrusion pressure, grit composition and size, media viscoelastic properties	Suitable for internal channels finishing	High cost
CNC Machining	Use of CNC Machines	Cutting speed, feed rate, cut depth	High degree of automation High repeatability	long processing time, internal complex surfaces can be inaccessible
Hot Cutter Machining	Heated machining tools are used to keep the component's integrity while reducing cutting forces compared to machining at room temperature.	Cutting speed, feed rate, cut depth Cutting tool temperature	High repeatability, Low Cutting forces as compared with CNC machining	Complex surfaces cannot be easily treated

Ball Burnishing	A surface plastic deformation is induced during the cold working finishing process of burnishing by sliding contact with the appropriate tool.	Feed rate, pressure	Low-cost process, non- chip machining	Internal surfaces cannot be treated
Ultrasound	The internal porosity and outward flaws of AM polymers were minimised by	Ultrasound frequency and amplitude	Internal volumes can be treated, no chemical reactions are caused the simultaneous application of pressure and ultrasonic vibrations	Hollow parts cannot be treated, depth will be limited

Sectors	Applications	
Aerospace	Aircraft interior and cabin parts	Molds and Tooling
	China Eastern Airlines	Advanced Composite Structures Layup tools
	Spare newspaper holders and electronic flight bag supports	Piper Aircraft - Polycarbonate Hydroforming Tools
	China Eastern Airlines	Airbus - Autodesk - Plastic mold for a partition wall
	Door handle covers	BAE Systems
	Air grill-Lufthansa Technik	CARACOL
	Spacer Panel - Airbus	Additive Engineering Solutions
	Curtain Header - Diehl Aviation	Rockets
	Airbus A320 sidewall - Etihad Airways	Lockheed - Rocket Fuel Tanks
	Aerodynamic models and mockups	3D Printed Rocket Thrusters
	Prototypes	United Launch Alliance-ECS duct system
	Marshall Aerospace and Defense-Ducting adapter [125]	Unmanned Aerial Vehicles
	NASA - Inlet guide vanes (IGVs) and acoustic liners	Aurora Flight Sciences
	Taylor-Deal Automation	Surrogates
	Fluid and air handling parts	Bell Helicopter
Automotive	Components for Cars	Motorcycles
	Urbee Car	Fender and Fork Covers
	Electric Vehicles	Prototypes
	Strati Car	3-D-Printed Shelby Cobra
	LM3D Swim	ORNL Utility Vehicle
	YOYO	Ford - Stratasys
	Project Chameleon Platform	Airless tires
	Nikola Corporation (EV Trucks)	
Naval	Submarine Hull	Drones- Dive Technologies
	WC Cabins	Molds
Academic applications	Prototypes	Bioderived Materials

	Excavator Cabin	PLA reinforced with Poplar fibers
	Embankment Dam Model	
Architecture and construction	Architectural Models	Windows
	BCN3D - SUNTEM 3D	Furniture and Decorative items
	BigRep STUDIO	Skanska cladding
	Houses	Chairs and Tables
	Canal House in Amsterdam (Kamer Maker)	Off-site Construction
	AMIE structure (ORNL BAAM system)	Concrete Molds
	Qingdao Unique Products	
Energy	Wind Turbines	Hydropower
	Prototypes	Turbine Components
	Horizontal wind turbine blades	Tubes
	Vertical Wind Turbines Diverters	Magnets
	Wind Turbines Blades with Internal Structures	Molds and Tooling
	Nacelle covers	