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CRITICAL REVIEW

An overview of fused filament fabrication technology and the advancement in PLA-biocomposites

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Abstract

The escalating significance of 3D printing in various industries is underscored by its ability to rapidly and cost-effectively produce distinctive parts. Among the 3D printing methods, fused filament fabrication (FFF) has emerged as a highly productive and cost-effective approach. While extensive efforts have been made to enhance the qualities of FFF products, challenges persist in material availability and quality compared to traditional methods. This study provides a meticulous overview of the FFF process, delving into various 3D printing processes, polymers, and polymer composites. Despite documented efforts to augment mechanical, thermal, and electrical properties, material constraints remain a focal point. Our analysis extends to various PLA/biocomposites, shedding light on achieved improvements and potential applications. Looking forward, the future trend in FFF technology suggests a paradigm shift towards enhanced material diversity and performance. Anticipated applications span beyond traditional use cases, encompassing sustainable manufacturing, medical devices, and eco-friendly construction materials. This comprehensive review not only consolidates the current state of FFF and PLA-biocomposites but also anticipates future trends and potential applications. This research enhances the current knowledge of additive manufacturing and sets a standard for assessing developments in FFF technology by comparing them to previous works.

Keywords 3D printing · Fused filament fabrication · Polylactic acid · Biocomposite · FDM parameters

Highlights

- The additive manufacturing (AM) process and its various techniques are discussed in detail. A get-to-know for newcomers.
- Fused filament fabrication (FFF) materials (polymers and polymer composites) and PLA/biocomposite are discussed in detail.
- Various parameters used in the FFF process are discussed.
- Applications of FDM in the various sectors.
- Research gaps in the PLA/biocomposite are presented for future work.

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1 Introduction

The demand for three-dimensional (3D) printing applications has significantly increased over the past few years, and this trend is anticipated to continue. 3D printing is a method that uses a computer-integrated machining system to construct objects [1]. This technology could potentially heighten the use of raw materials and reduce waste while simultaneously delivering precisely dimensioned end products. Rapid prototyping (RP) was created in 1981 by Hideo Kodama, a Japanese researcher. Later, the stereolithography (SLA) process was instituted by Charles W. Hull. After that, Carl Deckard invented selective laser sintering (SLS) technology that utilises a laser beam to fuse the powder grains [2]. The development of this technology was followed by a batch of inventions such as contour sculpting, inkjet printing, powder bed fusion (PBF), and fused filament fabrication (FFF). The most notable 3D/AM techniques have been classified by ISO and the American Society for Testing and Material Standards (ASTM) [3]. AM technology is divided into seven categories by ASTM. Extrusion of materials is one of the seven

AM categories; the others are sheet lamination, vat photopolymerisation, binder jetting, material jetting, material extrusion, direct energy deposition, powder bed fusion, and material extrusion [4]. Each technique offers a unique set of capabilities, which vary depending on how it is performed.

The AM methods are primarily developed to create fine-resolution complicated printed structures. Two essential benefits are time and saving money; additional features of this technology include large printing structures, lessened print flaws, rapid prototyping, and improved mechanical qualities shown in Fig. 1. AM technology was primarily used to fabricate products for visualisations and validations of concepts. However, the rapid development of this technology has driven the manufacturing of end-use products, components, and tools [5]. The part made using additive manufacturing technology is built layer by layer using digital data prepared by computer-aided design (CAD) and computer-aided manufacturing (CAM) [6]. Through advancements in technology, 3D printing has the potential to revolutionise manufacturing and logistics operations through the use of a variety of techniques, materials, and equipment. Several industries have successfully used additive manufacturing, including biomechanical, automotive, aerospace, and building and construction sectors [7]. The worldwide market size for various 3D printing technology is exhibited in Fig. 2.

The most extensively used additive manufacturing technique for thermoplastics is fused filament fabrication (FFF). FFF is a technology in which the melted material filament is layered onto the building platform via a nozzle. It is a popular additive manufacturing method because of its fast production, cost-effectiveness, ease of access, wide range of material adaptability, and capacity to manufacture complicated components [10, 11]. Crump created FDM in 1988 to help market this technology, and in 1989, he established Stratasys. The method generates complex geometry while integrating the essential fundamental elements of additive manufacturing [12]. Other optimised series, such as FDM Dimension, FDM Titan, FDM Vantage, FDM Maxum, and

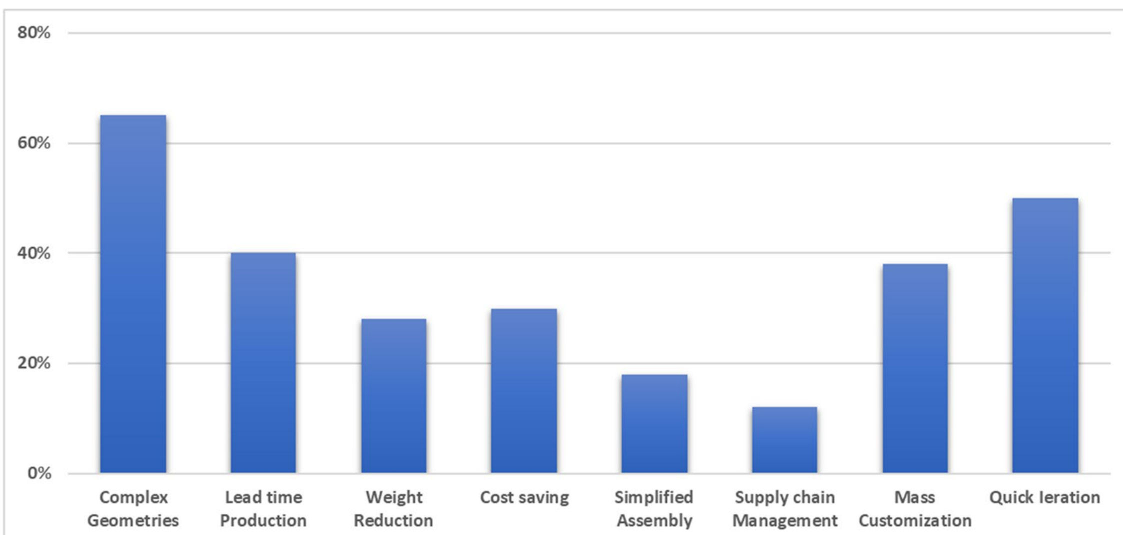
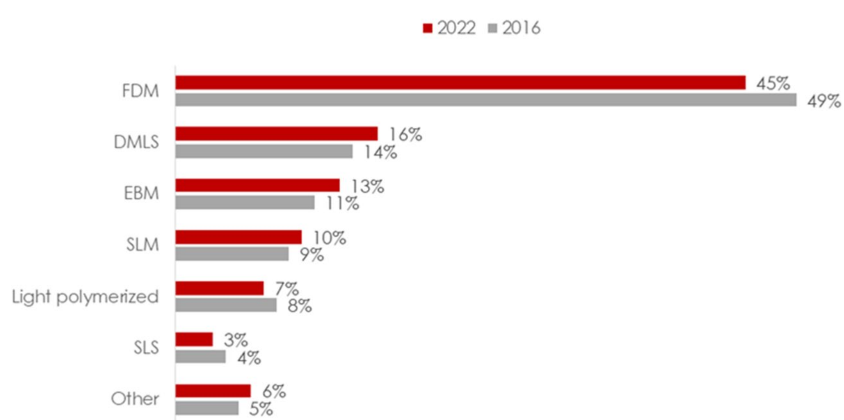


Fig. 1 Major benefits of AM technology [8]

Fig. 2 Worldwide market size for various 3D printing technology [9]



FDM 3000, was created to meet specific customer needs [13]. This technology involves melting thermoplastic filament and layering it over building plates in accordance with the CAD design. Up until the appropriate build structures are formed, the process is repeated. The bed is lowered after printing the first layer, followed by printing the second layer on top of the first layer, and so forth. Because of their favourable thermal and rheological qualities, plastics like acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) are among the most often used materials for FFF filament parts [14–16]. Apart from the named two popular materials, other materials that have been used include nylon, polyetheretherketone (PEEK), polyphenol sulphone (PPSF), polypropylene (PP), thermoplastic polyurethanes (TPU), high-impact polystyrene (HIPS), polyvinyl alcohol (PVA), and composite filaments [14, 17, 18].

According to the findings of research conducted on the literature reviewed, the FFF technology has been implemented in a variety of applications. This technique has the ability to generate useful goods by employing a wide range of polymers and polymer mixtures in the manufacturing process. Until now, the majority of the research that has been published has focused on developing new polymers and polymer composites that are suitable for use in FFF. This paper includes an overview of the 3D printing technology, new improvements in FFF technology, applications developed to obtain greater print quality, and a study of the materials utilised, process parameters, and applications made.

2 Additive manufacturing techniques

Unlike traditional processing, additive manufacturing necessitates the hardening of each layer before being printed on top of the following layer. The process is repeated until the computer-generated object is totally printed [19]. Each category of product is now available for purchase as a result of advancements in additive manufacturing processes and the availability of a wide range of materials for use in the product's construction. Each approach has its own benefits and drawbacks. As a result, several companies give customers the option of choosing the object's construction material powder or polymer [20, 21]. Because of recent developments, 3D printing is now more affordable and may be used in homes, libraries, and research facilities on a larger scale. The architects and designers employed 3D printing extensively in the project's early stages to create an aesthetically beautiful and useful prototype due to its quick and affordable prototyping capabilities [7, 22]. The use of 3D printing helps reduce the additional costs associated with developing a product or service. However, the application of 3D printing has recently increased significantly across many industries, from producing prototypes to final products. As an alternative, AM can create customised, low-cost 3D products in small quantities.

Contrarily, AM may print customised, small-quantity 3D objects that are reasonably priced. This is particularly useful in biomedical applications, where specific patient products are frequently required, and personalised functional products, which are currently becoming the trend in 3D printing, are increasingly desirable [23–25]. This AM/3D printing technology has been classified into seven categories by the International Organization for Standardization (ISO) and the ASTM, including material jetting, binder jetting, powder bed fusion material extrusion, sheet lamination, vat photopolymerisation, and direct energy deposition [26, 27]. The technique shown in Fig. 3 is used to categorise the many forms of 3D printing technology.

2.1 Material jetting

Liquid polymers are the raw ingredient in this process, which is employed as a raw material. The piezo print heads deposit polymer liquid droplets on the build plate, which are hardened by ultraviolet (UV) lamps. As a result of this technology, the ability to print poly jet images exists. Three distinct implementations of this operation are available [10, 29]. These three types are as follows: (1) drop-on-demand jetting, (2) poly jet technique, and (3) nanoparticle jetting [10, 30]. When dealing with larger objects, these are easier to use and have a lower entry barrier than the vat photopolymerisation (VP) approach. The benefits of this method are a smooth surface finish, great precision, and effectiveness [31, 32]. The two technologies that are used most frequently today are material jetting and inkjet printing (MJ). Compared to injection moulding, this technology produces goods having a more polished surface, enables the capacity to print in diverse materials, and there is less material waste because the printing process itself is so precise [33]. The inability to produce usable prototypes is one of this process's biggest flaws. This is because it uses waxes and polymers, which are more expensive and brittle than other additive manufacturing techniques [34].

2.1.1 Inkjet printing

Hewlett-Packard (HP) and Canon created the first contemporary inkjet printers in 1987. They are still in use today. Inkjet printers are essentially divided into two groups: continuous inkjet printers and drop-on-demand inkjet printers. Printers that print continuously are the most prevalent type [31, 35]. While the drop on demand (DOD) inkjet printer only generates ink when it is needed; however, the continuous inkjet printer consistently creates ink droplets. Continuous inkjet (CIJ) printing has a lesser resolution than drop-on-demand (DOD) printing, and the resolution of DOD printing

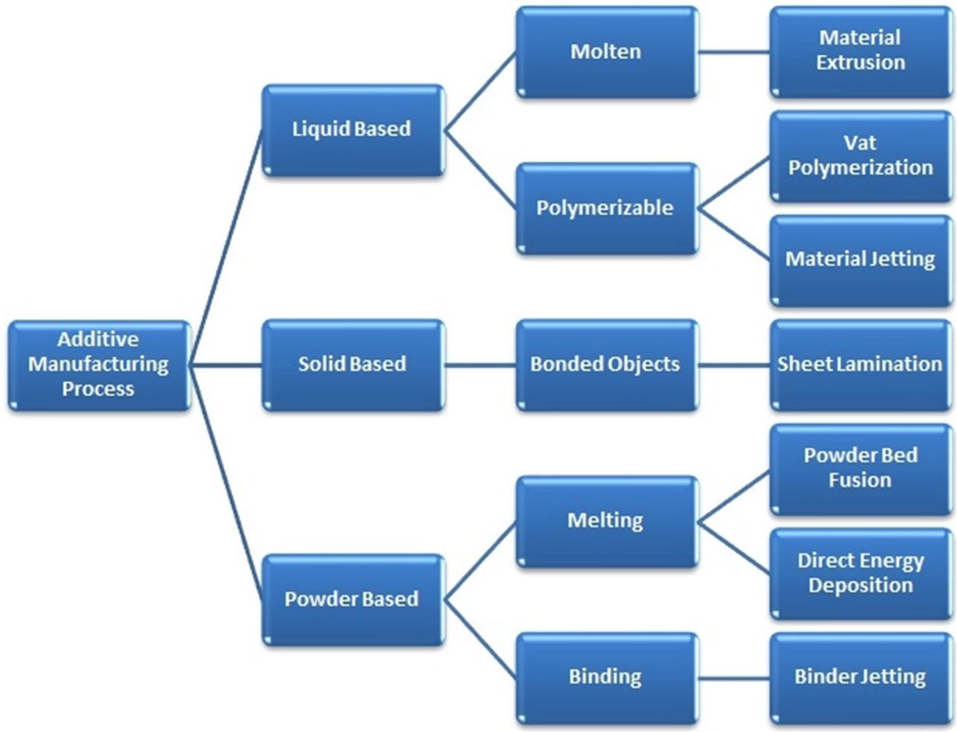


Fig. 3 Classification of AM process [28]

is higher [36, 37]. Figure 4 shows how the CIJ printing method regulates ink to flow through a piezoelectric crystal using a small nozzle. In this method, a high-pressure pump stretches the ink through the nozzle. The charger electrodes selectively charge the print head's ink; the resulting droplets create the picture on the matrix. The gutter receives the surplus materials and directs them there for recycling [38, 39].

In the DOD method, a thermal resistor's thermal buckling or piezoelectric actuation creates ink droplets. While the ink chamber is heated to a high degree at the start of the thermal process of DOD, bubbles are produced on the heater surface as a result of the heating; this is done to vaporise it. This will cause a pressure pulse, which will force the ink from the nozzle and cause it to be deposited on the objects [40, 41].

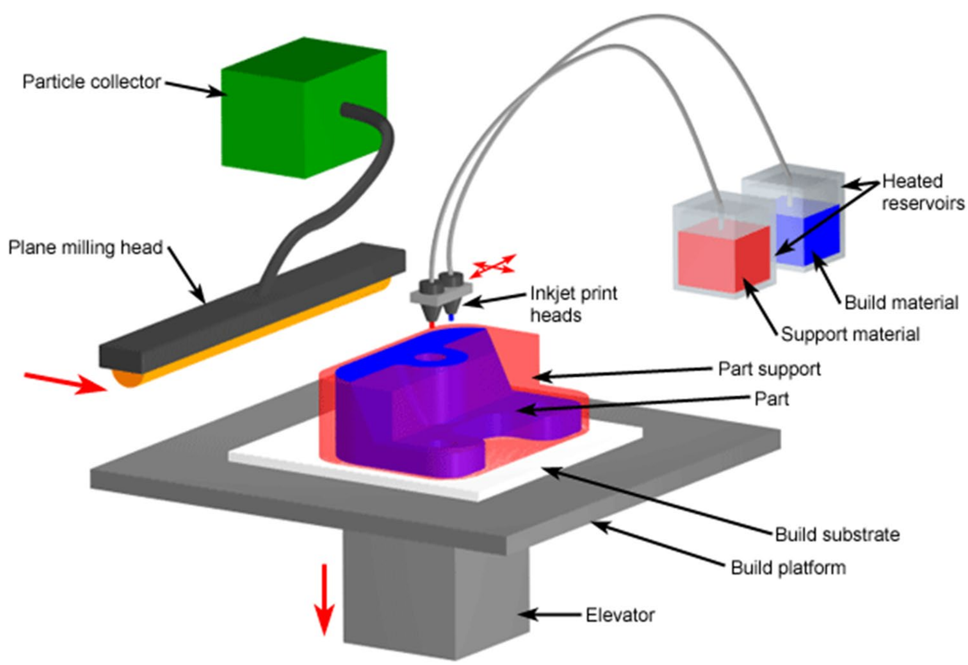


Fig. 4 Inkjet printing process [36]

This technology's benefit is that it reduces waste, benefits the environment, and does not require post-processing.

2.2 Vat photopolymerisation

In this method, a high-pressure pump stretches the ink through the nozzle. Electrodes selectively charge the print head's ink, and the resulting droplets are what create the image on the matrix. The gutter receives the surplus materials and directs them there for recycling [42, 43]. When metal is dispersed, resins are subjected to a laser; the resins undergo a chemical reaction that causes a transition from a liquid state to a solid state. Small monomers are joined together in a chain-like shape by the sun's photochemical process known as photochemical bonding. This approach is possible to get very high precision and surface quality. This process has accomplished an extremely high degree of precision and excellent finished products. Due to its speed, it is frequently employed for substantial construction projects with dimensions of $1000 \times 800 \times 500$ mm and a weight restriction of 200 kg or less [10, 44, 45]. Its drawbacks include the high cost of the machines, the need for additional processing time after resin removal, and the constrained supply of materials that are employed in the process [46].

2.2.1 Stereolithography

The SLA commercialisation methods' began in 1986, and it focuses on polymerising polymer chains. This SLA method uses two approaches: one is top–bottom, and the other is bottom-top. In this process, the top–bottom technique is superior than the other technique [47–49]. Epoxy/acrylates resins are irradiated with lasers utilising photopolymerizable resin monomers. Figure 5 depicts the computer system used to operate the laser head while the resins are utilised to cover the building platform. Initially, the product's boundary layer and supporting structures are printed, followed by printing the product's interior surface area. The building platform is covered with a thin layer of resin, which is exposed to the laser. This causes the photosensitive layer to go through polymerisation, and then the first layer is printed on the platform. After printing the first layer, the platform is slightly lowered along the *y*-axis, and the resins are spread over a predetermined region before the process is repeated. The extra material is removed from the platforms after each layer of material has been added. With a resolution ranging from 50 to 200 microns, this method prints the product layer by layer [10, 50, 51]. There are two main categories of stereolithography, depending on the situation: (1) projection-based stereolithography (PSL) and (2) scanning-based stereolithography (SSL). Similar to PSL, the SSL scans each layer separately [10, 52]. This SLA approach offers the best resolution compared to other AM processes and is rather swift. This SLA strategy's disadvantage is that printing is expensive and it involves a time-consuming operation.

2.2.2 Direct light printing

Carbon, in 2015, had developed an innovative membrane that can now help significantly speed up traditional DLP 3D printing [53, 54]. This type of 3D printing can create parts in under 10 min because it lacks the layer lines that are present in most other 3D printing techniques. DLP 3D printing is now feasible using visible white light and improved

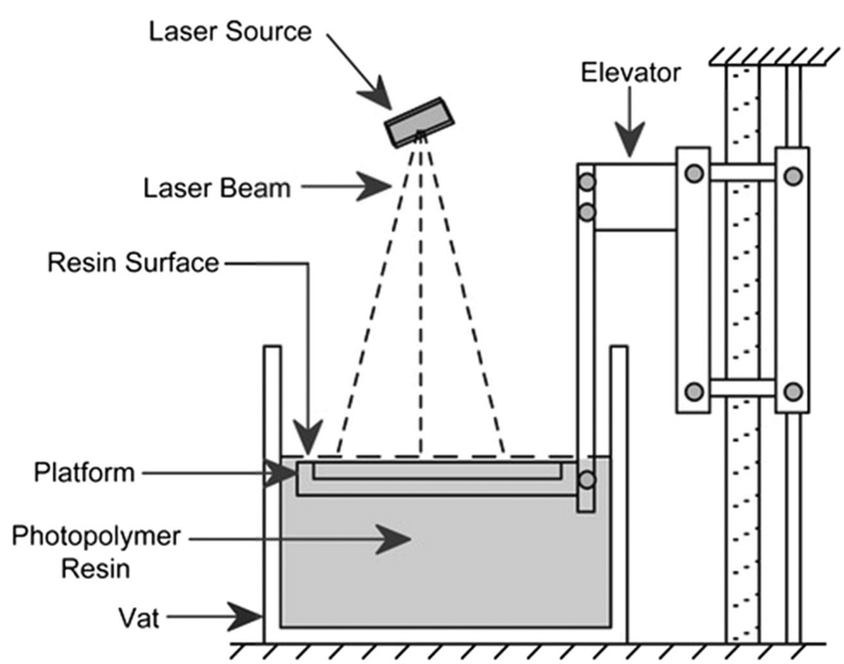


Fig. 5 Stereolithography process [47]

vat photopolymerisation. When a 3D model is created, it is saved as an STL file using CAD software. The STL file can then be divided into multiple layers by slicing or hosting software. Each layer is sent consecutively to a 3D printer and contains geometrical data. The DLP projection system is used to project an image onto a clear bowl. UV light activates the photo initiators, monomers, and blockers, causing the layer to polymerise and cure. The build platform is raised or lowered by a quantity equal to the layer thickness during the curing process, as shown in Fig. 6 [55]. The process must be repeated in order to project a new image when the 3D portion is finished. Using UV light with wavelengths between 360 and 420 nm, a monomer and an oligomer are transformed into a polymer [56]. Resins are the primary raw materials utilised in this procedure (standard, clear, castable, high temperature, rubber, and metal-impregnated). Most dental models, jewellery, prototypes, and automobile parts use this application [57].

2.3 Sheet lamination

To make the finished item, raw materials (worksheets) are cut with a laser or a cutter according to their shape before the laminating process [58, 59]. Rather than dissolving, the sheets are layered on top of one another and bonded together. Two of the most significant manufacturing methods employed in this procedure are laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM) [60, 61]. In addition, the speed of the process, the low operating costs, and the simplicity of material management all contribute to the system's overall efficiency. Although ceramic, paper, and metal can also be used for sheet lamination, polymer is by far the most common material [60–62]. One of the numerous benefits of this method is that it can be used to make ceramic and composite fibre items without the need for any additional support structures. Lack of resources and difficulty removing excess materials after lamination are two of the technology's drawbacks. Compared to other procedures, sheet lamination generates a large quantity of waste. The lamination process will decide how strong the bond is. In some circumstances, adhesive bonds might not always be sufficient to guarantee long-term strength and homogeneity.

2.3.1 Laminated object manufacturing

Before being sent to the platform for manufacturing, raw materials are usually retained in a roller and cut with a cutter or laser to produce sheet material [62, 63]. Figure 7 depicts the application of a second layer made in the same manner atop the first. Applying pressure with a hot roller, the adhesive coating is sandwiched between the two sheets. When the laser is used, waste is cut down to size and recycled accordingly. Surplus items are taken in and transported to a recycling centre. In this method, the final product is made using plastics, metals, fabrics, paper, and synthetic materials [58, 62–65]. Comparing this method to conventional ones, its key advantage is that it is frequently used to produce high-strength products. Another benefit is when manufacturing larger products, there is a reduction in tooling costs and a reduction in manufacturing time. The LOM method does not require the usage of support structures or post-processing tools [52].

2.4 Binder jetting

This procedure results in the liquid binder bonding with the powder to produce the end product. The desired form is then produced using an electrical heater after the powder has been evenly spread on the bed and the bonding agent has been poured over it by the print head [34, 38]. The powder bed is immediately lowered after the production of the first layer, and the powder is then scattered across the previously

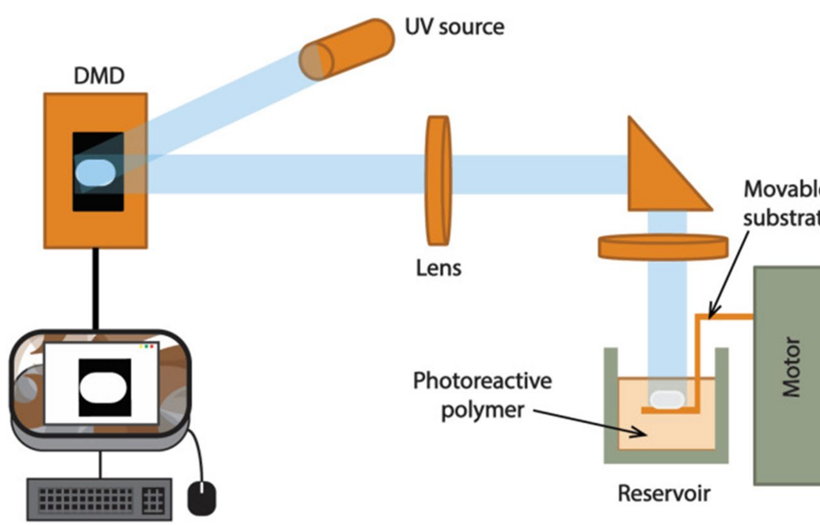


Fig. 6 Direct light printing process [55]

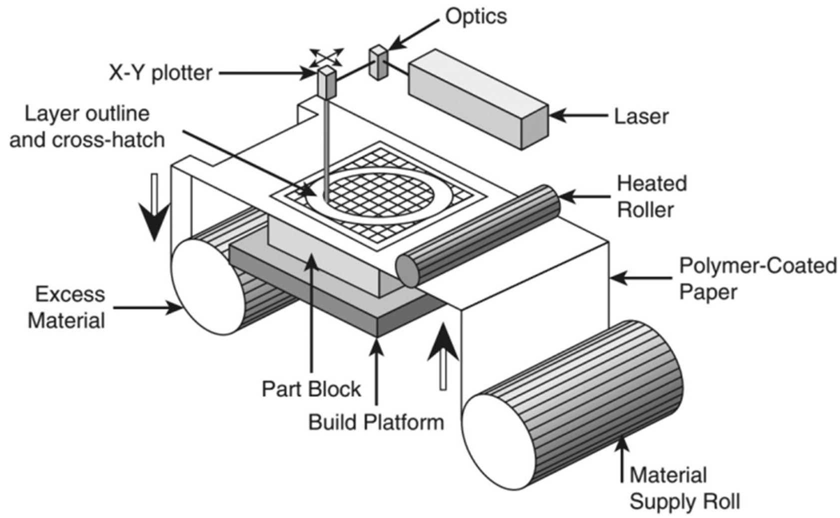


Fig. 7 LOM process [59]

printed layer. The operation is then carried out, as shown in Fig. 8. When compared to other additive manufacturing processes, the energy consumed is inexpensive, and so is the cost of operation [32, 38, 66]. This technique is capable of producing a wide variety of parts, and it is generally more efficient than other processes. In the case of binder powder, the double-material method results in various variants and mechanical qualities. The requirement for post-processing, the prolonged processing time, and the fact that it is not always ideal for structural features are some of its drawbacks [67, 68].

2.5 Powder bed fusion

One of the techniques utilised in additive manufacturing is powder bed fusion. The primary raw materials are in the form of powder. Powder forms the majority of the basic ingredients. By passing the materials over the machine's base plate and exposing them to heat, laser, or electron beams, the materials are first heated or sintered. The *z*-axis then swings downwards, allowing a brush or wiper to equally distribute the powder throughout the layer, and the process is repeated [69, 70]. Electron beam melting (EBM), direct metal laser sintering (DMLS), selective laser melting (SLM), selective laser sintering (SLS), and selective laser melting are the main techniques used in this procedure (SLM) [71, 72]. Another feature of the PBF method is that the layers before it are warmed to remove anisotropy. Another advantage of this method is that it is used for complex constructions that do not require additional support [73]. This technology's key advantages are that it is low cost, needs no special product support structure, can be utilised with a wide variety of materials, and the leftover powders from the process may be recycled. Some of the method's downsides include a slow print speed, a long print time, the need for additional

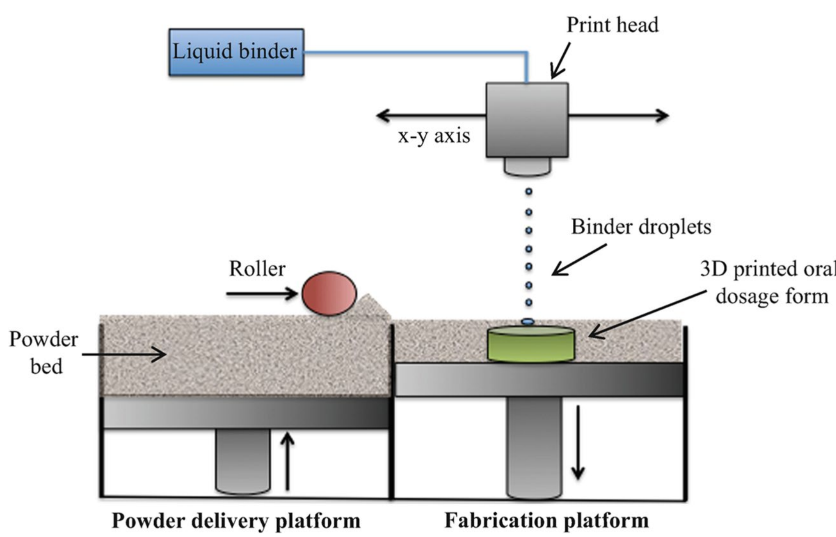


Fig. 8 Line diagram of binder jetting process [38]

post-processing time, a high power consumption, poor structural qualities, and a rough surface roughness [69, 74, 75].

2.5.1 Selective laser sintering

One of the greatest powder-based additive manufacturing techniques is SLS, and Carl Deckard invented it in 1987. Using a laser source, the powder particles are sintered together to form a solid structure, which is then removed [76, 77]. In this SLS technique, it is necessary to utilise two chambers. It uses a building chamber for printing and a feed chamber with a roller for putting powder onto the bed. Initially, the powder is fed from the feed chamber to the base plate of the build chamber, where it is evenly placed with the help of an application roller. Immediately prior to the laser exposure, the construction chamber is heated; after which, the Co_2 laser is irradiated over the powder to cure the material. Then, the building chamber is moved slightly downward, and the feed chamber is used to apply the powder to the printed layers and the process continues in this manner, as demonstrated in Fig. 9. A supporting structure is formed by any excess powders in the building chamber; this structure is then removed after the process is complete, and the excess material is recycled [76, 78, 79]. This approach is a cost-effective and flexible way to create prototype items with a higher density of components. In contrast to the SLS method, the operation costs are substantial because of the laser input's high power [30, 80, 81].

2.5.2 Electron beam melting

Another AM technique, known as electron beam melting (EBM), was created at Chalmers University of Technology in the late 1990s. EBM fabricates items using a layer-by-layer method, similar to SLM. In contrast to a laser, an electron beam is employed in EBM to melt and consolidate the powder material, as shown in Fig. 10 [82, 83]. The metal powder in the selected area is scanned by the intense electron beam to fuse it. This layering procedure is repeated until the metal components are completely dense. Compared to SLM, EBM has more difficult optimization requirements due to its more advanced processing parameters [84]. When using an electron, the only electrically conductive materials are metals, but when using a laser, any material that absorbs energy at the wavelength of the laser can be employed. In order to establish a vacuum when modifying the chamber's pressure, a small amount of helium is let in. When the chamber is vacuumed, a moving defocused electron beam scans the start plate and produces a heat buffer that stabilises the build temperature. The build platform descends based on the powder layer's thickness, 50–100 nm as the temperature stabilises between 600 and 750 °C [85, 86]. A defocused beam on the build platform uses a rake mechanism to heat and gently sinter the powder. The desired design outlines are preheated with a magnet, then melted using an electron beam that is deflected irregularly along the contour. Many points will fuse together to create a melted contour. The bulk of the material inside the contour is then melted using the hatch melting technique and is finely focused on an electron

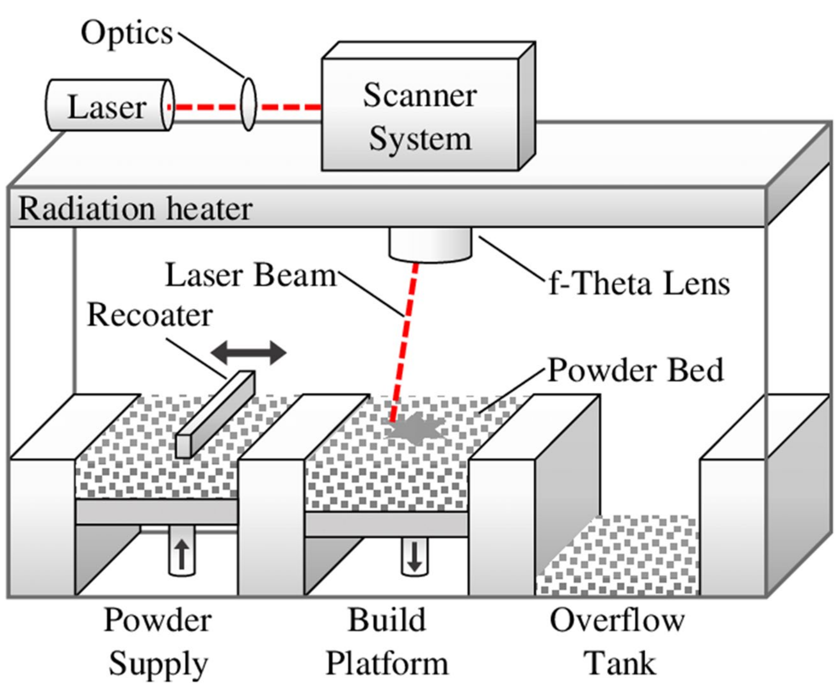


Fig. 9 Selective laser sintering technique [78]

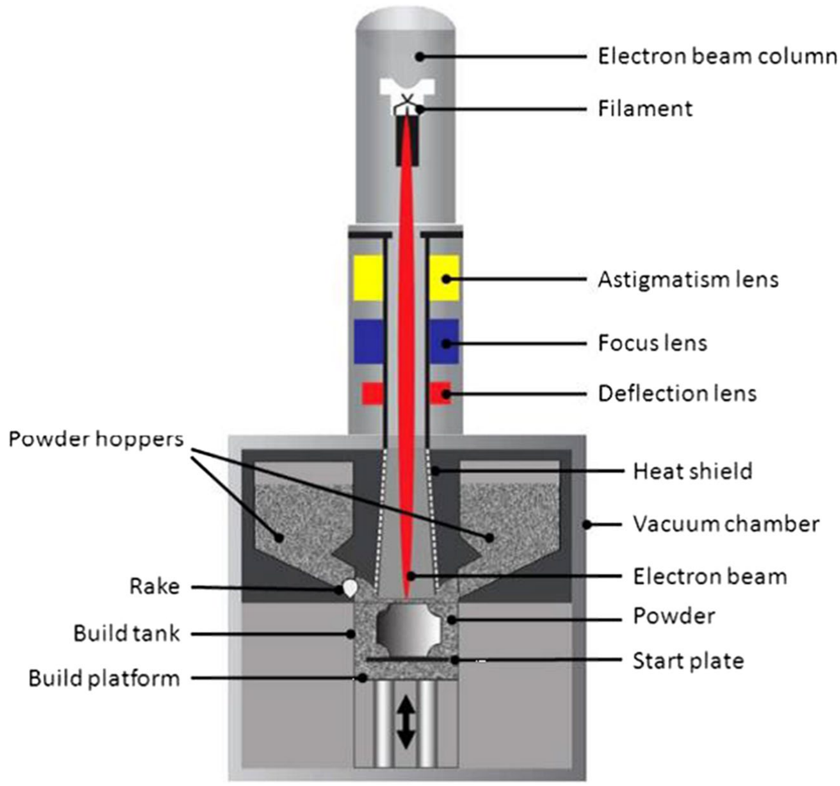


Fig. 10 Electron beam melting technique [94]

beam. To make the final product, each layer must be heated to a specific temperature while it melts [50, 69, 87].

2.6 Direct energy deposition

In contrast to PBF, a laser and a portable chamber are placed together in this procedure. While the laser is operating, metal powder is concurrently guided into the nozzle and to a pre-set location, melting the powder and solidifying the layer in the process [88, 89]. The mobile chamber could move in a number of directions and is not fixed to one axis. The two versions of this DED technique are distinguished by the material feedstock used: metal powder and metal wire. The most typical material used in this procedure is metal powder. Compared to the PBF method, the DED process may use a range of substrates, enabling this technology for high-precision goods [75, 90]. This process also enhances the component density and prevents void formation. This approach makes use of a number of crucial techniques which include direct light fabrication (DLF), laser-engineered net shaping (LENS), and direct metal deposition (DMD) [89, 91]. The benefits and drawbacks of this approach are as follows: It can produce larger pieces than other methods, has a high build rate and a quick construction time, may be used for repair applications, and wastes less material overall. However, the machine's shortcomings include its low build resolution, high capital cost, lacks any necessary natural supports or prerequisites, and overhangs are impossible [92, 93].

2.6.1 Laser engineered net shaping

When commercial laser power and efficiency substantially increased in the 1970s, laser-based material processing emerged as a prominent research area. A CAD file can be used to create three-dimensional components using the laser engineering net shaping technique (LENS). As indicated in the schematic of the laser-designed net shaping method in Fig. 11, an extremely potent continuous wave Nd-YAG laser and LENS can be utilised to create a melt pool on a substrate, and the melt pool can then be used to directly inject metal powder [76, 95]. In order to prevent metal oxidation, argon is used to remove oxygen and moisture from the LENSTM process chamber. With argon serving as the carrier gas, powder feeders transport the metal particles to the deposition head. Then, multi-material and bimetallic structures can be constructed by employing powder feeders that can deliver many materials at once. One of the two methods, either directing a laser beam directly onto the substrate or surrounding it with tiny powder particles, can be used to create weld pools. A very thin geometry piece is deposited as the substrate is moved beneath the laser beam. Immediately following the placement of the first layer, this correction is made in the positive *z*-direction. This process is

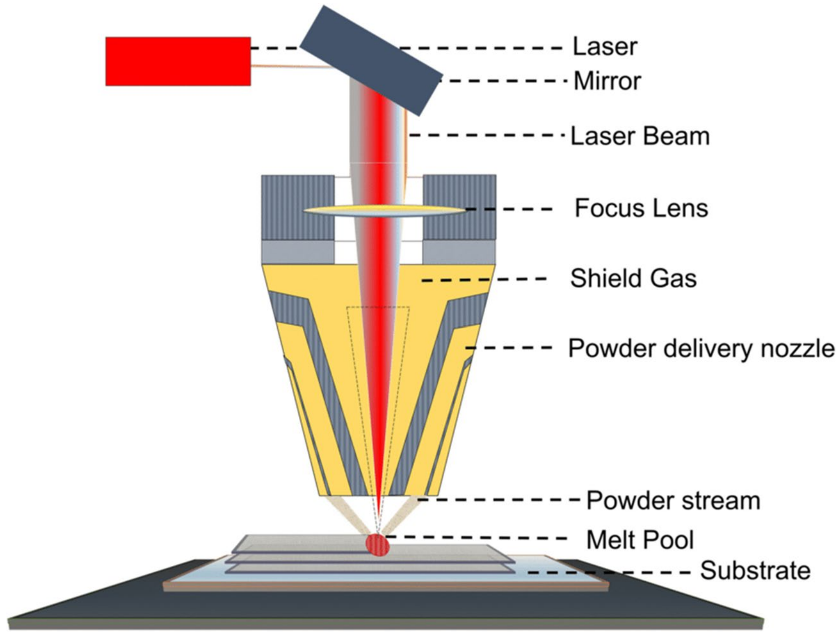


Fig. 11 LENS technique [99]

repeated once the component is complete [74, 78, 96]. Utilising LENS over traditional metal AM production methods has various benefits, including the ability to produce unique and imaginative components [97, 98].

2.7 Material extrusion

A build plate or previously created substance is fed to a polymer filament through the nozzle, which builds the structure layer by layer. This material extrusion technique is required to create intricate structures that are hard to fabricate using standard production methods [100, 101]. It can also extrude various materials simultaneously while using this extrusion procedure. Comparatively speaking, fused filament fabrication (FFF) and fused filament fabrication (FFF) are the most commonly utilised techniques in comparison to other approaches [50, 102]. In summary, this procedure offers a lot of pros and drawbacks. The printing technique is straightforward, the initial and ongoing costs are inexpensive, and the equipment is modest in contrast to other printing techniques. However, because of the *z*-weak axis's part strength and structural delamination brought on by warping and other temperature changes may be required, making this a less efficient technique for novel printing materials than other methods [103, 104].

2.7.1 Fused deposition modelling or fused filament fabrication

The 1989 invention of FDM was created by Scott Crump, a co-founder of Stratasys. ABS, PLA, and PC are used as the primary materials in the thermoplastic polymer extrusion process known as FDM [105, 106]. As can be seen in Fig. 12, the FFF setup has the filaments stored in a roller that is coupled directly to the extruder head. The build platform moves in the *z*-axis, while this head navigates in the *x* and *y* axes. The moving head is propelled by a motor, and the filament is directly connected to the extrusion head. This method uses two types of material filaments. The technique uses 1.75 to 3.0 mm filament. The product design is created by the CAD programme and saved as an STL file. Consideration has to be taken of the machine temperature, building orientation, and slicing settings before cutting the file, as depicted in Fig. 13 [107–109]. These crucial machining factors have an impact on the final product's mechanical characteristics. The programmed slices and tool route are then identified as G-code. A numerical control code for extrusion is known as the G-code. The 2D layer is then produced over the build platform, and the layer is constructed one on top of the other to produce the 3D objects. It is then heated to the semi-liquid stage. The filament is heated to temperatures between 150 and 300 °C before being printed across the plate with a dimensional accuracy of 100 m. The necessary object is printed after the base is completed. After each layer is printed, the printing platform lowers and the next layer is printed [109, 110].

To improve the product's strength and surface quality, post-processing of the FFF product is done. Researchers have created various approaches to prevail over the shortcomings of FFF print components, as discussed in further detail in the preceding section. Thus, on how to improve the qualities of 3D printed items by using (1) chemical solutions, (2) heat, (3) lasers, and (4) ultrasound are detailed in this section.

Fig. 12 FFF technique [95]

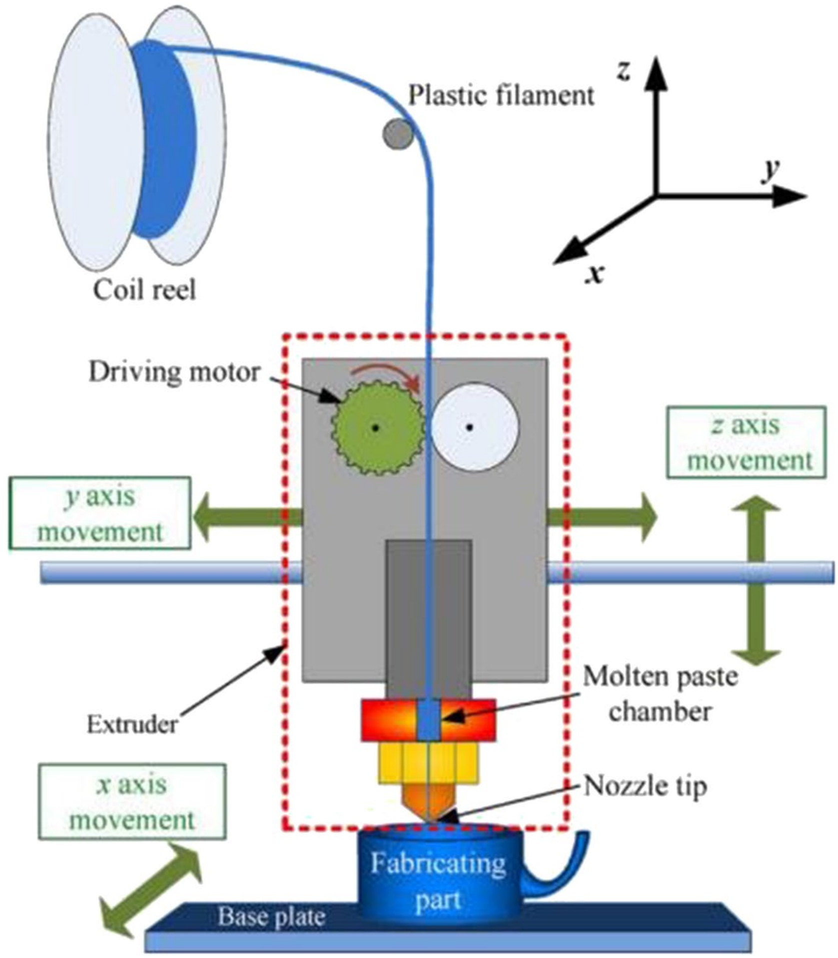
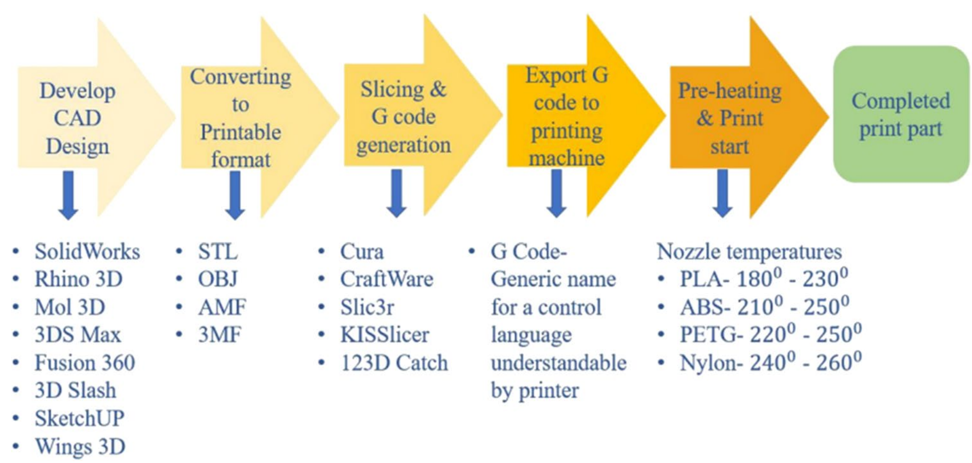


Fig. 13 FFF process flowchart



Chemical treatment Chemical treatment techniques are used to improve the printed products' surface quality. The substance that is most frequently used to reduce surface roughness is acetone. Depending on its condition, the component can either be treated with cold or hot acetone vapour or submerged in the acetone solution. Processing by immersion releases no hazardous gases and is faster than processing by cold vapour. Additionally, it is substantially less expensive than hot vapour procedures [111, 112].

Laser treatment Laser treatment is another technique for improving the quality of FFF-produced products. Numerous studies have demonstrated that the surface roughness of a 3D printed part can be reduced by subjecting it to a CO_2 laser. When a CO_2 laser is used to treat a 3D printed object, the material quickly heats up and melts. Using a photochemical ablation technique, the polymer is sublimated, transitioning directly from a solid to a gaseous state. This process results in a smoother surface, which removes undesirable imperfections and improves surface uniformity. Numerous studies have revealed that the ABS surface's smoothness does not significantly improve compared to PLA [113, 114].

Heat treatment process FFF print parts are typically subjected to heat treatment, often referred to as thermal annealing, as one of the most common procedures for enhancing both the surface quality and the strength of the final product. The influence that this post-processing has on the mechanical properties of polymers and composites has been the subject of a number of studies, the majority of which have been carried out on complete prints. The interlaminar toughness of polymers can be increased through the process of thermal annealing, which, as a consequence, makes the performance of annealed polymers superior to that of injection-molded specimens, according to the findings of a number of research investigations [115].

Ultrasound treatment The use of ultrasonic therapy is growing in popularity for FFF-produced components. To improve the quality of the components, this can be done before, during, or after printing. This technique has been used effectively to enhance the surface quality of items in several other sectors. Since this method uses neither chemicals nor heat, the final product has no negative effects. Because this method does not include the use of chemicals or heat, the finished product is not subjected to any adverse effects as a result of its application. In order to investigate the effect that ultrasound has on printed polymers and composites, there have only been a few of early tests conducted so far, and all of them have been rather simple. It has been discovered in a few trials that providing ultrasonic vibration during printing can increase the final product's surface quality while at the same time minimising the staircase effect and layer thickness [116].

3 Materials

The FFF technique utilises a variety of materials, each of which has its own unique set of mechanical, thermal, and characterisation properties. These qualities change according to the material. Depending on the use and the established specifications, different materials are employed. There are currently a number of restrictions on the kinds of materials that can be utilised with this FFF technology. High melting point materials are not employed in this technique since the melting chambers of the FFF machines now in use have a temperature of roughly 300 °C [117]. Due to these restrictions, this process uses various low-temperature materials, including thermoplastic polymers [118].

3.1 Polymers

Generally used materials in 3D printing are polymers, which are also utilised to create prototype items. The materials utilised in the FFF technique most frequently are polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polypropylene (PP), nylon/polyamide (PA), polyethylene (PE), and polycarbonates (PC) [10, 119]. Due to their poor physical characteristics, certain pure polymers, like ABS, PLA, and PA, are typically utilised for prototypes. To overwhelm this, high melting point polymers are utilised, including polyetheretherketone (PEEK), polyetherketoneketone (PEKK), polystyrene (PS), and polyethyleneimine (PEI). Prototypes can be made from various materials, including pure polymers like ABS, PLA, and PA. These materials are a good choice because of their superior mechanical, thermal, and chemical resistance properties [120]. In addition to ordinary ABS, this FFF process also uses some ABS special materials as polymers, including ABSi, ABS-M30, ABS-M30i, ABS-ESD7, and ABS plus [121, 122]. The main polymers used with composites in the FFF method are produced from these materials, including PLA, ABS, NYLON/PA, and PEEK.

3.1.1 PLA

Made from sugar beets, corn starch, tapioca roots, and starches or chips, PLA is a non-toxic, compostable, and biodegradable substance. PLA replaces thermoplastics derived from petroleum in biomedical and tissue engineering applications. After cellulose acetate, PLA is the bioplastic that is most commonly used worldwide. The material's lower temperature results in cheaper operating costs and better mechanical qualities. The main shortcomings of this PLA are its low melting point and slow crystallisation rate. Around 55 °C and 180 °C, respectively, are the glass transition temperature and melting temperature of PLA, which can be classified as semi-crystalline or amorphous. Due to this shortcoming, the applicability in various sectors will be constrained [122–124]. Tensile, impact, shear, and pressure loading modes were all discussed in terms of mechanical properties. Compared to conventional polymers like polypropylene, polystyrene, and polyethene, PLA exhibited better mechanical qualities (PE). PLA displayed superior mechanical properties over more common polymers, including polypropylene, polystyrene, and polyethene (PE). The lack of toughness in PLA prevents it from being used in products requiring plastic deformation at high-stress levels, although having equivalent tensile and Young's modulus (excellent stiffness) to PET. Over the past five years, interest in strengthening PLA has increased [125].

3.1.2 ABS

ABS stands for butadiene-containing polymers, styrene, and acrylonitrile blends and copolymers; it is a collective noun that can be used to refer to any of these materials. In the 1950s saw the introduction of plastics like ABS as a more rigorous replacement for styrene-acrylonitrile copolymers (SAN) [126, 127]. SAN, formerly known as nitrile rubber, was combined with other elements to create ABS. When exposed to room temperature, the combination of SAN, which is glassy, and nitrile, which is rubbery, creates an amorphous, robust, and impact-resistant structure. ABS perform horribly in several areas due to its complicated morphology, large range of compositions, and cumulative effects. The FFF method of 3D printing, on the other hand, uses ABS quite commonly as a common material. However, choosing different compounds has a unique set of limitations [128, 129]. The creation of an ABS composite filament reinforced with graphene oxide (GO) with the addition of 2 wt% GO was one of several discoveries made by scientists to address the issues concerning the mechanical qualities of ABS. The ABS filament was successfully printed into a three-dimensional sculpture using this technique. When GO is added to ABS, the material's tensile strength and Young's modulus can both rise [130].

3.1.3 Nylon/polyamide

Nylon offers superior chemical resistance over ABS and PLA, as well as higher tensile strength and Young's modulus [131, 132]. The high strength in tensile and impact testing and their strong resilience and low creep are a few of the most important benefits of FFF-printed nylon parts. This material has improved its mechanical capabilities when exposed to high temperatures because at higher temperatures, the bonds between layers become substantially stronger [133, 134]. Due to its propensity to absorb moisture, it has been discovered that nylon has a negative impact on the mechanical properties of printed goods. The amount of study done to ascertain the mechanical properties of nylon and the impact of various material-related parameters is low when compared to ABS and PLA [132]. It has been observed that a printed object's tensile strength increases when the layer thickness is reduced, much like with ABS and PLA, because the link between layers becomes noticeably stronger [135]. Polyamide 12 (PA 12) is the nylon material most widely used in the 3D printing industry since it is inexpensive. The extraordinary functionality of nylon which includes, among other things, reduced mould shrinkage, chemical, wear, and temperature resistance, is largely a result of its crystallinity [98, 135, 136].

3.1.4 Polypropylene

The polyolefin homopolymer polypropylene is one of the most popular low-density and reasonably priced thermoplastic semi-crystalline materials on the market today. The polyolefin homopolymer polypropylene is a homopolymer. Due to their physical and chemical properties, polypropylene (PP) usage is frequently seen in a range of industries, including the military, home appliances, autos, and construction. As opposed to other technical plastics (such as PC, PA, and others), polypropylene (PP) has poor thermal, electrical, and mechanical properties when exposed to dry shear conditions and has a high coefficient of friction [137–139]. Its mechanical properties can be enhanced by mixing polypropylene with inorganic fillers as nanoparticles. Martin et al. [140] evaluated the effects of adding GO to polypropylene with and without maleic-anhydride-grafted-polypropylene (PP-g-MA) as a compatibilizer agent. They used extrusion and injection processes to generate a composite material. According to the findings, friction and wear rates in PP nanocomposites rise with the amount of load applied and the shear speed [141]. A significant friction coefficient reduction occurs when it is brought down to 74.7% of the shear speed. This new value for the coefficient of friction signifies a significant decrease in the coefficient of friction. Another study compared the printing capabilities of polypropylene filled with 30% glass fibre to the mechanical qualities of unfilled polypropylene. The glass fibre content of the polypropylene was kept at 30%. According to the findings of Thomsan's research, Young's modulus and ultimate tensile strength of a polymer are increased by around 40% when glass fibres are included under the same printing conditions [141]. Similar increases in module strength were observed in investigations that focused on improving the printability, qualities' pull, and toughness of PP compounds containing spherical microspheres for FFF application [142]. In this research, 3D printed PP with cellulose nanofibril were employed.

3.1.5 Polyether ether ketone

Another class of polymers used in 3D printing is high-performance polymers, also referred to as engineering polymers, in addition to the ones previously mentioned. These polymers have certain functions built into them. This polymer, which belongs to the PAEK (polyaryletherketone) polymer family, is one of the most well-known high-performance polymers now available on the market. PEEK is an organic thermoplastic polymer that is colourless, semi-crystalline, and performs well. It is used in engineering to create parts for drones, race cars, rockets, and other objects requiring great mechanical capabilities [143, 144]. There have not been many investigations into how the mechanical characteristics of PEEK are affected by the print orientation (horizontal or vertical), nozzle diameter, printing speed (or extrusion speed), the temperature of nozzle, and printing speed (or extrusion speed) [145–148]. Due to its intrinsic qualities, PEEK has the potential to be used to print components for medical applications with increased dependability [81, 149]. Dental implants, joint replacements, spinal implants, bone tissue engineering, prosthesis systems, and orthopaedic implants are some of PEEK's most common medical uses [81, 150]. Numerous researches have shown that the distribution of the tensile strength vs modulus of ABS may be illustrated using a scatter plot (as well as PLA, nylon, and PEEK). PEEK has a significantly higher tensile strength than PLA, ABS, and nylon, in that order. High-performance polymers have been developed; however, the mechanical property of polymer prints still falls short of those of conventional production methods [151, 152]. In order to address this issue, scientists have been experimenting by adding various components with enhanced functionalities to pure polymers in the hope of increasing the final product's mechanical behaviour.

3.2 Polymer composites

Due to their low melting point, low cost, process flexibility, and widespread availability, polymers are initially the only filaments used in the FFF method. The growing use of 3D printed polymer products poses a severe problem due to their lack of mechanical strength and functionality, despite their sophisticated geometry. There are a few problems that arise when using pure polymers as a filament, which is why they are usually combined with additional substances to make the result stronger [153, 154]. One possible solution to this problem is combining various materials to provide the mechanical and functional properties needed. Interest in creating composite materials that work with contemporary printers has significantly increased in recent years. The creation of novel printable composites reinforced with ceramic fibres, metals, and nanoparticles, among other things, has led to a number of exciting findings. Figure 14 displays the diversity of composites employed in the FFF technique.

3.2.1 Polymer matrix composites

To create a material with characteristics specific to each of the constituent materials, PMC uses polymers as the primary matrix materials and metals, typically in the form of powder, as reinforcement components. Due to the increased need for more advanced engineering materials that are both strong and lightweight, PMC has expanded dramatically in recent years [153, 156]. The combination of the matrix and reinforcing materials employed in the construction determines properties such as flexibility, adhesiveness, toughness, conductivity, processability, and strength [157]. Although the effect of viscosity on the composition of metal powder in PMC is a limiting factor, surfactants and plasticizers can be used to alter the composition of metal powder in PMC [158]. The most frequently used matrix materials for PMC are ABS, PP, and PA matrix polymers, whereas iron and aluminium are the most frequently used metal powders for PMC.

3.2.2 Polymer ceramic composites

Ceramics are highly helpful in bio-medical applications, where flexible, biocompatible materials are required for implants and other similar devices [153]. Although polymer ceramic composites can be made from bio ceramics, which diminish their limiting characteristics, their use is still constrained due to their fragility and low mechanical strength. Bio ceramics are the preferred material for applying bone grafts [33, 159]. TiO_2, ZrO_2, Al_2O_3, and calcium ceramics in polymer matrices like polyamide (PA), polypropylene (PP), and polylactic acid are the most often utilised ceramics as reinforcing materials (PLA). Bio-composites have enabled a substantial advancement in the field of bio-medical engineering and the current healthcare industry by assisting in the production of artificial human organs and tissue engineering [160]. Bio-composites/materials are substances with a high degree of compatibility with a simulated biological fluid that is strikingly similar to the structure and makeup of human blood plasma. Polycaprolactone (PCL), polyether ether ketone (PEEK), and polymethyl methacrylate (PMMA) are a few examples of biomaterials utilised in FDM [92].

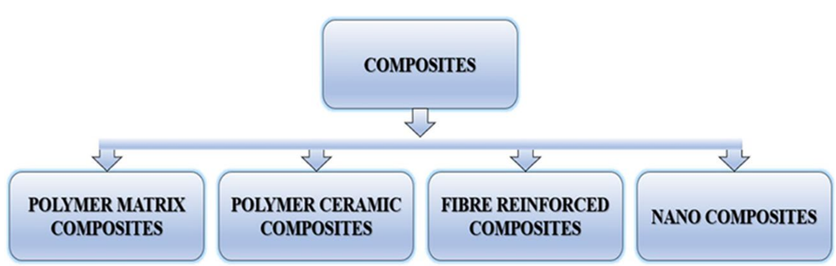


Fig. 14 Composite type in FFF process [155]

3.2.3 Fibre-reinforced composites

Glass and carbon fibre-reinforced plastics (CFRP) are two types of fibre-reinforced polymers (FRP) that offer excellent strength while reducing the weight of the completed product [161]. In order to replace parts that were previously made of metal and with reduced weight, fibreglass-reinforced plastic, or FRP, is being used more and more frequently in production. This is especially true in the transportation industry, which includes the aerospace and automobile industries. The variety of industries in which FFF technology can be used has increased with the use of fibre-reinforced polymers (FRPs) as raw materials. A few of the excellent attributes of CFRPs include their superior dimensional stability, wear resistance, corrosion resistance, lightweight construction, and high strength-to-weight ratio. However, these FRPs severely impact the environment due to their non-biodegradability and recycling them after disposal is a global concern [161]. Since environmental awareness is developing globally, a lot of research is being done to create a replacement for FRPs. Natural fibres have the potential to replace synthetic fibres due to their benefits, including their low cost, minimal abrasive wear, low density, simplicity of supply, environmental friendliness, and biodegradability [162, 163]. Natural fibres that are readily available include bamboo, wood, flax, sisal, coir, jute, oil palm, and vegetable fibres. According to the International Monetary Fund, the subcontinent, China, and the south-eastern nations have some of the world's fastest-growing economies and are home to a wealth of natural fibres. Since traditional uses for these fibres represent the majority in these developing countries, it is critical to find cutting-edge application fields (like FFF) to boost their economies and position them as the leading producers of natural fibre commodities [164].

3.3 Nanocomposites

FFF products have weak mechanical and thermal properties, but by adding nanoparticles with superior mechanical and thermal qualities and better raw materials, they can be made better [157]. As a result of the lack of adhesiveness and interaction between nanofillers and polymer components, the brittleness of the composite material is increased when nanofillers are included in its composition [165]. In past experiments, adding nanomaterials to matrices made of polymers and metals like carbon nanotubes, nanoceramic particles, and metal nanoparticles has significantly improved the properties of the finished product [166, 167]. To optimise the weight composition of nanoparticles in a composite, the MFI, viscosity, and other characteristics are used.

3.4 PLA-bio composites

More than 30% of all applications in FFF use PLA, one of the most widely used biodegradable plastics, because PLA is fragile, has low hardness and flexibility, and cannot be used without first being combined with other materials. It must first be used in a composite. Composites have been made using a number of materials, including PLA. Hence, finding composites made from waste materials, agricultural by-products, and products that are both economically viable and environmentally advantageous has been a priority.

3.4.1 Natural wood fibre

A lot of scientists have started to look at the viability of employing PLA composites to reinforce natural fibre. The effects of the functional mineral addition on the characteristics and processability of PLA-reinforced wood fibre (WF) composites were examined by Ozyhar et al. [168]. For PLA-reinforced wood fibre composites, they zeroed down on calcium carbonate and alkenyl succinic anhydride (ASA) as a beneficial mineral supplement. The impact of mineral quantity on the material properties of 40% PLA composites with fibre reinforcement was investigated by adding 10, 20, and 30% weight percent of minerals, respectively. The results demonstrate that up to a 20% weight percentage, mechanical characteristics of the material can be preserved when PLA is substituted with ASA. After the study, it was discovered that adding ASA-treated calcium carbonate to the composite formulation enhanced the adherence of the fibre to the PLA, allowing the formulation to be produced with a lower proportion of PLA while still keeping the characteristics of the material. Insights from this work were an essential first step towards incorporating a combination of modified natural fibres as reinforcing components in the PLA matrix. Fibres developed from modified bamboo and coconut are two such examples. WF Zhang and colleagues thoroughly analysed PLA/natural fibre composites [169]. The casting method was used to create PLA composites with three different natural fibre types, including bamboo, wood, and coconut. The findings showed that composites' mechanical and thermal properties might be enhanced by adding three different types of natural fibres. Natural fibres could be used after the researchers made their modifications to boost the durability of composites. Compared to other composites, the PLA/coconut fibre composite has shown the group's best thermal and durability properties [170, 171]. This study offered a workable alternative that the PLA sector may use soon. In summary, our research offered a feasible path for the development of the PLA industry.

Du and colleagues [172] found that adding pulp fibres to PLA improved both the material's tensile strength and crystallisation. Polymer composites made of natural fibres like PLA and cellulose were produced by combining the method of moulding wet-layered fibre sheets with conventional composite production techniques. High-yield hardwood pulp fibre made up 40% of the total fibre needed for optimal composite strength, whereas 50% comprised kraft pulp fibre and high-yield softwood. The maximal tensile strength of 121 MPa is only slightly stronger than the tensile strength of natural PLA. According to the findings, the storage modulus and elasticity of the composite were improved by the incorporation of pulp fibres, and the crystallisation of the PLA polymer was also stimulated. However, neither the composite glass' transition temperature nor the PLA's crystallinity demonstrated any discernible changes during the trials.

3.4.2 Non-wood natural fibre

Leaf Natural fibre reinforcements in PLA composites have been the subject of several studies that aim to assess their effectiveness. Natural fibres extracted from leaves, such as sisal and leaf fibre, have been used in and are being used in numerous investigations on the reinforcing of PLA-based composites. Mechanical properties of benzoyl peroxide (BP) surface-treated banana/sisal fibre (BSF)-reinforced polylactic acid (PLA) composites were investigated. The earlier study on reinforced PLA hybrid composites with banana/sisal fibre conducted by Asaithambi et al. [173] served as the foundation for the current investigation. To make BSF-reinforced PLA hybrid composites, researchers employed twin-screw extrusion and injected them into moulds. The flexural and tensile strengths of the material were measured with a universal testing machine (UTM). The findings of the study indicated that a cross-linking strategy is a viable alternative to conventional methods for improving the PLA matrix's compatibility with BSF. Additionally, it was found that the BSF/PLA composite made via extrusion and injection moulding had extraordinarily high mechanical properties when compared to other processes. As a result, it was decided that additional research would help open the door for a wider scope and better future prospects for prospective BSF-reinforced PLA composite applications. Non-wood-generated natural fibre polymer composite reinforcing with PLA has been investigated [174, 175]. In jute/PLA composites, Jiang et al. [176] investigated hydrothermal ageing and structural deterioration. However, with biodegradable materials, the combined actions of heat and moisture may cause hygrothermal ageing. The 50 °C liquid ageing of the composite jute fibre/PLA had an impact on the tensile properties, chemical fibre, matrix degradation, and water absorption.

The jute/PLA composite lost its tensile strength, ductility, modulus, and mechanical characteristics due to hygrothermal ageing. At last, X-ray tomography will assess how a jute/PLA composite would be affected by hygrothermal degradation. There have been several definitions of PLA put forth. The definition of PLA used in this study will be that provided by Yu et al. [177]. It is a thermoplastic linear aliphatic material made from renewable resources. The study discovered that PLA is produced using two processes: polycondensation of lactic acid and ring-opening lactide polymerisation. It also discovered that PLA/jute fibre composite had a slightly greater total tensile strength than PLA. Interestingly, of all PLA-based composites, PLA has the lowest tensile strength. The findings of this study demonstrated that adding fibre improves the mechanical properties of composites made of PLA before they start to deteriorate once the fibre content approaches 30%. According to Oksman and Selin [178], PLA plastics and composites can be used as a matrix in a composite system with reinforcements made of natural fibres. In comparison to other thermoplastic composites currently utilised in vehicle panels, flax-reinforced PLA composites have been found to be 50% stronger. The PLA stiffness doubled from 3.4 to 8.4 GPa when flax fibres at a concentration of 30% were added. One of the most important aspects of using renewable resources in the industry is the ability to use traditional manufacturing techniques. In this instance, PLA/flax composites' extrusion and compression moulding were not problematic.

Grass Bamboo fibre [179], elephant grass [180], and switch grass [181] are among the grass-derived natural fibres that have been reinforced utilising PLA composite in several studies. Based on a previous study, Gunti et al. [180] discovered that elephant grass composites outperformed jute and sisal composites mechanically. Injection moulding was used to create the composites, which had different amounts of treated and untreated fibres. The treated elephant grass/PLA composite had tensile strengths that were 24% higher than plain PLA and 18.14% higher than treated jute/PLA. This study discovered that fibres enhance the strength and modulus of the PLA matrix. Sukmawan et al. [182] looked at how bamboo fibre affected the mechanical parameters and failure traits of cross-ply green composite laminates. Before hot pressing, a hand-layup PLA/bamboo fibre cross-ply composite (0/90) was created using biodegradable PLA of the dispersion kind. The laminate plastic reinforced with bamboo fibre composite had a strength that was three times that of mild steel and had a similar base strength to laminate plastic reinforced with glass fibre. Based on the findings of the investigation, it appears that a PLA/bamboo fibre laminate cross-ply (0/90) could be able to replace glass fibre-reinforced composites in the role of material for the skin of sandwich structures. Abdul Khalil et al. researched bio-composites with bamboo fibre reinforcement [183]. Due to the rising need for biodegradable and renewable resources, the usage of bamboo fibres as insulation in composite materials has increased significantly in recent years. Contrary to what is commonly believed, considerable improvements in manufacturing technology allow customers to make sensible decisions and develop desirable preferences. Utilising more durable raw materials, such as bamboo fibre, to create high-end, sustainably manufactured products of exceptional quality has improved their quality skills.

Straw fibre Crop straw is an affordable, environmentally friendly agriculture waste. Research into composite materials consisting of straw fibre is needed in order to utilise agricultural waste. According to El Messiry and Deeb, one of the problems associated with current intensive farming is the production of waste from agricultural products [184]. The popularity of composites derived from renewable raw resources has increased recently. Numerous studies have been conducted recently; these composites made of wheat, rice, corn, soy, and abutilon fibre used a heated two roll-mill in a range of ratios to create poly (lactic acid)/rice straw (RS) composite [185]. They put PLA/RS composites' mechanical qualities to the test. The tensile strength and elongation (Eb) of the composite fell from 5 to 25% as rice straw fibre content rose. In addition to bio composites made from soy and PLA and wheat straw, Pradhan et al. [186] in their research found that PLA composites for untreated soy and wheat straw are clearly biodegradable. Natural biomass delays the degradation of the PLA component, demonstrating the use of treated or modified components in composites. With the addition of quickly biodegradable biomass components with priming or beneficial effects, the likelihood of using modified or handled biomass in composites increases. A hot-pressed maize straw fibre/PLA composite was created by Ding et al. [187], who had observed its mechanical properties and deteriorating performance.

According to the findings, the mechanical properties of the composites deteriorated as the proportion of cornstalk fibre in the mixture increased (tensile strength and elongation during breakage). At a percentage point of 10%, the elongation ratio of the break was 20.3%. The rate of breakage is 10% of total items. When the amount of maize stem fibre in the composite was 13%, the tensile strength of the composite was 24.38 MPa. After 120 days, there was an increase in the degree of disintegration of the maize straw fibre and the rate at which the polylactic acid composite broke down. Increases in maize straw fibre improved the composite mass reduction and decreased the PLA molecular weight. Wang et al. [188] described and analysed abutilon-reinforced PLA natural composites. The production of PLA and abutilon bio composites using an extruder and a melting mix is the focus of this work. The data from the DSC demonstrated that the fibres were an essential component in fostering the crystallisation of the PLA. The abutilon fibres also improved the thermal stability of PLA. High interfacial adhesion leads to higher storage modulus values. The mobility of the PLA polymer molecules diminishes when fibres are introduced to the PLA matrix, which lowers the tan delta. The enhanced properties and increased energy absorption of these bio composites demonstrate the potential of abutilon fibres as a green composite enhancement.

3.5 PLA/natural mineral fibre bio composites

Natural mineral fibre is one of these materials that is currently attracting interest when compared to other natural fibres. Due to its low cost, robust mechanical, physical, chemical, and biodegradable capabilities, among other qualities, it is already in widespread usage. Mineral fibres that have undergone specific processing, such as basalt fibre [189] and asbestos fibre, are utilised as reinforcement elements in composites. In a recent study on the production of PLA composites that were reinforced by short basalt fibre and their feasibility assessment for applications involving 3D printing, the researchers found that the PLA composites were effective. Sang et al. [190] tested the efficacy of KH550-treated composite reinforced PLA/basalt fibre (KBF) as a 3D-printable feedstock. Using the fused-deposition modelling (FFF) technique, PLA/KBF feedstock filaments of varying forms and sizes were effectively fabricated and printed. This might be because the interlayer adhesion was impacted by the extremely complicated PLA/CF viscosity. The outcomes also demonstrated that PLA/KBF outperformed PLA/carbon fibre in terms of flexural and tensile qualities (CF). The most current study has shown that PLA/KBF is a technologically advanced and reasonably priced feedstock that may be employed in 3D printing applications for complex designs and variable sizes. Kurniawan et al. [191] examined the effects of plasma polymerisation on silane-treated basalt fibre for testing of mechanical and thermal properties. Compared to the untreated composite, the mechanical properties of the composite were 45% and 18% greater, respectively, according to the results. This improvement was also due to the experiment's optimal 4.5-min basalt fibre irradiation.

4 Parameters

In this study, the process parameter plays an energetic function. The FFF process produces a product that satisfies the customer's requirements. Because of this, FFF products have low pricing and quick lead times while yet containing high-strength, high-safety components. The process's choice of parameters determines the FFF products' overall performance [192]. Considerations for quality, strength, and build time are all essential. FFF is a complicated process for which choosing the optimal parameters is very challenging because of the presence of various competing factors that affect both the accuracy of the variable and the quality of the material. Choosing the right process settings makes it possible to increase both the component's efficiency and the mechanical attributes of the finished item. The efficiency of manufacturing and the features of the finished product were determined by process parameters [110]. The infill pattern and density, raster angle, and breadth are the most important factors to consider [108]. Additional variables include the construction direction, air gap, printing speed, and operating temperature. The significant factors that have an impact on the diverse product quality are shown in Fig. 15.

4.1 Layer thickness

It describes the volume of material deposited in a single pass along the *y*-axis of an FFF 3D printer. The heights of material deposition will never exceed the diameter of the nozzles on the extruder, and they will never be less. In this instance, performance is solely dependent on the extruder tip diameter. The layer's height has been shown to play an inescapable role in the manufacturing component's bending and impact properties in earlier experimental studies [194, 195]. A minimum layer thickness is preferred for better bending because it was discovered that increased layer thickness had high impact qualities and improved bending capabilities. Additionally, to decrease the angle of slide and surface roughness in FFF printed components, an orthogonal experimental design was made to find the permissible values for various printing parameters, with layer height being one of the criteria [196]. Figure 16 displays the FFF product's layer thickness.

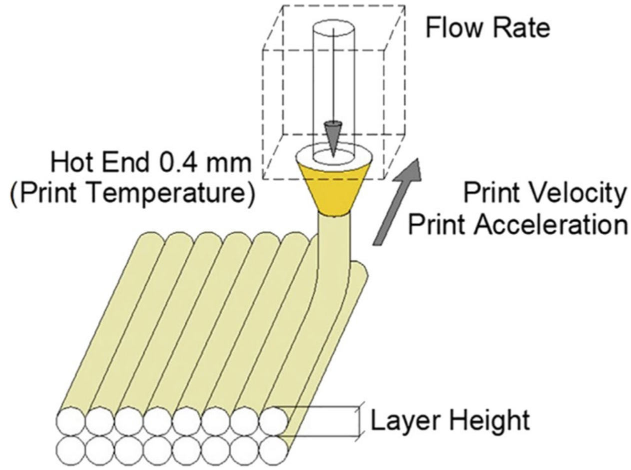


Fig. 16 Layer thickness of printed substance [196]

4.2 Raster angle

On the model's build area, it shows the *x*-axis direction of material deposition. Raster angles varied widely, from 0 to 90 degrees. Raster angularity is frequently expressed as a distance from the *x*-axis. Wu et al. [10] observed in exploratory research that the dominance of raster (i.e. 45°, 30°, and 0°) and layer height (i.e. 0.2, 0.3, 0.4 mm) were connected with 3D features. The graphic depiction of the raster angle employed in this experiment is shown in Fig. 17 and was printed with a brand-new, high-performance substance called polyether-ether-ketone. EsSiad et al. [197] demonstrated that the layer positioning affected the mechanical characteristics of samples made from acrylonitrile butadiene styrene. For material deposition, angles like 0°, 45/ – 45°, 45°, 90°, and 45/0° were selected. The results demonstrate

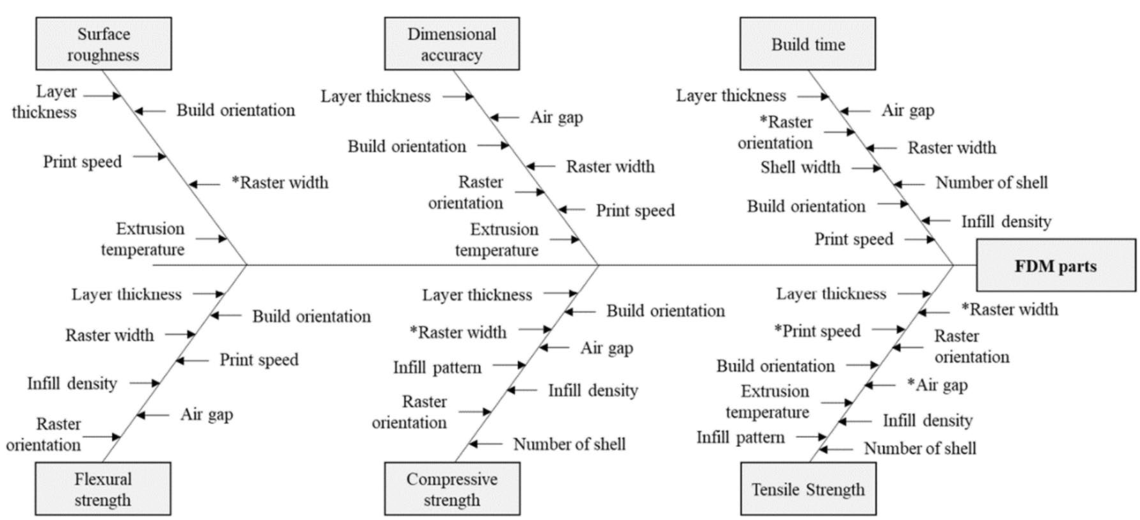


Fig. 15 Factors affect the quality product [193]

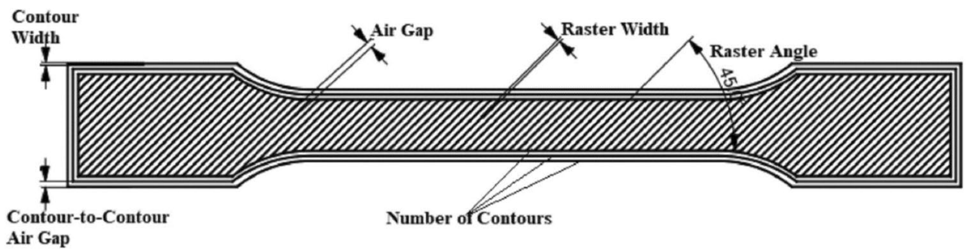


Fig. 17 Standard orientation of specimen [198]

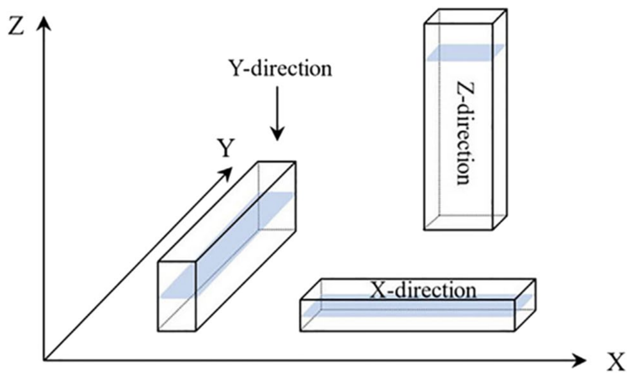


Fig. 18 Different build locations

that the ultimate yield strength is greatest at the 0° orientation, where molecules line parallel to the stress axis, and at the weakest between 45° and 90°.

4.3 Orientation of build

It describes adjusting a particular component in relation to the machine tool's three primary axes on a build platform (*x*, *y*, and *z*). Consider the research done by Feng et al. [199], printed their two test specimens for the PA12 filament category in two distinct orientations using an FFF printer. The separate build orientation printing method for each type is shown in Fig. 18. In their experimental work, the researchers also showed how the build orientation affects the compressive and mechanical qualities of ABS components made utilising FFF. The tensile strength exhibits similar patterns, with an observed maximum drop of 60% when the construction direction is altered from 0° to 90°.

4.4 Infill density

The density of a 3D printed part is the total amount of substance used in its creation. The characteristics of the printed component directly depend on the infill density. A component with a higher density requires more time to build, but it offers superior mechanical qualities over the earlier component. A component with lesser density, however, has mechanical qualities that are dramatically impaired [200]. Figure 19 shows the various infill patterns with 25, 50, 75, and 100% infill density.

4.5 Temperature

The temperature at which the material that is going to be extruded will be placed into the heating nozzle of the FFF is commonly referred to as the extrusion temperature. It has an impact on the printing medium's viscosity, which in turn affects the printed part's attributes. By maintaining the right temperature, the fluidity of the filament substance may be enhanced or diminished, which may have an impact on the component being formed. According to Wang et al. [144], the internal tension that arises when the material is extruded through the nozzle cools down from its starting temperature to the temperature of the chamber is linked to the temperature of the material. The created object could fail as a result of the internal tension brought on by the change in deposition speed, which can result in inter- and intra-layer deformation.

4.6 Air gap

The time elapsed between two successive bead depositions in the same direction is displayed. The air gap value could be zero, positive, or negative, depending on the circumstances when there are no air gaps between the deposited components, as shown in Fig. 20 as they are in direct contact with one another. Degradation of subsequent material deposition due to positive air gaps results in a loosely packed structure that necessitates rapid assembly of the relevant component. When time is not an issue and we need a denser structure, we use a negative air gap. Because the beads partially overlap, the component becomes denser due to the negative air gap [109, 201]. For instance, a good illustration of how to visualise the air gap is the illustrative interpretation of the air gap used in the investigational study conducted by Rayegani et al. [109].

4.7 Infill pattern

It alludes to the method utilised to print the manufactured component's interior structure. Alafaghani et al. [202] illustrate the range of possible filling patterns,

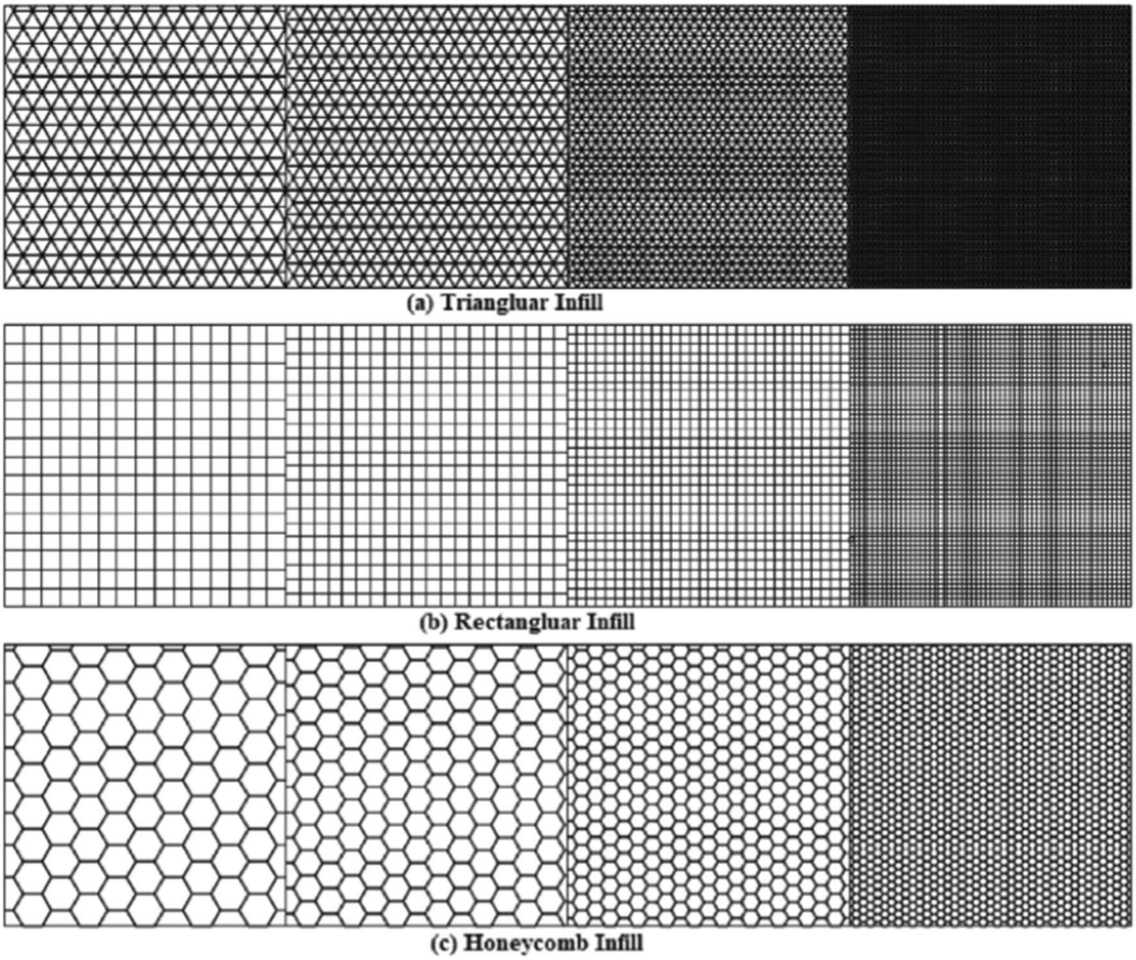
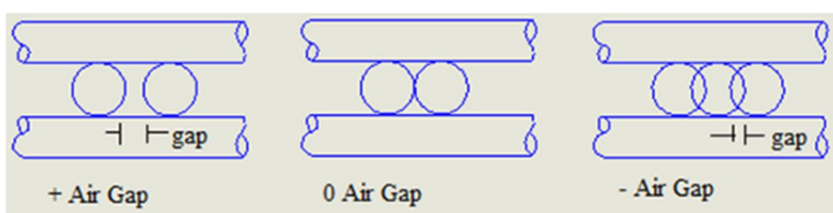


Fig. 19 Different infill pattern and infill percentage [198]

Fig. 20 Diagram demonstrating different air gaps [109]



including hexagonal, linear, and diamond patterns. The hexagonal pattern is FFF's most typical infill pattern [203]. In their experimental work, B. Liseli et al. [204] showed the value of linking the infill pattern's impact on the material's mechanical properties. Because it might inevitably affect how produced components behave, it is proposed that linking the laying pattern to their mechanical qualities is vital. This is due to the fact that a certain pattern may not generate sufficient results for a component subjected to other forms of load, while other patterns may produce superior results for tensile or compressive qualities.

4.8 Raster width

It gives details on how long the deposition path was used to construct the specified component. The diameter of the nozzle has a major impact on the route width. According to the study by Dey et al. [108], the raster width has an unavoidable effect on how long a particular component is created: the wider the raster width, the shorter is the build time.

5 Applications

In the current technological age, 3D printing is developing quickly worldwide. As a result of wood being a renewable resource and an environmentally benign material, many companies have begun to replace their products with 3D printed wood components. The current state of affairs mostly shows that 3D wood is employed in the manufacturing and medical industries. Rapid prototyping, fashion, the automobile sector, construction, guns, education, and actuators are just a few of the many uses for 3D printed wood. The global usage of 3D printing in various industries is shown in Fig. 21.

5.1 Aerospace

With FFF, it is possible to build intricate geometric components for unmanned aerial vehicles (UAVs) more quickly and economically [18]. Stratasys and Aurora Flight Sciences worked together to print a jet-powered unmanned aerial vehicle (UAV) that is under 33 pounds in weight [57]. This small, lightweight UAV is made up of more than 80% additively manufactured parts. Almost all of the components are printed using FFF technology. Examples include the honeycomb structures seen inside of wings. The building's construction included the use of acrylonitrile styrene acrylate (ASA) and Ultem®, a PEI trademark resin. Regarding the use of FFF in the printing of UAVs, references from [206, 207] are provided. Items utilised in aircraft applications should typically include relatively little empty space. Mechanical requirements for printed parts must match those for aviation components. Preparing FFF printed parts for aerospace applications is challenging since they are anisotropic and have a high void content. The production method might potentially save time and fuel if the 3D printing technology is developed effectively [208, 209]. Reinforced composites are also being used more frequently to increase the strength of the UAV components seen in Fig. 22. By modifying PEI/CNT composite filaments, Gardner and colleagues were able to create filaments with better mechanical and electrical properties.

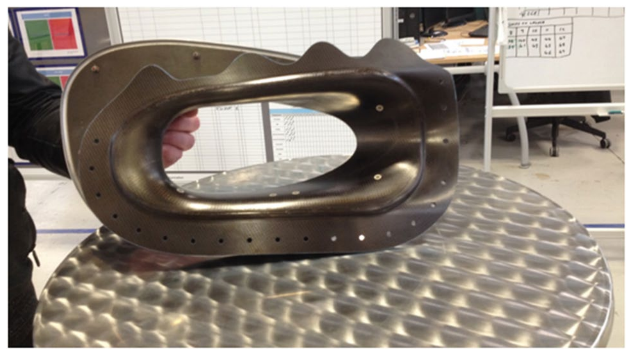


Fig. 22 Bespoke neo drill scoop for use in aerospace [210]

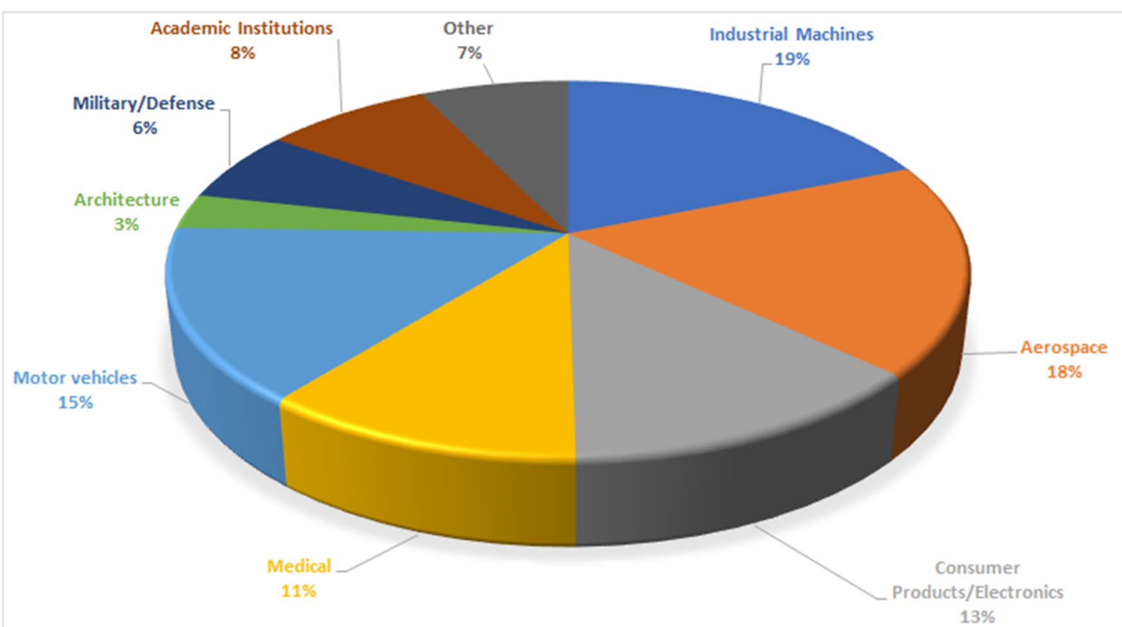


Fig. 21 3D printing applications of various industries in global [205]

5.2 Automobile and other industries

The automotive sector, functional prototypes, architectural models, jewellery, toys, home goods, and end-user items are just a few industries that utilise the FFF technique. High-strength polymers, including nylon, polycarbonate, and ULTEM, have succeeded in a number of crucial applications for the automobile manufacturing sector. One of the most common applications of the FFF technique is in the manufacturing of jigs, check gauges, fixtures, interior accessories, lights, air ducts, and bezels on full-scale panels in the automotive sector. This is one of the most popular uses of the FFF technique [211]. The jewellery industry also makes use of this technology to cut costs and create complicated geometries while reducing waste. The food business, which has risen recently as a consequence of its numerous perks, including custom-designed delicacies and a streamlined supply chain, will find the FFF technique to be particularly helpful when it comes to time and financial savings. Applications for items like senior citizen food, sweet food, and space food are now being developed in the food sector [212, 213]. In addition to making prototype products, this process is utilised to create home goods like cleaning supplies and children's toys. Figure 23 depicts the first energy-efficient vehicle made up using the FFF.

Fig. 23 First energy-efficient automobile vehicle printed with FDM [214]

5.3 Biomedical

Tissue engineering and creating patient-specific implants for bones and prosthetics using FFF technology are growing in popularity. The microarchitecture of tissues and organs may be completely mapped out using computed tomography (CT) techniques, which can subsequently be utilised to process tissues utilising 3D printing methods [215]. In addition to the required mechanical properties, materials suitable for use in the processing of FFF feedstock must be biocompatible [216]. Biomaterial scaffolds can improve their internal architecture and porosity control by 3D printing, enabling more exact design. Biocompatible scaffolds can be produced by mixing bioactive particles with polymers and treating them with FFF technology [95, 217]. Since traditional scaffold processing procedures cannot add the necessary network, as shown in Fig. 24, processing scaffolds with regulated porosity and a linked network for tissue engineering may be difficult. In recent years, there has been an increase in the utilisation of FFF technology to print biocompatible composite scaffolds with better pore size and distribution.

Using these printed scaffolds, a few papers have been published in vivo research. FFF technology has demonstrated how to implant biocompatible PLGA/TCP/HA composite scaffolds into a rabbit femoral bone defect. According to Andreeßen and Steinbüchel, the scaffolds have been proven to promote the formation of new bone while also showing how the scaffolds deteriorate over time. The making of artificial vascular scaffolds was the subject of a study by Kabirian et al. [219]. The idea of adopting this method in the future for tissue-engineered vascular grafts is made possible by the author's discovery that the breakdown rate of a 3D printed PLA scaffold in vivo is slow enough to offer the mechanical support required for cell growth. In order

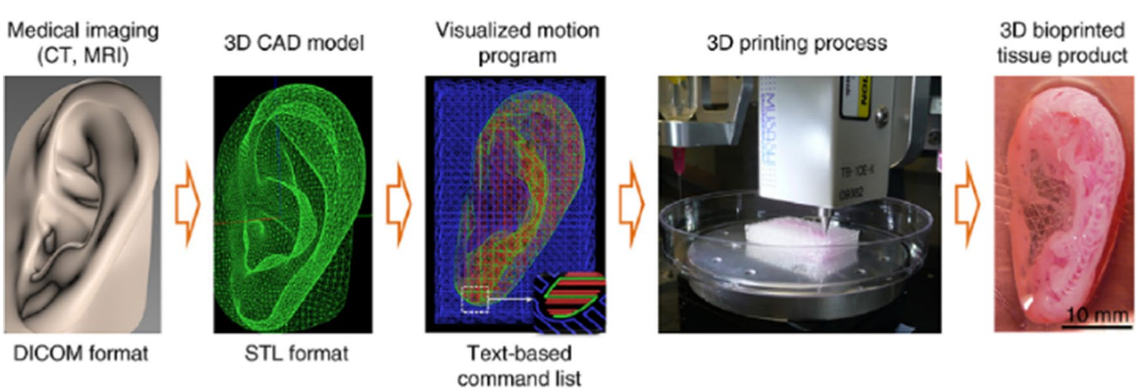


Fig. 24 FFF printed tissue engineering use in medicine [218]

to improve their functionality, these scaffolds are further improved by the addition of nanoparticles like MWCNT, graphene, and Fe3O4. A combination of magnetic Fe_3O_4 particles, mesoporous bioactive glass (MBG), and PCL was extruded into multifunctional scaffolds to improve osteogenic activity [220]. The use of 3D printable composite ink comprised of graphene and biopolymers allows for the development of durable, biocompatible, and environmentally friendly technologies. This procedure involves extruding composite liquid ink, which quickly hardens and is then placed layer by layer on the build platform [221].

5.4 Electronics

Researchers were able to employ FFF to print parts for conductive, dielectric, energy storage and sensor products. For instance, combining the processability of thermoplastics with the high permittivity of ceramics to print dielectrics is feasible. Given the high quality of the printed part and the absence of voids in a 3D printed ABS-BaTiO3 composite component, Castles et al. showed that the dielectric properties are identical to those of bulk specimens [222]. FFF can print dielectric products, such as passive transmitters if the print settings are carefully regulated. Copper-based fillers, which tend to oxidise, should be avoided; they can be replaced by carbon-based fillers, which offer conductive channels within polymers. Due to their low melting points; carbon-based polymer composts can also be simply and inexpensively transformed into filaments. Various combinations of composites are PLA/carbon black filament from proto pasta; the PLA/conductive PLA/graphene filament from black magic and the electrify filament from multi 3D are all fantastic options. These filaments have a volume resistivity that ranges from 0.6 to 30 cm [223]. Figure 25 demonstrates the use of 3D printing in various electronic components.

5.5 Tooling

The ORNL research team has put a lot of effort into creating composite manufacturing tools and moulds, which are crucial to the process [225]. Moulds are printed in the desired shape at the BAAM facility for procedures like compression moulding, vacuum-assisted resin transfer moulding (VARTM), and hand layup. By using these methods, the quality of the mould surface can be preserved by covering an undersized mould or machining an enormous mould, among others. When compared to traditional mould production procedures, printing requires less time and money in terms of total manufacturing time and total cost. In order to create a 3D printed mould, Maravola et al. [226] used an ABS composite that was 20 weight percent reinforced with short carbon fibres. The mould was then evaluated. Utilising VARTM, carbon fibre-reinforced composites were produced using this mould. These moulds are so durable that they kept their dimensional stability even after being used to make and remove composites. Figure 26 shows the 3D printed silica sand mould.

For use in the hand layup procedure, Sudbury and associates [228] created printed tools. Both flat and curved moulds have been produced. To preserve the surface quality of the final product, curved moulds are machined, and planar moulds are coated with epoxy grades. The tool's toughness is measured by how many pulls the composite made can

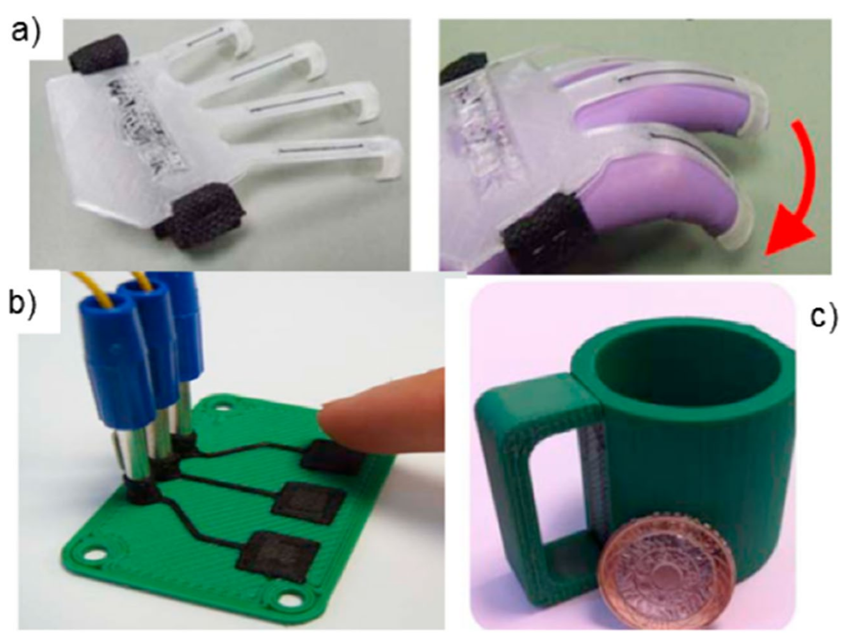


Fig. 25 Electronic components made up of using the FFF process. **a** Piezoelectric sensor. **b** Capacitive sensor. **c** Smart vessels printed [224]

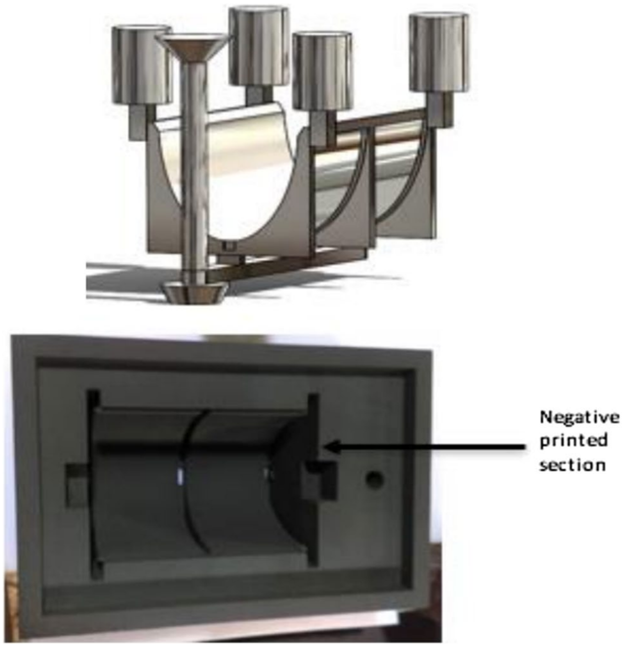


Fig. 26 3D printed silica sand mould [227]

withstand. Both the overall cost of printing and the durability of printed parts have been said to be superior to those of traditional methods.

5.6 Construction

Since the application has only been employed in the building industry since 2014, it is clear that the industry is still developing. The creation of multiple techniques and materials has only recently been made possible by a few academic studies on printing three-dimensional (3D) concrete structures. Casting, moulding, and extrusion are examples of traditional manufacturing processes used in the building industry. The building sector can use 3D printing to find solutions when faced with constraints like geometric complexity and hollow constructions. The contour craft technology was developed by B. Khoshnevis and colleagues and is employed in space applications as well as the automated construction of buildings and structures [229]. It can be used to build affordable housing and a lunar base shelter fast since it can use resources that are already in the area. In recent years, 3D printing has become more and more common when building homes in China. The house's components are additively manufactured using FFF technology and printed in sections before being assembled. Building 200 homes will cost less than $5000 each home [230, 231]. It is anticipated that adopting FFF-constructed buildings, which are primarily green in nature, can save more than 30% of energy costs [232]. The different applications of the FFF technique in a building are shown in Fig. 27.

6 Technical challenges in FFF

Because additive manufacturing (AM) can create complex shapes, is flexible in design, and allows for product customization, it inevitably poses a risk to traditional production. However, finding real-time product applications for AM will be a difficult task. The size of the object, low manufacturing efficiency, mismatched layers, producing overhanging components, poor precision, under and over-extrusion, and production expenses are a few of the major problems that AM runs into. Here are a few risks that AM poses.

6.1 Build volume

Due to additive manufacturing's inability to print high-volume components, producers are forced to separate bigger components into smaller subparts or subassemblies, which then need to go through the necessary assembly steps. As a result, it will take longer to make a complete component, and integrating the components will cause further issues like decreasing strength, among other things.

6.2 Stair stepping

Stair-stepping is the most common issue with FFF parts, and it requires post-processing that raises the cost and duration of the component. When compared to the actual basis models, the printed components may have certain approximation category errors because of the discontinuities in the layer structure. Typically, these odd mixtures appear in sections and shapes with horizontal slopes. According to reports, this anomaly enervates the dimensional properties of most 3D printing techniques. By lowering the layer thickness, these stair-stepping mixtures can be made less severe. This layer thickness reduction happens uniformly on most surfaces.

6.3 Void formation

The term "void" refers to a gap or space that appears between the layers of an additively manufactured component as it is being produced. The component is fragile, and due to the voids, they are prone to poor mechanical properties. FFF has anisotropic properties because these cavities function as a catalyst for delamination and the development of porosity between subsequent layers. It has been shown that voids that form during the fabrication process have a greater impact on anisotropy. While this is

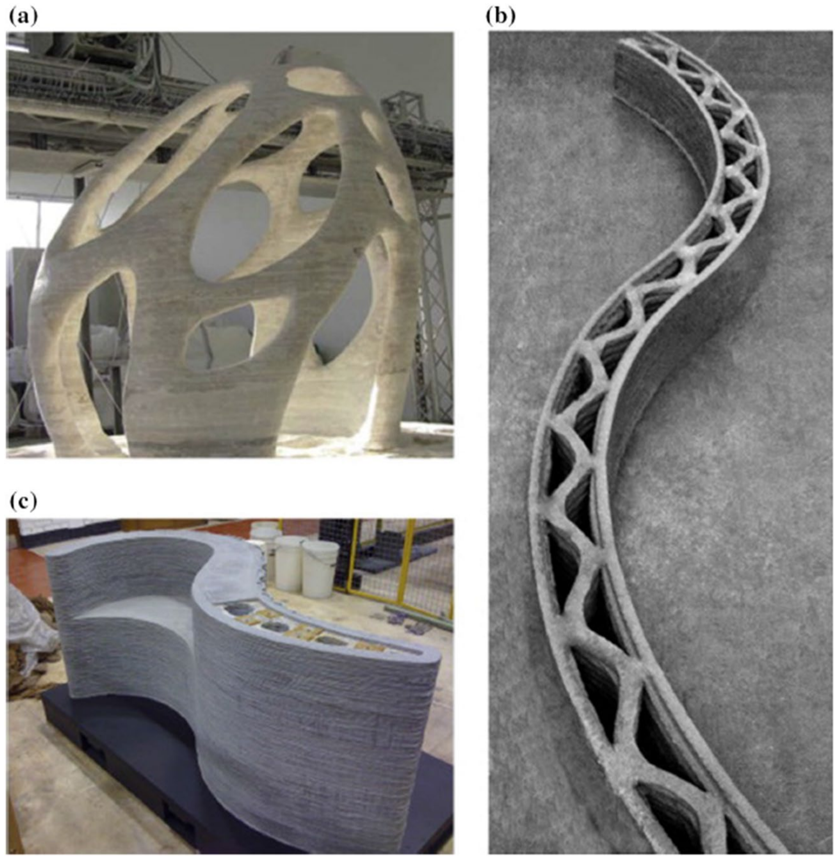


Fig. 27 **a** D-shape, **b** contour crafting, and **c** concrete printing [233]

true, it is yet unknown how much of an impact it will have. In order to evaluate the quality of printed components, it is necessary to evaluate and quantify the impact of these voids on the component's overall quality.

7 Research gap

According to the aforementioned literature, PLA composites embedded in micro/nano biomaterials had superior mechanical characteristics than pure composites. It was pointed out that the mechanical characteristics of composites depend on more than only the characteristics of the PLA and biomaterials. Other significant elements include the weather, internal bonding, pattern, infill percentage, weight % of micro wood power, build orientation, and construction methods. Additionally, it was noted that there is a lack of expertise in various process factors (infill pattern, infill percentage, raster angle). Table 1 shows the various research carried out in the PLA/biocomposites and the research gaps. This will help to enhance the mechanical characteristics of the biomaterials blend with the PLA in future research works.

8 Conclusion

The different materials that can be utilised in 3D printing (AM), their mechanical properties, and the applications of the fused filament fabrication (FFF) technique were all thoroughly investigated in this study. The results of this study show that one of the most popular, financially rewarding, and conveniently available manufacturing technology types available today is FFF technology. This research examines a range of materials composites with polymers, with fibre-reinforced composites exhibiting the highest overall properties. The end product is of the highest imaginable quality because of the use of a concentric pattern and a zero-degree angle. Additionally, reducing the layer's thickness will noticeably improve the product's overall quality. At the moment, the primary focus of research in FFF is on the development of new polymer composites and the optimization of the parameters in order to produce products of a higher quality that can be used in a wide variety of manufacturing applications. Fibre composites, on the other hand, present some challenges. Two of the most frequently noticed issues with this FFF method are nozzle clogging and stair step effects.

Table 1 Research gap on the FFF printed PLA/biocomposites

Reference	Materials	Objectives	Finding	Research gap
Nyberg et al. [234]	Harakeke powder and PLA3052D Harakeke fibre content (0, 10, 20, 30) Hemp fibre content (0, 10, 20, 30)	Investigate the possibility of employing the natural fibres hemp and harakeke in the form of individual composites by making use of a PLA matrix	As the percentage of fibre in a sample increased, the glossiness decreased and the texture coarsened Reduced tensile strength in conjunction with increased fibre content. Lower strengths are probable as a result of void content inside the filament, voids between strands in samples, and weak interfacial bonding	No detailed mechanical properties on bending, flexural, or impact testing. The infill parameters used were not detailed
Tao et al. [235]	Wood flour (WF)-14 µm (size) and PLA4032D WF-(5wt%)	Wood flour (WF)-filled polylactic acid (PLA) composite filaments for a fused deposition modelling (FDM) method are the subject of this study	The microstructure of the PLA fracture surface and the interfaces between the WF and the PLA were altered after WF was added. Roughness develops on the composite fracture surface. Clear gaps may be seen at the WF/PLA surfaces, indicating weak interfacial adhesion. The tensile stress of specimens was raised by adding WF, indicating augmentation of the composites' dimensional stability	Greater effort and optimization should be put on mechanical properties. Insufficient experience with varying process parameters (infill patter, infill percentage, raster angle)
Mangat et al. [236]	PLA and chemically treated waste natural fibre (NFi3DS)	For the purpose of using chemically treated waste natural fibre (Nfi3DS) created through fused filament deposition (FFD) to biomedical applications, it is necessary to investigate both the mechanical and microbiological properties of this material	Silk fibres have been found to have superior tensile strength to those of sheep wool fibres, as evidenced by the fact that the specimen containing silk fibres achieved the highest level of flexural strength In comparison to pure PLA and PLA/silk specimens, the biodegradation of PLA/sheep wool specimens was significantly slower	A significant research effort is required to fully understand mechanical properties. (pulling, twisting, and smashing)
Ertan et al. [237]	PLA and bio-carbon	The purpose of this study is to learn more about the tribological characteristics of a bio-based hybrid material consisting of PLA and biocarbon reinforcement	The incorporation of biocarbon into PLA went off without a hitch. The SEM analysis confirmed the strong adhesion between biocarbon and PLA. In 3D printing, biocarbon had the lowest yield, as evidenced by nozzle-clogging errors. After a dry sliding test against an Al2O3 ball, the PLA sample made with 30 vol.-% carbon showed the least amount of wear volume	No detailed mechanical properties

Table 1 (continued)

Reference	Materials	Objectives	Finding	Research gap
Vigneswaran et al. [238]	PLA and wood powder	To evaluate the mechanical characteristics and statistical analysis of the developed PLA/wood composite	Increasing the infill density raises the energy absorption rate and the toughness Due to the correlation between layer thickness and performance, increasing the thickness of a composite's layers reduces the material's tensile strength	No detailed characterisation on the composite filament
Wang et al. [142]	PLA and CNF	To evaluate thermal, mechanical, and water absorption tests of PLA/CNF composite	CNF prepared by enzymatic hydrolysis and high-pressure homogenisation showed good homogeneity in length and diameter The addition of PEG600 increased the elongation at break and reduced the tensile strength of the PLA filament	No optimization analysis. Lack of knowledge of using different process parameters. No detailed mechanical properties
Cali et al. [239]	PLA and HEMP (powder from hemp canapule fillers 20%)	The purpose of this study is to learn more about HEMP and WEED, two innovative organic bio-composite filaments made of polylactic acid (PLA) loaded with organic by-products	The tensile strength of the newly created composite is remarkable When compared to PLA, the elastic modulus is 133% higher, and the yield strength is 16% higher. The elastic modulus increases noticeably when WEED (powder from hemp inflorescence fillers 20%) is added, however the material's yield stress and ultimate stress are still significantly lower than those of PLA	Lack of knowledge using different process parameters (infill patter, infill percentage, raster angle). No optimisation analysis
Yu et al. [240]	PLA and RSP	The purpose of this study is to learn more about the impacts of rice straw burial days on its morphologies, mechanical characteristics, crystallisation properties, and thermal stability	Both the tensile strength and the tensile modulus of RSP/PLA bio composites were diminished by increasing the amount of time rice straw was buried in the soil. The thermal stability of the fused deposition modelling printed RSP/ PLA bio composite was enhanced by burying rice straw in the soil	Lack of knowledge using different process parameters. No detailed mechanical properties and optimisation
Kain et al. [241]	PLA/lemongrass fibre	Examining the effects of fused deposition modelling on the mechanical characteristics of polylactic acid/lemongrass fibre biocomposites	Due to the weakness of its intermolecular and intramolecular hydrogen bonds, LF's (lemongrass fibre's) thermal stability is low. There is a clear downward trend in tensile strength, notched impact strength, and flexural strength of these biocomposites as LF content increases (0–10 wt%)	Lack of knowledge using different process parameters. No optimisation analysis

Table 1 (continued)

Reference	Materials	Objectives	Finding	Research gap
Scaffaro et al. [242]	PLA and wood powder	Examining the influence of infill pattern on mechanical properties of 3D printed wood/polylactic acid (PLA) composites using fused layer modelling (FLM)	Analysis of mechanical properties and characterisation revealed that infill orientations of 15° crossed and 30° crossed result in significantly higher connection quality between adjacent filament strands than 0° infill orientation, which results in void formation. The mechanical characteristics improved noticeably as the fibre content increased. To a certain extent (at least up to 25 wt. %), mechanical characteristics are enhanced by the presence of fibre	No optimisation analysis
Jing et al. [243]	PLA, *Posidonia oceanica* leaves (POL), and *Opuntia ficus* indica (OFI)	To investigate the characterisation and mechanical behaviour of PLA/OFI and PLA/POL bio composites	Increases in filler content in the PLA-OFI system are accompanied by an increase in agglomeration phenomena and an increase in voids caused by the existence of lumens that were not accessed by the polymer. At high filler content, the presence of the fillers resulted in a considerable decrease in breaking qualities (TS and EB) related to the tensile characteristics. A significant improvement in impact strength 14% and 20% for PLA/POL-10% and PLA/OFI-10%, respectively	Not focussed on compression properties and optimization

Nano-polymer composites have recently attracted a lot of attention in a variety of applications, particularly in the medical field, where they are being used for scaffoldings and tissue production. However, nano polymer composites have only been used in a very limited number of research projects so far. The possibility that the nanocomposites under consideration could minimise the problems associated with bonding and clogging is a substantial advantage. The product's overall strength and durability will rise, and the surface quality will be enhanced through post-processing. In conclusion, it is hoped that the current review will be useful for investigators working in the field to realise the FFF in overall and to discover the gaps that need to be filled in future study in this area to make improvements.

8.1 Recommendations for subsequent advancement

Material enhancement: investigate novel materials or modifications to existing ones to overcome current constraints in FFF.

Process optimization: explore advanced FFF process parameters for improved efficiency and quality.

Application diversification: investigate potential applications beyond the current scope, such as implants, surgical tools, and mechanical parts such as gears and pulleys.

Sustainability focus: consider the environmental impact of materials and processes, aiming for more sustainable 3D printing.

Collaborative research: encourage interdisciplinary collaborations to leverage insights from other fields for enhanced innovation.

Author contribution Mahendran Samykano: writing—original draft preparation, supervision, conceptualization.

Rajan Kumaresan**:** data curation, writing—original draft preparation.

Jeevendran Kananathan: writing—reviewing and editing.

Kumaran Kadirgama: supervision, writing—reviewing and editing.

Adarsh. K. Pandey: writing—reviewing and editing.

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Declarations

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Consent for publication Consent to publication has been received from all co-authors before the work is submitted.

Conflict of interest The authors declare no competing interests.

Additional declarations for articles in life science journals that report the results of studies involving humans and/or animals Not applicable.

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