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Review

A Comprehensive Review of Additive Manufacturing Technologies for Composite Materials

Gabriela Galib [1], Francisco J. G. Silva [1,2,*], André F. V. Pedroso [1,3], Raul D. S. G. Campilho [1,2], Rafael Lucas [1,4] and Rita Sales-Contini [1,5]

[1] CIDEM, ISEP, Polytechnic of Porto, Rua Dr. António Bernardino de Almeida, 4249-015 Porto, Portugal
[2] LAETA-INEGI, Associate Laboratory for Energy, Transports and Aerospace, Rua Dr. Roberto Frias 400, 4200-465 Porto, Portugal
[3] Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Rua Dr Roberto Frias, 400, 4200-465 Porto, Portugal
[4] School of Engineering and Sciences, São Paulo State University, Guaratinguetá 12516-410, São Paulo, Brazil
[5] Aeronautical Structures Laboratory, Technological College of São José dos Campos Prof. Jessen Vidal (FATEC), São José dos Campos 12247-014, São Paulo, Brazil
* Correspondence: fgs@isep.ipp.pt; Tel.: +351-22-83-40-500

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Abstract: Additive manufacturing (AM) is a term used to describe technologies that utilize 3D model data to create physical objects by depositing materials in the form of powder, wire and/or resin. One of the applications of AM is in manufacturing composites, where two or more materials are combined to form a helpful engineering material. This review article covers the most common AM technologies used in composite manufacturing, including Laminated Object Manufacturing (LOM), Fused Deposition Modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Energy Deposition (DED). The work intends to provide a structured set of information for beginners or practitioners, helping to acquire the essential knowledge in this field in just a document, and this represents its main novelty, as no other articles have been found to provide a deep but synthetic set of information about this subject. The article describes each process's main characteristics, advantages, and disadvantages and provides a brief SWOT analysis, offering examples of their use. In summary, AM of composite materials has the potential to transform 3D printing from a prototyping method into a robust manufacturing technique. However, there is no universally superior AM technique, and the most appropriate method must be selected for each application.

Keywords: additive manufacturing; composites; composite manufacturing; SWOT analysis

1. Introduction

Additive Manufacturing (AM), as defined by ISO/ASTM 52900:2021 [1], is a "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies". This technology encompasses several techniques [2], including binder blasting, Direct Energy Deposition (DED), material extrusion, material jetting, Powder Bed Fusion (PBF), plate lamination, and vat photopolymerization, each offering unique advantages and challenges [3]. Other terms such as additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication and freeform fabrication have historically been used to describe the same method [1].

AM was introduced over three decades ago when the first Stereolithography (SLA) patent was granted in 1986 to Charles Hull [4]. Since then, AM techniques have become the preferred method for producing highly complex-shaped Rapid Prototypes (RPs) [3] and specialized parts in small lot sizes. The variety of 3D printing materials has doubled in recent years [4, 5].

Initially, AM used polymers, but later, ceramics, metals, and composites were introduced. Composites are used to produce desired products and facilitate the process. Still, only a few of the available AM techniques have been utilized for composite production: Laminated Object Manufacturing (LOM), Fused Deposition Modelling (FDM), SLA, Selective Laser Sintering (SLS), and Direct Energy Deposition (DED), some of them [6]. This paper discusses the AM techniques mentioned above and their role in producing composites.

The use of AM provides several advantages in the production of composite parts [7-9], as concluded below [10]:

1. Geometric complexity and customized production, AM provides enhanced design freedom and flexibility of parts that cannot be fabricated via subtractive or formative manufacturing methods [11].
2. Rapid prototype and lower cost. AM can shorten delivery time and cost; consequently, designers can provide multiple design iterations that can be fabricated with fast response times [12, 13].
3. Tailorable composition and properties. AM can produce functionally graded materials (FGMs) in a single run, combining structure and function with the time-saving process, reduced part numbers, and lower cost fabrication [13, 14].
4. Co-continuous phase reinforcement composite. AM provides opportunities to fabricate co-continuous phase reinforced composites with well-defined architectures [15]; the question is whether making such composites with properties that are at least as good and preferably superior to those achieved by conventional forming [10].

Currently, these technologies are being utilized for different purposes in various industries and society, such as engineering, medicine, education, architecture, cartography, and entertainment. Throughout the development of additive manufacturing, multiple terms and definitions have been used, often regarding certain application areas and trademarks, leading to ambiguity and confusion, which hinders communication and the broader application of this technology[1]. Additive manufacturing is categorized into seven groups, according to ISO/ASTM 52900:2021 [1] standard:

- Binder Jetting (BJT) is an additive manufacturing technique with a liquid adhesive to join powder materials selectively [16],
- DED: An additive manufacturing process that uses focused thermal energy to melt and fuse materials as they are deposited [17-20],
- Material extrusion (MEX): An additive manufacturing technique that selectively dispenses material through a nozzle or orifice [21],
- Material jetting (MJT): An additive manufacturing process where droplets of feedstock material, such as photopolymer resin and wax, are selectively deposited [22],
- PBF: An additive manufacturing technique that selectively fuses specific areas of a powder bed using thermal energy,
- Sheet lamination (SHL): An additive manufacturing technique that bonds sheets of material to create a part [23],
- Vat photopolymerization (VPP): An additive manufacturing process where a liquid photopolymer is selectively cured by light-activated polymerization in a vat [24].

The ASTM D3878–16 [25] Standard Terminology for Composite Materials (the latest version was released in 2023 as ASTM D3878-20b) defines a composite (material) as “a substance (material) consisting of two or more materials, insoluble in one another, which are combined to form a useful engineering material possessing certain properties not possessed by the constituents”. A composite material is heterogeneous on a microscopic level but can be considered homogeneous on a macroscopic level for specific engineering purposes. The different components of a composite maintain their separate identities and do not entirely dissolve or merge into each other; even though the constituents of a composite material are not fully incorporated, they still work together in a coordinated manner. Composites can be classified into four categories: bio-composites, composites based on scale, composites based on reinforcement type, and composites based on matrix materials, as illustrated in Figure 1.

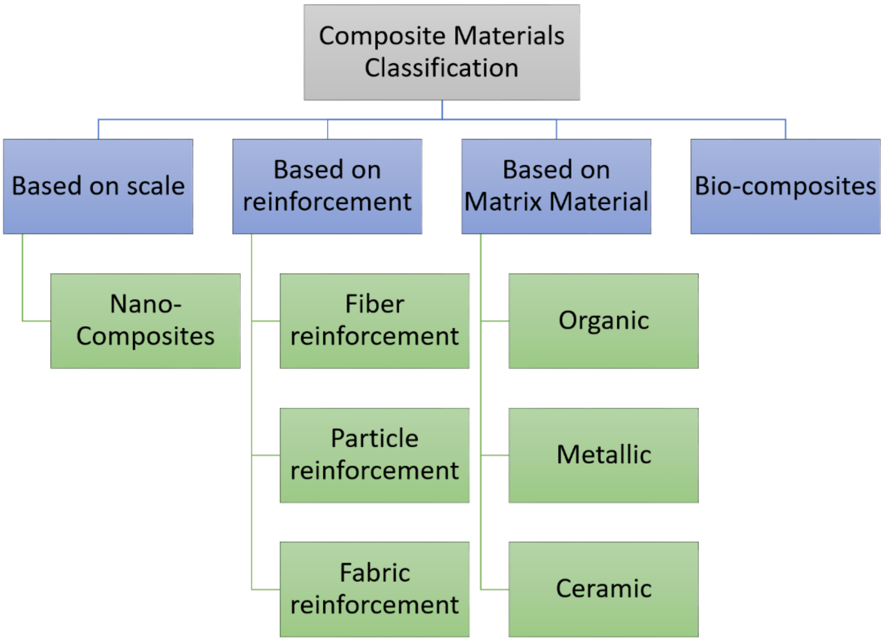

Figure 1. Composites materials classifications (adapted from [26-29]).

However, these materials are more commonly classified based on matrix constituents or the reinforcement type. The primary composite classes for the first one include organic-matrix composites (OMCs), metallic-matrix composites (MMCs), and ceramic-matrix composites (CMCs). "Organic-matrix composite" is a term that generally refers to two classes of composites: polymer-matrix composites (PMCs) and carbon-matrix composites (commonly known as carbon-carbon composites), as shown in Figure 2. The matrix is typically a continuous phase throughout each system's component. The second one, referring to the reinforcement form, consists of particulate reinforcements, continuous or discontinuous fibre reinforcements, and fabric reinforcements (braided and knitted fibre architectures are included in this category), as shown in Figure 3 [19].

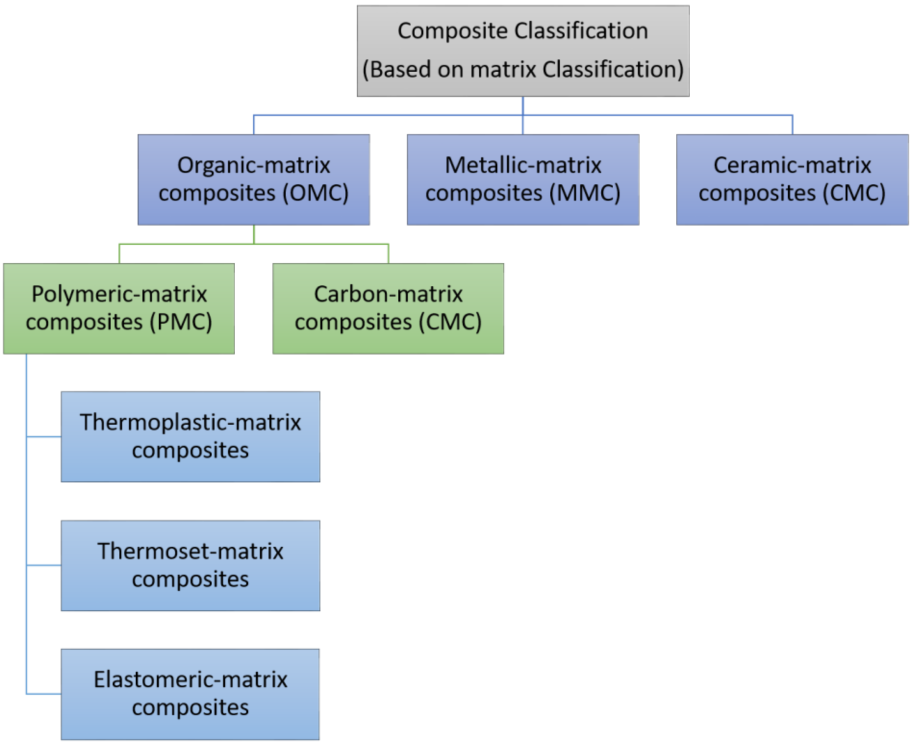

Figure 2. Composites Classification (based on matrix material, adapted from [26, 30]).

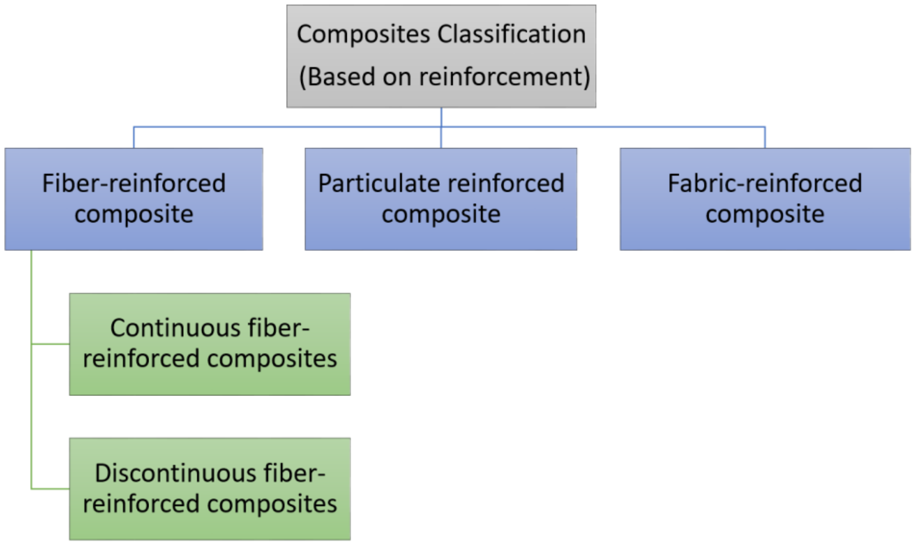

Figure 3. Composites Classification (based on reinforcement, adapted from [26, 30]).

2. Methodology

To conduct this review study, the scientific search platform SCOPUS was used to explore “Additive Manufacturing Techniques” topics. An advanced search was performed on the platform, targeting titles, abstracts, and keywords from 2000 to 2020. The search results are presented in Figure 4, revealing about 7500 articles on the subject. As seen in Figure 4, the number of research articles published in the last few years has drastically increased, depicting the interest that this subject deserves from the scientific community. Thus, a concise, deep and structured review can help students and researchers approach this subject for the first time, providing information to make the reader aware of the basic concepts of the latest developments in this field. Based on the total number of articles found, a fine selection of the most relevant was performed, giving rise to the present review.

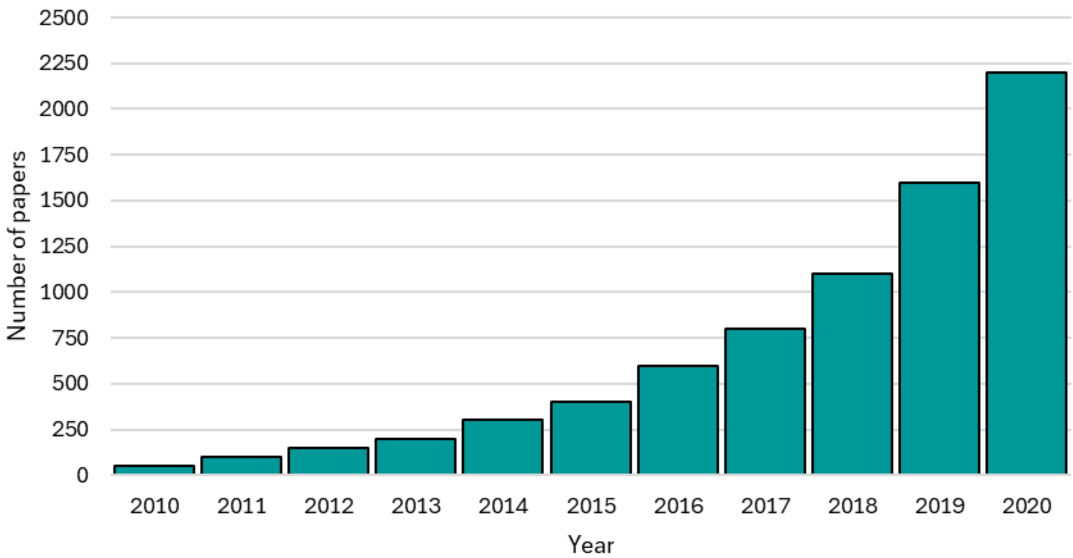

Figure 4. Number of articles addressing Additive Manufacturing Techniques (2010–2020).

Research on additive manufacturing techniques has indeed raised since 2010, driven by the widespread adoption of Information Technologies (IT) to enhance additive manufacturing processes in aerospace, automotive, medical, and consumer goods industries. The exponential growth in research output highlights the increasing interest and investment in this field, with a notable rise in scientific publications reflecting advancements in IT applications, new materials, and process enhancements. These IT technologies have significantly improved the efficiency, precision, and capabilities of additive manufacturing, leading to innovative solutions and expanded applications across various sectors [31-33].

3. Additive Manufacturing Techniques

3.1. LOM

Sheet lamination, often called LOM (Figure 5), was developed in 1991 by Helisys of Torrance, CA, USA. This technique allows the creation of 3D parts by sequentially layering the sheets and adhering these together using a bonding agent. The raw material is supplied as a continuous sheet wound around a spool [10, 34-37].

The process starts when the sheet is pulled over the building platform and attached using a heated roller. Then, 2D cross-sections are cut with a laser or cutter, removing unwanted material. The excess material (non-part sheet) is collected on another drum. Once a layer is complete, the platform is lowered, and a new sheet is bonded onto the previous layer. This process is repeated until the prototype is finished. LOM technique can be employed with paper, metals, plastics, fabrics, synthetic materials, and composites [10, 34-37].

The precision of the part relies significantly on the thickness of the sheet and the accuracy of the cutting mechanism. Depending on the curing stage and material, standard machines can roll new layers between 13 to 40 mm/s with a heat exposure of 5 to 20 s. Depending on the sheet material, each layer's thickness can be 0.04 mm or larger. Although partially an additive manufacturing method, it is commonly known as a subtractive one since it combines both additive and subtractive elements. The parts often undergo post-processing through machining or drilling to achieve the required accurate dimensions. Further post-processing for curing may also be necessary depending on the bonding agent applied [4, 36, 38, 39]. LOM is suited for creating large-scale structural prototypes. While it lacks the mechanical robustness of SLM, it is cost-effective for initial design iterations [40].

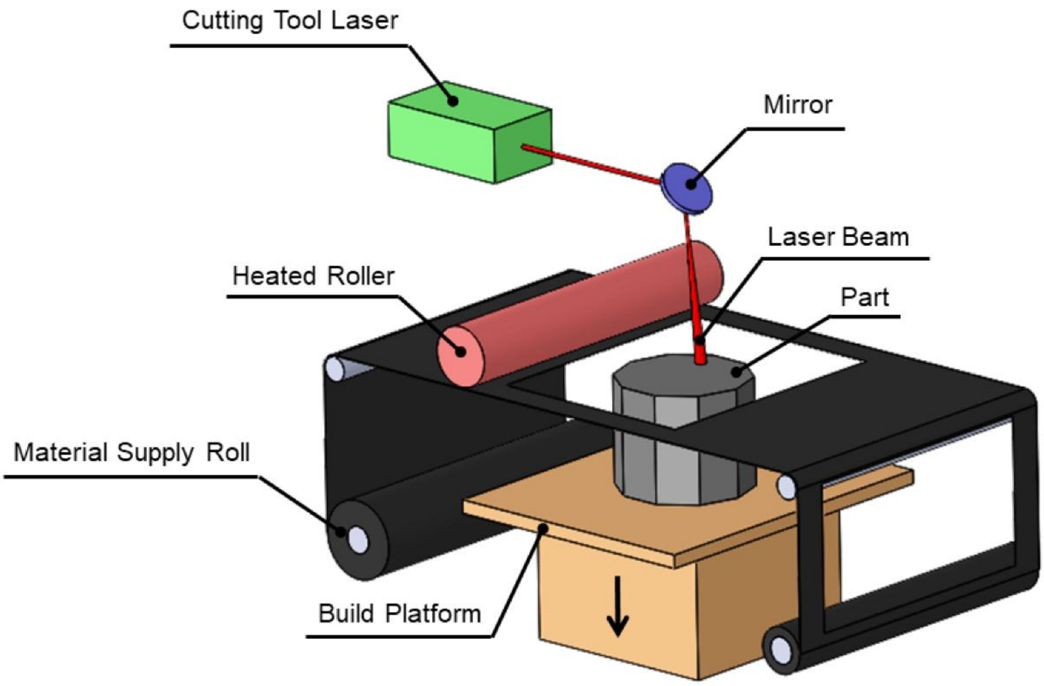

Figure 5. Schematic representation of a LOM setup [41].

Klosterman et al. [42] showed the manufacturability of a polymer matrix composite C-shaped panel using curved LOM (Figure 6). The new laminator design is shown in Figure 6a, with the resulting part and a similar body armour panel in Figure 6b. During curing, the LOM paper mandrel shrank by 11% in the z-direction but remained unchanged in width and length. The "C9" shell experienced minimal dimensional change due to spring-back and fit nearly perfectly on a newly fabricated mandrel, as illustrated in Figure 6b. In this case, a commercial prepreg of continuous unidirectional glass fibre was used. This material consisted of an epoxy matrix with a fibreglass reinforcement of 52 to 55% fibre volume fraction (vt%). A curved LOM machine was used to lay up and shape green composite laminates from the mentioned prepreg feedstocks, followed by vacuum bagging and oven curing. The accuracy of most directions was under 1%, while deviations of around 7.9% were detected in the height direction. The composite achieved a shear strength of approximately 25 MPa, enough for standard applications. The main problem with LOM was the incapability of the heat roller to consolidate and cure the parts fully, confirmed by microstructural investigations, which revealed weak interfacial bonding.

Therefore, a post-consolidation cycle is recommended to enhance the interfacial bond strength between the layers and reduce the void content to less than 5% [4, 34, 42, 43].

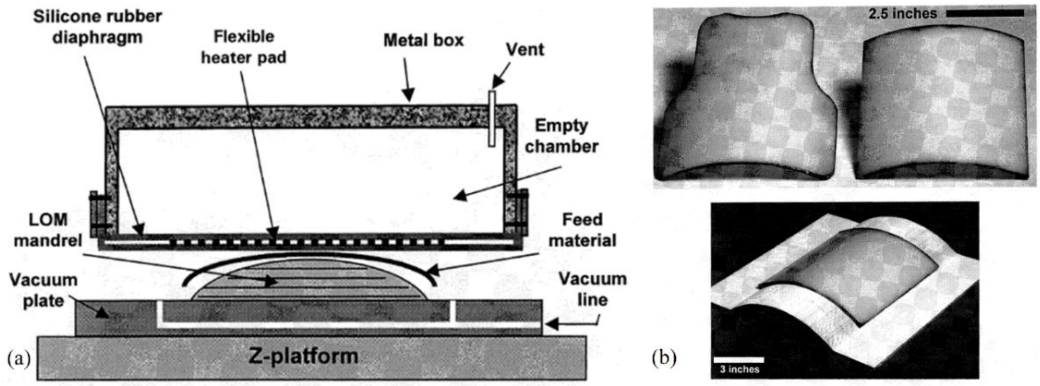

Figure 6. (**a**) Cross-sectional schematic of Curved LOM laminator and platform; (**b**) cured, glass fibre epoxy composite parts made with Curved LOM (adapted from [42]).

Sonmez and Hahn [44] studied heat transfer and stress in LOM to understand the impact of process parameters on the stress and temperature distributions. It was concluded that larger rollers were more advantageous for bonding as they led to a less concentrated stress distribution. Kansas State University researchers have developed a new method for continuous fibre-reinforced thermoplastic composites called laser-assisted AM (Figure 7). The purpose of this method is to reduce waste associated with LOM. Instead of using pre-cut prepreg sheets, the authors proposed using prepreg tape. The tape strips were layered using a CO_2 laser beam and consolidation roller before laser cutting each layer. This method has superior mechanical properties due to continuous fibre reinforcement, a high fibre-weight ratio, minimized void content, and superior interfacial bonding. A comparison between the tensile properties with other AM and conventional composite manufacturing methods can be found in Figure 8 [34, 42-45], where SF stands for Sustainable fibre [46], GF stands for Glass fibre [47], ELF stands for End Light fibre [48], and CF stands for Carbon Fibre [49].

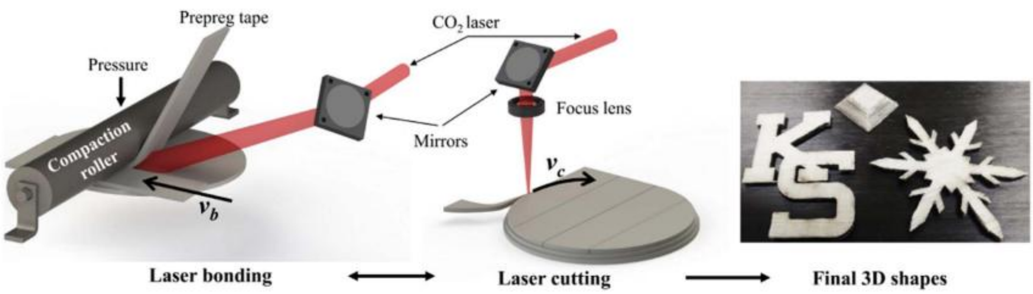

Figure 7. Schematic representation of the proposed additive manufacturing method.

LOM also allows the production of large-scale monolithic ceramic parts and continuous fibre-reinforced ceramic composites, which are challenging to produce using other additive manufacturing methods [36]. However, LOM has limitations such as materials waste, delamination, anisotropic properties along planar directions, and the inability to produce complex geometries, resulting in limited usage (Table 1) [10, 49].

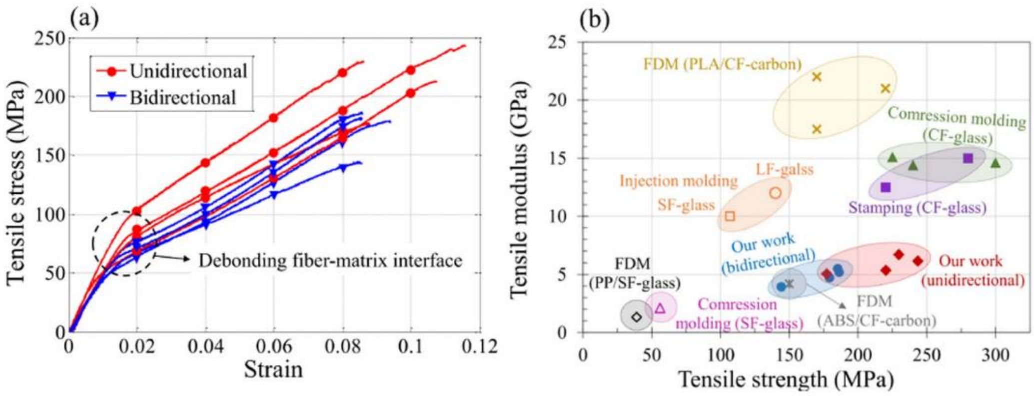

Figure 8. Tensile properties of 3D printed samples produced by the proposed method. (**a**) Stress-strain curve, and (**b**) Young's modulus (E) versus tensile strength (σ_u) comparison with FDM [46-49].

Table 1. Limitations & Capabilities/Strengths of the LOM process.

Capabilities/Strengths	Limitations
Enables the construction of large prototypes (800 × 500 × 550 mm^3)	Models' stability and resistance can be limited by the bonding strength between the glued layers, which varies with the materials' physical properties.
Simple and economical setup	The sheets' thickness determines the height of the layers.
Fast processing time	It does not provide the opportunity to include intricate details or delicate contours.
No support structures are required.	The excess material that is generated during the manufacturing process goes to waste, which in turn increases the overall production costs.
	The model requires post-processing, which involves removing excess material, sanding, and applying paint or varnish to preserve it.

Fabricating composites using this method heavily relies on the development of composite laminates. LOM allows the layers of the product to be changed by using laminates made up of different material compositions, which results in varied composites, making this a unique additive manufacturing method. For instance, LOM has been used to develop FGMs or a composite of TiC/Ni with the help of combustion synthesis as post-processing [50]. However, since many different sets of laminates need to be integrated, automating this process is challenging and has limitations [6, 51].

3.2. FDM

Wohler's Report from Stratasys, Inc. states that FDM is currently the most widely used additive manufacturing technology; this process is also known as Fused Filament Fabrication, or FFF, in the case of small equipment (desktop). By the end of 2010, 15,000 FDM commercial machines had been sold, which accounted for 41.5% of the market share. FDM involves heating a coil of thermoplastic material fed to an extruder head that heats up the material and deposits it through a nozzle layer by layer to build the part. In FDM printers, the build platform usually moves in the Z direction, while the nozzle moves in the X and Y directions to create the part. The critical elements of the FDM system include material feed mechanism, liquefier, print head, gantry, and build surface [34, 52, 53]. Figure 9 shows the schematic representation of this process.

The FDM (Fused Deposition Modelling) process is a 3D printing technique that uses a material filament. The filament feeds an extrusion head, which heats the material and extrudes it through an extrusion nozzle. This nozzle deposits the material in specific locations, forming a layer. The heat from the extruded material dissipates, and it gradually cools and solidifies while the head or build platform moves vertically. This movement allows the deposition of a new layer on top of the previous one, and the process repeats until the final 3D model is complete [52, 54]. FDM is used for creating affordable, patient-specific orthopaedic models and prosthetics. The introduction of biocompatible and sterilizable materials has enhanced its relevance in medical applications [46]

Creating a layer involves passing a certain number of filaments to outline the section and filling the interior area. This filling process can be completed, resulting in a solid or sparse object with a grid or other geometric configuration to reduce material usage, the weight of the part, and the machine time needed to manufacture the component, which can be done without significantly affecting the functional performance of the final product. It is essential to keep in mind that during the FDM process, support structures are needed when producing protrusions and other surfaces that are not supported. As a result, some machines use two extruder heads and two materials- one for structural support and the other for support material. After an immersion cycle, the support material can be manually removed or dissolved using sodium hydroxide (NaOH) or caustic solutions [45, 47].

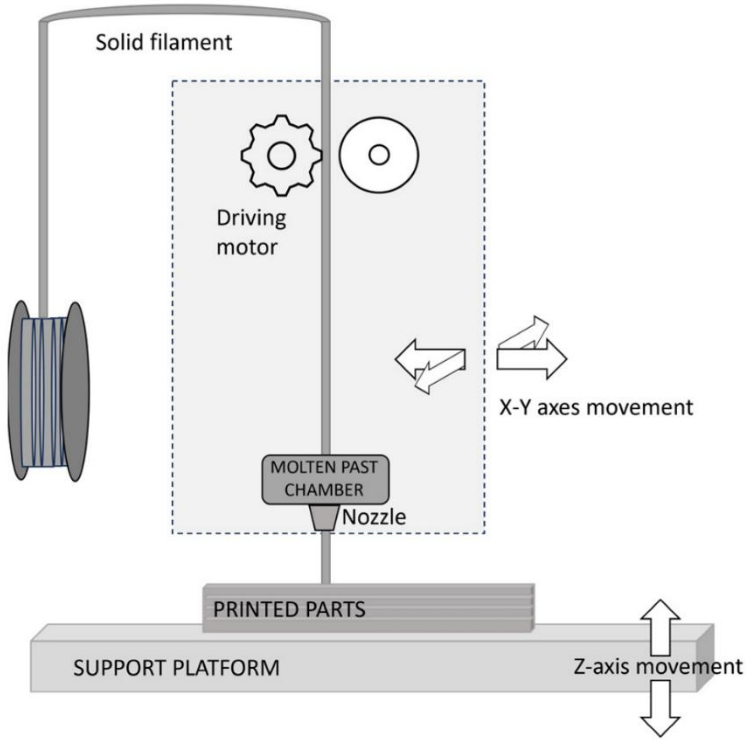

Figure 9. Schematic representation of the FDM process as described by Acierno and Patti [55].

FDM is a simple, user-friendly process that does not require special operating conditions like a sealed build chamber or complex thermal properties. Additionally, raw materials are easy to acquire, handle, and store [52, 54].

Specific process parameters are critical when using FDM, including bead width, air gap, model build temperature, and raster orientation. Extensive research has been conducted on the effects of raster orientation on tensile and compression test results [56]. During the FDM process, an infrared camera can monitor the temperature distribution [57]. Intensive research focuses on the surface roughness and cross-sectional shape of parts fabricated through FDM. Various building rules have been proposed to enhance the strength and accuracy of FDM printed parts. Some of these rules include dealing with stress concentration at corners, considering that smaller bead width leads to extra printing time and better surface quality, building parts in a way that ensures tensile loads are carried axially along printed directions, and using negative air gap to enhance both strength and stiffness [56]. Recently, there has been a growth in the use of fibre reinforcement in FDM. Most research efforts have been directed toward developing filaments with additives of short fibres [34]. Figure 10 presents a schematic of 3D printed composites by FDM with long fibres.

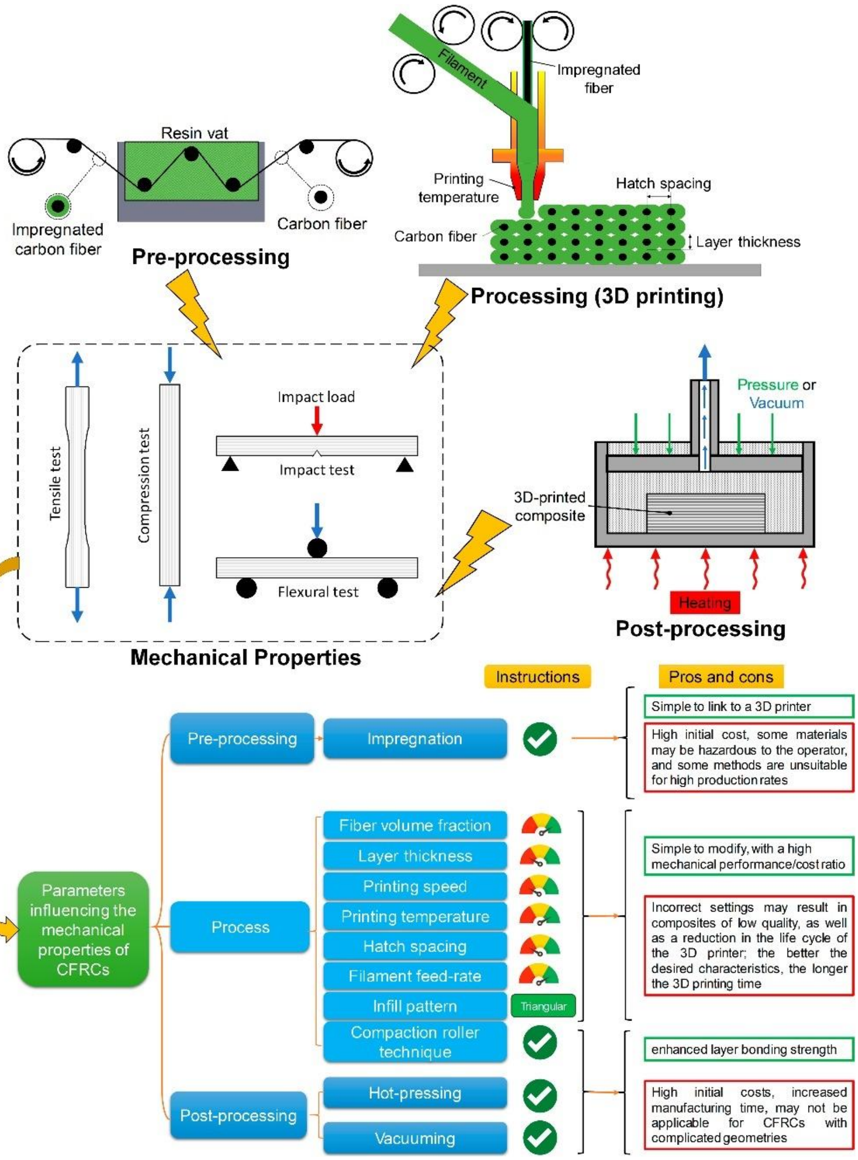

Figure 10. Schematic representation of 3D printed fibre-reinforced composites by FDM [58].

Adding fibres to the filament reduces tape swelling while increasing stiffness during deposition [59]. Glass fibre-reinforced polypropylene (PP) was evaluated by Carneiro et al. [46]. The study found that adding glass fibres led to a 30% and 40% increase in the *E* and strength, respectively, compared to pure PP. To address low aspect ratios in short fibre-filled parts, thermotropic liquid crystalline polymers (TLCPs) with excellent σ_u, such as ABS and polypropylene (PP), were utilized in fibre-reinforced FDM parts [60]. The temperature at which TLCP is processed is a critical factor that affects its surface morphology and mechanical properties. When ABS and PP are filled with 40% fibre mass fraction (wt%) TCLP, their *E* increases by 100% and 150%, respectively. Also, it was found that a higher CF ratio results in a higher decomposition temperature, which provides excellent thermal stability [34].

A study by Ning et al. [61] investigated the impact of weight ratio and CF length on the physical properties of FDM samples with an ABS matrix. The results showed that 5 and 7.5 wt% CF content improved σ_u and *E*, respectively. According to the research, longer CF can enhance σ_u and *E*; however, it might cause a reduction in toughness and ductility. The FDM process with aligned CF resulted in a 115% increase in mechanical strength and a 700% increase in *E* when using 30 wt% CF-ABS composites. The CF-ABS parts were shown to possess a higher strength than aluminium. Adding CF decreased the triangular channels between beads, reducing die-swell and increasing thermal conductivity. However, it also caused internal voids within the beads, leading to stress concentration and failing to lower stresses [53, 62].

One of the significant challenges that researchers face in additive manufacturing is continuous fibre reinforcement. Continuous fibre composites offer substantial improvements in mechanical properties compared to discontinuous fibres, but a robust and standard paradigm still needs to be developed for 3D printing. Matsuzaki et al. [49] developed an innovative technique for in-nozzle impregnation of continuous fibre and thermoplastic matrix. The resin filament and fibre were supplied separately before being heated and mixed in the printing head. The mixture was then ejected onto the printing bed. Figure 11 presents a schematic of this process and shows the resulting specimens. Reinforcement materials for 3D printing included CF and twisted yarns of natural jute fibres. Figure 12 shows the superiority of continuous fibre composites over short fibre reinforcement and other 3D printing methods.

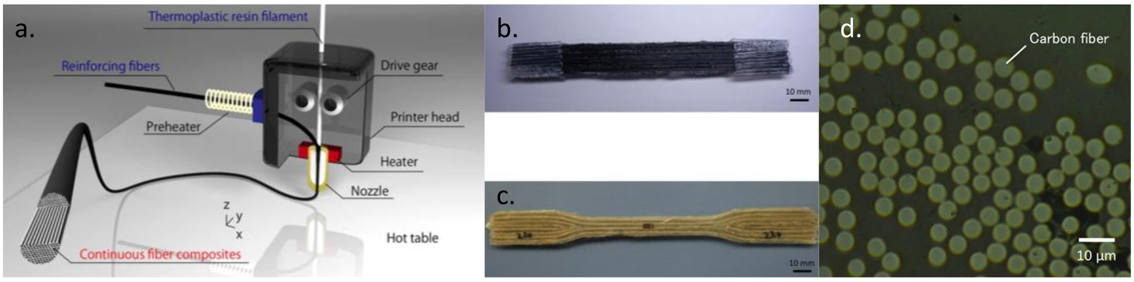

Figure 11. (**a**) Schematic representation of the 3D printer head using in-nozzle impregnation based on FDM. 3D-printed (**b**) CFRTP and (**c**) dumbbell-shaped JFRTP specimens. (**d**) magnified cross-section of the CFRTP specimen (adapted from Matsuzaki et al. [49]).

This technique was used by Tian et al. [63] *apud* Parandoush and Lin [34] to print parts made of composite polylactic acid (PLA) and CF. However, there were gaps between PLA filaments, which can be addressed by increasing the resolution. According to Li et al. [64], the σ_u of continuous CF-reinforced PLA, which was prepared using FDM, can reach mechanical strength as high as 91 MPa. On the other hand, in the case of short CF, the σ_u is only 68 MPa. Regarding Yu et al. [65], CF and PLA weak bonding can significantly affect the mechanical properties in this method; however, surface modification of CF bundles with methylene dichloride and PLA particles improved adhesion and increased tensile and flexural strength. Tian et al. [66] performed a systemic analysis on the interface and performance of printed continuous CF -reinforced PLA composites and the effect of process parameters on the temperature and pressure in the process.

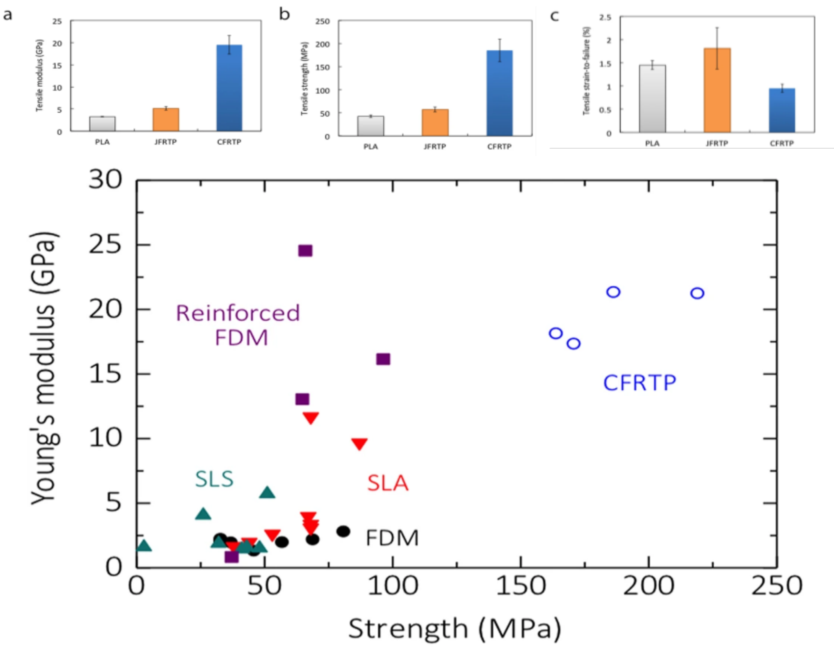

Figure 12. (**a**) E, (**b**) σ_u, and (**c**) tensile strain-to-failure of specimens fabricated by 3D printing; (below) Young's moduli and strengths of continuous carbon-fibre composites fabricated in the present study compared with composites fabricated by FDM [62, 67, 68] and using commercially available 3D printers, such as SLS [69], SLA [50] and FDM [70, 71].

Continuous Kevlar fibre-reinforced 3D printed nylon structures were evaluated by Melenka et al. [72] using commercial desktop printers to predict their tensile properties. Increasing the volume of fibre reinforcement improves stiffness and ultimate strength. CF is inserted between the layers of 3D-printed polymer to enhance strength and fatigue life, and a thermal treatment is conducted to increase the mechanical properties further [73]. However, studies by Zak et al. [74] have indicated that increasing the number of CF layers results in larger void areas, negatively impacting σ_u. The process of impregnating plastics into the fibre bundle can be accomplished within the temperature range of 200–230 °C. A layer thickness of 0.4 mm to 0.6 mm and hatch spacing of approximately 0.6 mm can ensure bonding strength between lines and layers. Following these parameters can achieve a maximum flexural strength of 335 MPa and a flexural modulus of 30 GPa [34].

Table 2 presents the advantages and disadvantages of the FDM process, adapting information from some studies [34, 50, 63].

Table 2. Limitations & Capabilities/Strengths of the FDM process.

Capabilities/Strengths	Limitations
FDM is a simple and easy-to-use process that can be carried out without special operational conditions or industrial facilities.	During manufacturing, parts and models often require support structures to be built alongside them.
Acquiring and operating desktop equipment is more cost-effective compared to other technological processes.	The surface finish of the parts is striated and follows the direction of the building layers.
Acquiring, handling, and storing the raw material is straightforward.	The part must undergo post-processing to remove support structures and smooth surfaces, eliminating layer striations.
The parts have good mechanical properties, are durable over time, and can be post-processed like any conventionally produced.	The parts present anisotropy in the Z (vertical) direction, which may restrict their functional application.
Manufacturing appearance models and semi-functional prototypes can be done more efficiently and economically with a cleaner and faster solution.	It is a slower process than other technologies, such as SLS or MJF.
	Low-cost desktop equipment has limited accuracy capabilities.

3.3. SLA

SLA parts are manufactured through selective curing of thermosetting resin layers with an ultraviolet laser. High-energy lasers may be used for thermal curing [74]. A photo-reactive semi-viscous liquid resin is used to create a desired part [10], involving adding different materials or additives based on the specifications of the final product. The liquid feedstock material is typically placed in a vat, and two different technological processes can be employed: either top-down or bottom-up [4, 75]; as illustrated in Figure 13, it is worth noting that in this case, discontinuous fibres are mixed with the photopolymer resin and, to align the fibres external field transducers were used. The top-down method submerges the building platform into the resin vat. Then, a sweeper blade is used to distribute the resin evenly over the platform, followed by a top laser that scans and cures specific areas of the resin layer. Once this layer is complete, the platform is lowered into the resin to proceed with the next layer. This method allows for incorporating additives as needed and enables the creation of larger objects with acceptable precision. However, the bottom-up SLA printer has a vat filled with material, and the building platform is suspended over it. The laser source is placed beneath the building platform, and the thin resin layer is scanned below it. As the build-plate is lifted, a new material layer can fill the space beneath the part. The scanning procedure is then repeated for the subsequent layer [74, 76].

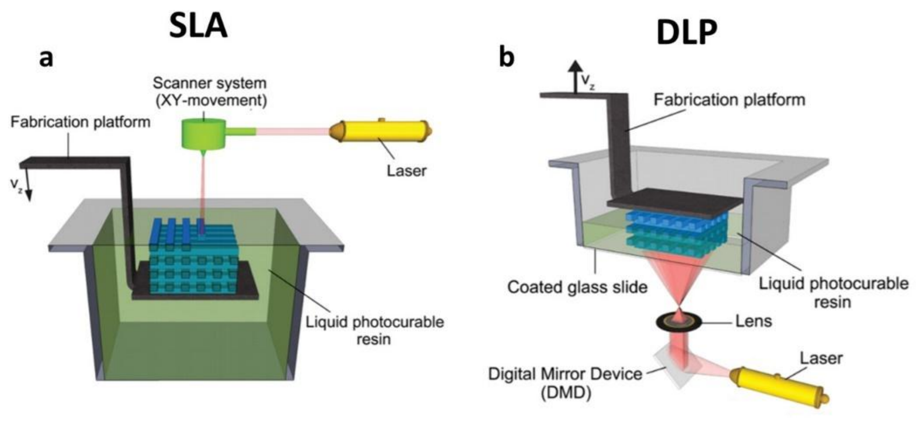

Figure 13. Scheme of (**a**) top-down SLA and (**b**) bottom-up DLP [77].

The bottom-up approach can incorporate Digital Light Projection technology (Figure 13b) based on SLA. This technology has advanced to cure an entire layer at once, rather than using a laser to individually cure each point of the cross-sectional area. The projected image of the cross-section is beamed from the bottom onto the vat, and UV light is used as the energy source. The projected image is capable of curing the entire cross-section effectively. As the elevator lifts the cured section, the next layer is cured. The process is highly accurate, limited by the resolution of the projected image's pixels (Figure 14). After printing all the layers, they combine to form a green part. However, this part is incomplete and requires a final thermal-curing process to develop its mechanical properties. Digital Light Processing (DLP) technology is faster than traditional SLA but best suited for small or less-detailed builds [78-80].

There are two types of DLP, namely continuous and static. The continuous DLP, also known as CLIP (Continuous Liquid Interface Production), emits a constant beam of light that projects a changing image as the platform rises. As the elevator lifts the cured section, the fresh resin flows beneath it [81]. Static DLP flashes each 2-dimensional cross-section while the elevator lifts to the new height needed. Various DLP machines are available in the market [81].

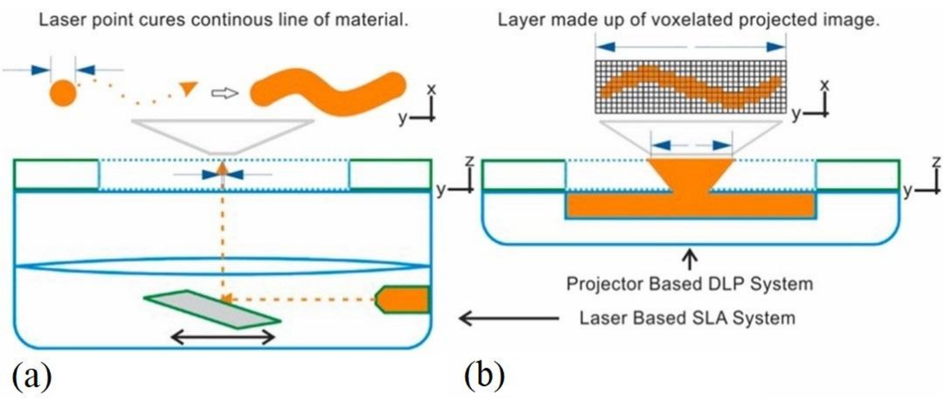

Figure 14. Printing principle of (**a**) SLA and (**b**) DLP [78-80].

Most DLP printers have a maximum build volume between 0.67 to 4.56 L, and resolution ranges between 47 µm and 100 µm [82]. Although the field is well-developed for customizable fashion, jewellery, and sports goods, it is also established for dental and medical work with biocompatible materials. The primary advantage of DLP is its precision and speed, enabling competitive mass production [83]. A stationary laser is used to cure each layer of resin. The laser's energy is controlled by a set of mirrors, which enable it to move across the layer's entire x- and y-axis. As the resin is exposed to UV light, it undergoes semi-permanent polymerization around the point where the laser passes, which forms a strong bond with the adjacent areas, creating a solid and uniform part. In most cases, the component is in an intermediate curing state (green body), requiring further processing to achieve optimal mechanical and thermal properties [76]. As mentioned, both SLA printing setups require support structures for the component, particularly for large overhangs and bridges beyond 30 degrees. Therefore, the parts' orientation in the build volume must be carefully selected when smooth surfaces are desired. It is worth noting that top-down SLA printers require less support, while bottom-up SLA requires more support with a reduced cross-sectional area [84]. The size of an SLA machine can vary depending on the size of the vat and the necessary amount of material. An overview of standard SLA printers was published by Waheed et al. [85], summarizing the pros and cons of each model in terms of materials, speeds, sizes, and volumes. Desktop SLA printers typically have a print volume of 145 × 145 × 145 mm^3, while industrial models can print up to 2000 × 2000 × 2000 mm^3. The dimensional accuracy and layer thickness can be customized and range between 0.15% +/− 0.01 mm to 0.5 +/− 0.10 mm and 25–100 µm, respectively [86-88]. SLA is one of the fastest single-point AM techniques, even though it is also one of the slowest full-build methods since typical speeds range from 10 mm/h to 17 mm/h [89]. A photopolymer is usually mixed with particles or fibres to create composites using SLA, enhancing its properties. However, this process can lead to some difficulties. Firstly, it is challenging to apply new layers because the reinforcing particles increase the photopolymer's viscosity. Secondly, the reinforcing particles may not be evenly distributed if they settle instead of being suspended in the liquid resin. Thirdly, bubbles may form in the liquid, leading to pores that may become sources of potential crack initiation. Lastly, due to the presence of solid particles, laser energy is partially reflected, which reduces absorption and may increase the curing time for the liquid [90-

92]. The Optoform process uses a paste containing various materials [93] to avoid some problems with photopolymer liquid. Thermal curing and photopolymerization can produce composites by reinforcing specially formulated polymer blends [93, 94].

SLA is a popular AM process for producing ceramic matrix composites due to its high printing accuracy, surface finish, and relatively fast build speed [95-99]. Materials like boron carbide (B_4C), graphene (C), and carbon nanotubes (CNTs) have high refractive index and light absorption; for this, fabricating ceramic and reinforcement materials with these properties is difficult as they allow low cure depth under UV exposure. Creating thick-walled parts without excessive porosity or cracking poses a significant challenge due to the volume shrinkage caused by a large amount of organic material during debinding. The debinding process, crucial for removing binding agents in additive manufacturing, is time-consuming and influenced by factors like specimen thickness [100, 101].

On the same line, glass fibres are preferred over ceramic or CF because they are less opaque to UV light [102], making them more SLA-friendly for making FRC (fibre-reinforced concrete). This technique has been used for the research of FRC using short fibres [103], continuous fibres [104], and fibre mats [90]. Although continuous fibres are preferred to enhance mechanical properties, mixtures with short fibres of higher aspect ratios show comparable properties [102]. Improving the properties by increasing the volume fraction is limited by the increasing layer formation and post-processing difficulty. However, the surface coating of the fibre reduces the mixture's viscosity [105]. Fibre supports inter-layer bonding by partially settling into uncured regions of previous layers [103]. Indeed, the uneven dispersion and haphazard orientation of short fibres in composite materials might reduce their efficiency and raise the fracture risk during mixing. Studies have indicated that the spatial distribution of inclusions significantly impacts the fibre-reinforced composites' performance. Furthermore, during the forming process, the orientation of the fibres in concentrated suspensions changes, which affects the composite materials' final properties [106, 107]. Table 3 presents the advantages and disadvantages of the SLA process.

Table 3. Limitations & Capabilities/Strengths of the SLA process.

Capabilities/Strengths	Limitations
Manufacture highly detailed 3D models with ultra-thin layer thicknesses (1–25 µm) and superior surface quality.	The printing time for this process is longer than that of other printing processes.
The 3D models created are isotropic, providing better molecular bonding between the layers of the 3D parts.	It requires support structures that, if not handled well, can collapse during construction or break during final curing.
Resins come in different configurations to achieve various properties. They are suitable for tasks and can replicate certain engineering materials.	Due to the brittle nature and photosensitivity of resins, exposure to sunlight can cause models to lose their shape and structure.
It enables obtaining larger build volumes without compromising precision.	Models cannot be used for outdoor applications or lamp creation and cannot be used in mechanical testing.
	Usually, resins must not be interchanged between equipment brands due to proprietary use.
	The cost of 3D printing using SLA equipment is higher than FDM (Fused Deposition Modelling).

3.4. SLS

SLS is a powder-based AM process where a laser scans a powder bed to form a 3D structure layer by layer and can be divided into four categories: Solid-State Sintering (SSS), liquid-phase sintering-partial melting, complete melting, and chemically induced binding. SSS is a thermal process between half and the full melting temperature. In this case, the force behind the process is the neck formation between adjacent powder particles (diffusion) and the free energy lowering due to the particles' growth. In liquid phase sintering-partial melting, a binder material usually becomes liquefied, while the structural material remains solid. The complete melting technique melts the powder entirely (also called Selective Laser Melting, SLM) and exhibits properties similar to the bulk material. Finally, no binder elements are used in chemically induced binding, and the laser-material interaction times are kept very short, preventing diffusion processes. Due to the heating, the material particles (e.g., SiC ceramic) disintegrated in their essential components. As the liberated atoms oxidize, they begin to function as a binder for the molecules that have not yet broken apart [108]. The process is illustrated in Figure 15 [34, 109].

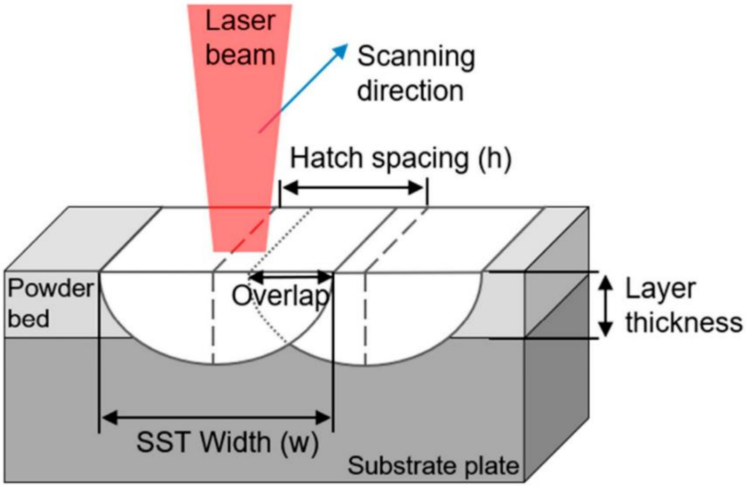

Figure 15. Schematic of Selective Laser Sintering [110].

The SLS process has found applications in various industries with the use of many materials, including wax, cermets, ceramic (e.g., Al_2O_3, FeO, NiO, ZrO_2, SiO_2, and CuO), polymer (e.g., PVC, PE, PP, PMMA, PS, PET, PA and PC), metals (e.g., Al, Cr, Ti, Fe, Cu), metals system (e.g., Fe-Cu, Fe-Sn, Cu-Sn) and alloys (e.g., cobalt-based, nickel-based, bronze-nickel, pre-alloyed bronze-nickel, INCONEL® 625, Ti- 6Al-4V, stainless steel, gas-atomized stainless steel 316L, AISI 1018 carbon steel, high-speed steel pre-coated foundry sand and alumina with polymer binder), bio-material metals–polymers and metals–ceramics combinations [111].

SLS has been used to process composites for two main reasons: (1) to facilitate the particle bounding process, (2) to combine different materials, improving properties [112] and (3) excels in producing lightweight and structurally complex parts using polymer and metal powders. It is widely used for aerospace components like ducting, brackets, and housings due to its ability to create parts with excellent dimensional accuracy and isotropic properties [113]. As an example, for the first case, Fe-Cu SLS is a composite material where Cu acts as a melted fluid during processing and binds Fe powders to form the composite. Cu is added only to consolidate iron powders and not to improve their properties [114]. Conversely, the PCL/HA (polycaprolactone/hydroxyapatite) system exemplifies the second approach, where hydroxyapatite (HA) is added to polycaprolactone (PCL) to enhance its strength and biocompatibility [115]. This latter application is the most common and will be further discussed here.

Liquid Phase Sintering (LPS) is not the most common method for consolidating SLS composites; instead, SLS typically involves the fusion of powder particles using a laser source. The SLS process subjects a powder bed to thermal cycles, allowing particles to merge into a solid part without complete melting, with the part being dictated by the powder's thermo-mechanical properties [116, 117]. Examples of such composites include the mentioned PCL and HA, as studied by Kumar and Kruth [6], PolyEther-Ether-Ketone (PEEK) and HA, by Tan et al. [118], and PA and nano-clay, by Kim and Creasy [119]. In PMC, reinforcement powder is used in particulate form because fibres as reinforcement may cause issues when forming a smooth powder bed and do not help increase the final density and mechanical strength. However, Yan et al. [120] reported that pre-modifying CF through oxidation achieved a uniform distribution of fibres and good interfacial adhesion. Adding the maximum weight ratio of CF enhanced flexural strength and *E*.

SLS composites have been employed in automotive components (e.g., Al-SiC composites), metallic moulds for injection (e.g., Nylon12/carbon black composite), turbine and engine parts (e.g., SiC/Ti), biomedical implants and prostheses (e.g., PEEK HP3), among others [111]. For instance, a car engine inlet manifold can be fabricated by SLS with carbon nanotube (CNT) and Polyamide (PA12) [121, 122]. The results revealed that the laser-sintering-induced segregated microstructures were favourable for electron conduction. However, the inevitable pores adversely affect the thermal conductivity of laser-sintered composites. Still, it has been shown that CNT/PA12 is potentially applicable in end-use applications [121].

In addition, instead of a mixture of a polymer powder and a reinforcement powder, it is possible to use a single composite powder, such as glass-filled polyamide (PA) powder [122], overcoming the difficulty of mixing the powders and yielding a uniform spread of composite components in the final product. However, if one of the components of the composite powder is a fibre, this can result in manufacturing problems [6]. This SLS has also been utilized to create Metal Matrix Composite (MMC), such as Fe and graphite [123, 124], cemented carbide WC–Co [125], WC–Co and Cu [126], Fe, Ni, and TiC [127], and Ceramic Matrix Composite (CMC), like SiC

[128, 129]. However, the SLS of ceramic and metal generally does not result in as dense products as PMC. Extra material is added to the powder mixture to achieve complete consolidation [6].

SLS can create particles in situ through laser-induced chemical reactions. This process uses the laser beam's energy to form chemical compounds and generate thermal energy to propagate chemical reactions. In situ, compound formation is better than pre-adding compounds due to its delicate and uniform distribution, better wetting, and release of exothermic energy that aids in binding [6]. Examples include Cu-based MMC reinforced with TiB_2 and a powder mixture of Cu, Ti, and B_4C [130].

Another way to manufacture a composite with SLS is by post-processing laser-sintered materials in a furnace for chemical reaction and infiltration. The most commonly used example is the production of Si/SiC composites. This procedure uses laser processing to treat SiC with a phenolic resin. After the resin cures in a furnace, some of the infiltrated Si combines with the carbon produced by the resin to form SiC, the final Si-SiC composite. The amount of SiC in the composite can be controlled by adjusting the degree of treatment of the green product with phenolic resin [131]. In Table 4, the main advantages and disadvantages of the SLS process are dissected.

Table 4. Limitations & Capabilities/Strengths of the SLS process.

Capabilities/Strengths	Limitations
The SLS process produces exact and isotropic parts, making it ideal for functional prototypes.	The natural surface appearance features a satin-matte, slightly grainy finish.
Compared to SLA or FDM, it is a faster process.	Slight variations in dimensions and surface quality may occur due to differences in materials and operating conditions.
The cycle time to produce parts of uniform height is consistent, making it suitable for small-batch printing.	The size of the printed part is constrained by the size of the dust container utilized in SLS equipment. The average build volume ranges around $300 \times 300 \times 300$ mm^3; however, larger machines can offer a build volume of $700 \times 380 \times 580$ mm^3.
No support structures are necessary, which minimizes the quantity of excess material.	The printed parts need to be cooled down significantly for SLS printing before they can be taken out and used. Additionally, the equipment used in the process requires cleaning and preparation.
No additional post-processing is required in SLS printing since it does not require the removal of support structures. The remaining dust can be easily removed with a brush.	Most post-processing and cleaning steps are done manually, which may result in slight colour or surface texture variations.
	It is considered an expensive process due to the cost of purchasing the equipment and requirements for its installation, as well as the price of the materials used, which are generally proprietary.

3.5. DED

One of the most critical developments in Additive Manufacturing is the increased use of DED, which is one of the main beam-based approaches for Metal AM, where the material is locally delivered as it is being melted, i.e., the process combines the material/energy delivery in the layer-by-layer formation [132]. The method holds three categories, namely Wire and Arc Manufacturing (WAAM), Direct Electron Beam Deposition (DEBD), and Direct Laser Deposition (DLD), with a broad preference for the latter. DLD is schematically illustrated in Figure 16 and provides an overview of the process [17, 133].

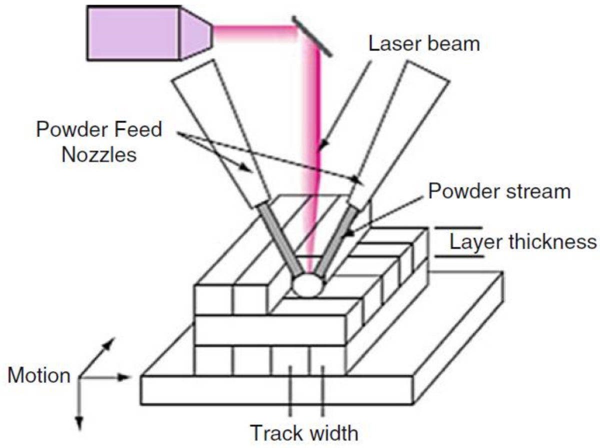

Figure 16. Schematic of a typical laser powder DED process (adapted from [131]).

Different DLD technologies/nomenclatures emerged in the past few years, such as Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD), Laser Metal Deposition (LMD), and Laser Cladding (LC) [126]. Those designations are treated generically as DLD in this paper [134]. DLD uses specifically a laser as a heat source. It has the potential to (1) rapidly prototype metallic parts, (2) produce complex and customized parts, (3) clad/repair precious metallic components, and (4) manufacture/repair in remote or logistically weak locations. Some of the advantages of DLD techniques compared to other AM systems are (1) reduced production times, (2) low fabrication costs, and (3) freedom of design and customization [135].

New DLD machines now incorporate various types of lasers, such as fibre, diode, and Neodymium-doped Yttrium-Aluminum-Garnet (Nd: YAG) lasers due to their enhanced efficiency and robustness, leading to simplified and improved processing capabilities [136, 137]. Additionally, besides the laser choice, many other parameters can be considered during DLD, such as (1) Laser/substrate relative velocity (traverse speed), (2) Laser scanning pattern, (3) Laser power, (4) Laser beam diameter; (5) Hatch spacing; (6) Inter-layer idle time; and (7) Powder feed rate. Those operating parameters are material-dependent, vary with DLD machines, and influence the final properties of end-parts [135, 138].

A handy application of DLD consists of its ability to produce composites. Since the process allows precise control over the powder feed rate, this can be used to gradually change the composition of a component during the deposition, as illustrated in Figure 17, which is known as FGMs [139-141]. The list of materials used in this case is extensive and includes Stainless Steel alloys (e.g., SS316, SS316L, SS304L, SS420, and SS630), Nickel base alloys (e.g., INCONEL®625, INCONEL®690 and INCONEL®718), Titanium alloys (e.g., Ti6Al4V and Ti48Al2Cr2Nb), among other particular metallic powder alloys developed for this specific purpose (Stellite 6 and Metco 42C) [137].

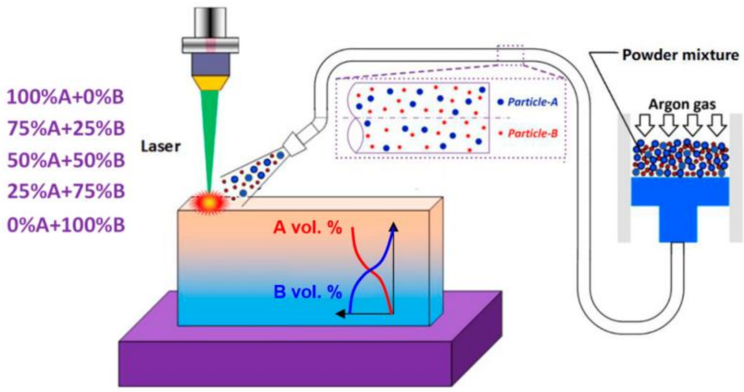

Figure 17. A visual representation of the Directed Energy Deposition (DED) process for FGMs, illustrating the deposition of two distinct materials onto the substrate using a laser-based energy source [141].

DLD may also be applied in composite production involving metallic and ceramic powders to enhance properties. Li et al. [142] reviewed recent advancements in AM applied to five types of MMCs. Future development trends are predicted, including the formation mechanisms and reinforcement principles of strengthening phases, material and process design to achieve targeted performance, innovative structural designs based on the unique properties of laser AM MMCs, and the manufacturing process's simulation, monitoring, and optimisation. The standard metal matrix employed in this application is Ti, although there are also records of Ni-based alloys. The typical ceramic reinforcements used are TiC, TiB, and TiN [143]. Regarding DLD, most practical uses are related to repairing parts such as steam turbine blades, dies, moulds, gears, diesel engine crankshafts, gas turbine burners, turbine blades (and repair, ensuring lightweight designs with enhanced strength-to-weight ratios), motor rotor shafts, rail tracks, and car parts, among others [144-150].

Conversely, practical examples of FGM are strongly related to the experimental perspective, with sample characterization only [139]. Humarán-Sarmiento et al. [151] employed DED using a laser beam to fabricate single-layer MMC coatings composed of Stellite 6 with 10%, 20%, and 30% WC-Co (12%) as a reinforcing agent. The study evaluates the influence of process parameters, including laser power, velocity, and powder feed rate, to optimise dilution and porosity. Additionally, the microstructural evolution, microhardness, roughness, and thermal behaviour of the coatings during fabrication are analysed. Shalnova et al. [152] investigated the formation of the structure, phase composition, and mechanical properties of Ti–6Al–4V/SiC metal matrix composites (MMCs) produced via direct energy deposition. Compositions containing 1 vol%, 3 vol%, 5 vol%, and 7 vol% SiC were examined. Adding one vol% SiC enhanced the strength of the Ti-alloy, increasing it to 1300 MPa, with a corresponding relative elongation of 2.1%.

Romio et al. [153] employed the DLD to reconstruct 16MnCr5 spur gear teeth using a combination of INCONEL® 625 and AISI 413 (Metco 42C). The former was used in the tooth core as a building material, while the latter was utilized as a coating to improve superficial hardness, as illustrated in Figure 18. This state-of-the-art enlightens the reader about using the DED to embed inserts into damaged pieces, although not considered MMCs. After the DLD, the tooth's involute profile was achieved by employing Wire Electrical Discharge Machining (WEDM), with the trajectory defined by digitizing one of the base material teeth. Wang et al. [154] employed Laser-Directed Energy Deposition (LDED) [155] to incorporate carbon nanotubes (CNTs) into WE43 Mg-alloy to enhance its wear resistance by utilising the exceptional mechanical and self-lubricating properties of CNTs. The incorporation of CNTs markedly improved the wear resistance of the WE43 coating by increasing its resistance to plastic deformation, facilitating the formation of a protective carbon film, and providing self-lubricating effects.

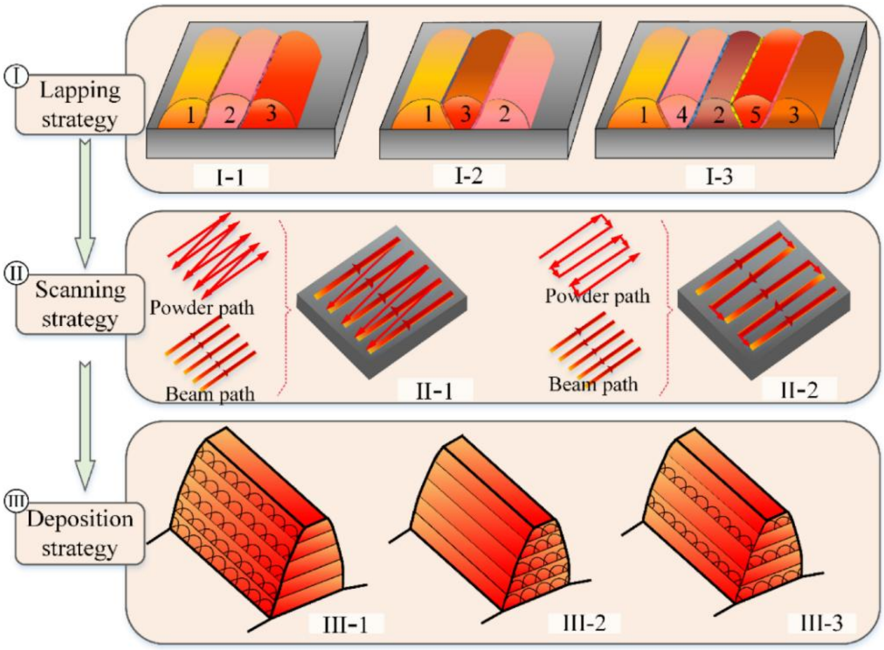

Figure 18. Optimisation of deposition strategies for the gear tooth: (I-1) hot lap joint, (I-2) cold lap joint, (I-3) optimised cold strategy; (II-1) co-directional scanning, (II-2) reverse scanning; (III-1) interlayer scanning perpendicular to the axial direction, (III-2) interlayer scanning parallel to the axial direction, (III-3) scanning directions of two adjacent layers perpendicular to each other [156].

Arlyapov et al. [157] *apud* Pedroso et al. [158] produced INCONEL® 625-based MMC samples through additive laser fabrication with 5 wt.% NiTi-TiB_2, employing an LS-3 fibre laser (IPG Photonics). Figure 19 depicts the AM process of this MMC.

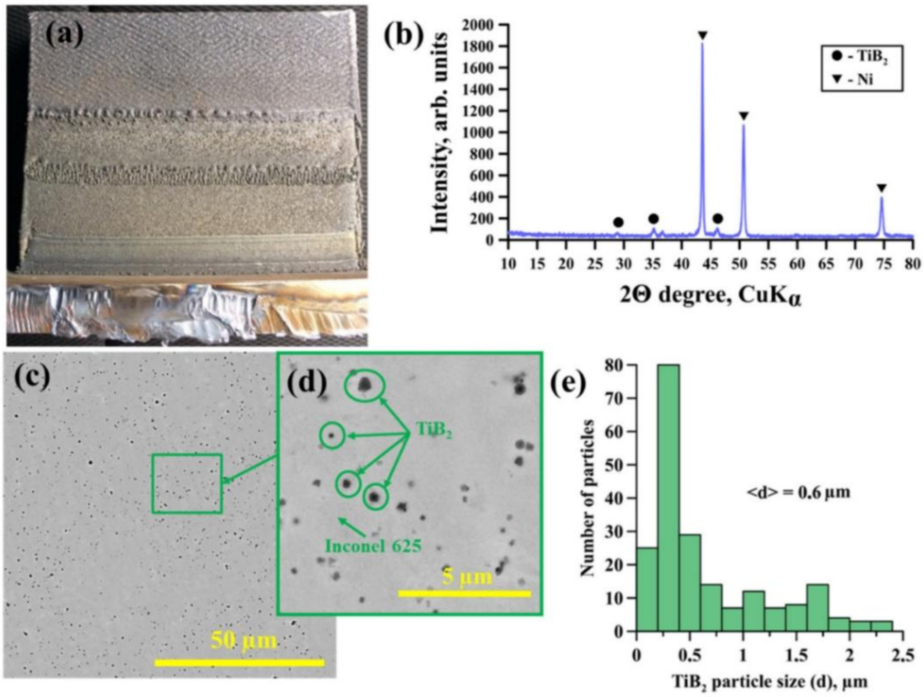

Figure 19. The MMC material was produced via DLD using a powder mixture of INCONEL® 625 and 5 wt.% NiTi-TiB_2 is presented with the following features: its external appearance (**a**), an X-ray diffraction pattern (**b**), SEM images of the microstructure (**c**,**d**), and a histogram illustrating the particle size distribution of TiB_2 (**e**) [157].

Ending this subsection, Table 5 presents the advantages and disadvantages of the DED process.

Table 5. Limitations & Capabilities/Strengths of the DED process.

Capabilities/Strengths	Limitations
DED allows for precise control over the powder feed rate, enabling the production of FGMs and MMCs with tailored compositions.	It requires careful optimisation of multiple parameters, making achieving consistent results across different materials and geometries challenging.
well-suited for producing complex, customised, and high-performance MMC parts with a reduced lead time	Often results in rougher surface finishes and less dimensional accuracy.
The layer-by-layer deposition process minimises waste, making DED a cost-effective method for MMC production [129].	MMCs produced via DED are prone to residual stresses and potential cracking, particularly in large or complex components.
DED enables the incorporation of reinforcing agents (e.g., TiC, TiB2, WC-Co, CNTs) that significantly improve the wear resistance, strength, and other mechanical properties of MMCs.	Improper optimisation of process parameters can lead to porosity and unwanted dilution of reinforcement particles, negatively affecting the mechanical performance of the MMCs.
Is highly effective for repairing and cladding high-value metal components	Although DED has been successfully applied to several metal matrix materials (e.g., titanium, nickel-based alloys), its use is constrained by the availability of compatible metal-ceramic powder mixtures and the ability to optimise them.

4. Discussion

This study comprehensively reviews AM technologies for composite materials, focusing on their characteristics, capabilities, and limitations. While the inclusion of a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) analysis (Table 6) in the article is a valuable contribution, the discussion can be enriched by incorporating a more structured, practical framework for guiding practitioners and beginners in choosing the most suitable AM technology for specific applications, involving defining clear objectives, comparing techniques systematically, identifying critical internal and external factors, and organising these insights into a user-friendly decision-making tool.

For AM to serve as an effective tool for producing composite materials, it is vital to define the manufacturing context clearly. The proposed framework identified the typology of components and performance requirements production conditions. To effectively utilise AM in composite manufacturing, it is crucial to define the production context:

- Component Typology: Identify whether the part is structural, aesthetic, or functional.
- Performance Requirements: Specify mechanical properties (e.g., σ_u, stiffness), aesthetic needs (e.g., surface finish), and production scale.
- Operational Constraints: Consider time, cost, and resource availability.

Defining these parameters was paramount to practitioners aligning AM techniques with the project's unique requirements, providing a solid foundation for selecting the most suitable AM technique for a given application. Also, building on the article's review of technologies like LOM, FDM, SLA, SLS, and DED, these techniques addressed material compatibility, dimensional precision, surface quality, mechanical properties, production efficiency and environmental impact issues. The review highlights the diversity of AM methods, such as LOM, FDM, SLA, SLS, and DED. Key observations include:

- Material Compatibility:
  - SLA excels with photopolymers, offering high resolution and surface quality.
  - FDM is versatile with thermoplastics and composite filaments, enabling cost-effective prototyping.
  - DED allows the use of metal and ceramic powders for high-performance applications.
- Production Characteristics:
  - SLA and SLS are well-suited for producing intricate details, though SLA requires more post-processing.
  - FDM offers simplicity and accessibility, which makes it ideal for rapid prototyping and semi-functional parts.
  - DED enables the production of FGMs but requires precision in parameter control.
- Sustainability Considerations:
  - AM processes, particularly LOM and FDM, generate less waste than traditional subtractive manufacturing.

However, specific techniques (e.g., SLS) require proprietary powders, raising material costs and environmental concerns. SWOT analysis is an essential tool as it allows for a broad view of the subject under study, considering both internal and external analysis of the process [159]. The data collected for the preparation of the SWOT analysis (Table 6) were gathered from the literature on the topic of additive manufacturing techniques using the previously presented methods, such as LOM studied by Park et al. [160], FDM by Jin et al. [54], SLA by Niendorf and Raeymaekers [75], SLS by Xiao et al. [106], and DED by Ahn [147] and other peers, and relevant points were identified and summarised.

Table 6. SWOT analysis on additive manufacturing processes applied to composites.

	Positive Factors	**Negative Factors**
Internal factors	**Strengths**	**Weakness**
	Versatile Material Application: These AM processes enable the use of a wide variety of materials, including Fibre-Reinforced Plastics (FRP) and MMCs, that can be tailored to specific load needs.	Limited Mechanical Strength: Some processes, particularly FDM and SLA, may produce parts with lower mechanical strength and poorer bonding between layers, making them less suitable for high-stress applications.
	Customisation and Complex Geometries: The layer-by-layer approach allows for the fabrication of highly complex and customised parts, benefiting industries such as aerospace, automotive, and medical devices.	Surface Finish and Accuracy Limitations: FDM and LOM techniques produce parts with rougher surfaces and less precision, often requiring post-processing.
	Reduced Waste: These processes typically involve material-efficient production, reducing waste compared to traditional subtractive manufacturing.	Porosity and Microstructural Inconsistencies: Techniques like DED and SLS may result in porosity or microstructural inhomogeneities, particularly in MMCs, affecting the final product's performance.
	Rapid Prototyping and Short Lead Times: Additive manufacturing technologies can quickly produce prototypes and functional components, accelerating product development and reducing lead times.	High Cost of Specialised Equipment and Materials: Advanced processes, particularly SLS and DED, require expensive machinery and high-quality materials, raising the initial investment and operational costs.

	Opportunities	Threats
External factors	Expanding Use in High-Performance Applications: The growing demand for lightweight and high-strength materials in sectors like aerospace, automotive, and renewable energy presents opportunities for increased adoption of FRPs and MMCs produced via these processes. Material Innovation and Research: Ongoing advancements in composite materials, such as improved fibre reinforcement techniques and novel metal matrix compositions, offer the potential for enhanced performance and more comprehensive application in additive manufacturing. Integration of In-Situ Monitoring and Process Control: Incorporating real-time monitoring and optimisation in DED and SLS can significantly improve part quality, consistency, and efficiency. Sustainability and Eco-Friendly Practices: These processes' ability to minimise material waste and enable the use of sustainable or recycled materials may align with growing environmental regulations and sustainability initiatives.	Competition from Traditional Manufacturing Methods: Established manufacturing techniques, such as injection moulding for FRPs and casting for MMCs, often offer lower production costs and higher throughput, particularly for large-scale manufacturing. Material and Process Limitations: The range of materials available for specific processes remains limited, with challenges in processing certain high-performance composites or achieving consistent properties across complex geometries. Technical Skill Requirements: The complexity of optimising process parameters and handling advanced materials in additive manufacturing necessitates a highly skilled workforce, which may limit accessibility in specific industries or regions. Regulatory and Certification Challenges: Adopting additively manufactured composite parts in industries like aerospace and medical devices may face regulatory hurdles and require extensive certification and testing to ensure compliance with safety and performance standards.

5. Conclusion

This article reviews the latest AM techniques for composite materials and presents the most commonly used methods. Recent advancements in materials have played a vital role in the composite AM field. Adopting established thermoplastic AM techniques has become possible due to the availability of melt-processable thermosetting resins. Besides, combining polymers and their composites with other materials, like metals, can help leverage each material's best properties. The research underscores the significance of AM in being an essential part of the process chain in the future concerning the transformation and production of composite components, from prototyping to functional end-use parts, across various industries, including aerospace, automotive, and biomedical engineering. AM's advanced features, enabling the ability to customize products to a high degree and create functional, complex 3D structures with complete control over material properties, have attracted much attention from various industries. The key contributions from this paper, in that regard, are:

- A structured overview of AM techniques:
    - Evaluated LOM, FDM, SLA, SLS, and DED.
    - Assessed their material compatibility, mechanical properties, surface quality, and cost-efficiency.
    - Demonstrated that the choice of technique depends on the component's specific typology, performance demands, and operational constraints.
- SWOT Analysis for Decision-Making:
    - Identified internal factors (strengths and weaknesses) such as precision, mechanical properties, and cost considerations.
    - Evaluated external factors (opportunities and threats), including advancements in material science, regulatory challenges, and market competition.
    - Provided a practical framework to guide the selection of AM techniques based on real-world needs.

Many challenges must be overcome before 3D printing for composite materials becomes a popular manufacturing method. Current issues include the formation of empty spaces during printing, inadequate adhesion between fibres and polymer matrix, and difficulties in printing continuous fibres. The relationship between the processing parameters of additive manufacturing and the mechanical properties of the final part is yet to be fully documented and understood. The implications for practice are:

- Highlighted that no single AM method is universally superior; the suitability of a technique varies with the application.
- For example, SLA offers high precision for intricate designs, while FDM is better suited for cost-effective rapid prototyping.
- Tailored Selection Process: reinforced the importance of aligning AM choices with production conditions, such as material availability, time constraints, and sustainability goals.

This study demonstrated that selecting the most suitable AM technique for composite fabrication is a complex but essential task, and it also requires a nuanced understanding of the interplay between material properties, manufacturing conditions, and application requirements. By combining a detailed review of AM technologies with a structured SWOT analysis, this work offers a practical and theoretical tool to guide users in making informed decisions. This framework addresses the immediate needs of the scientific and industrial communities and lays the groundwork for future advancements in AM technology, contributing to its evolution as a transformative manufacturing solution for composites.

6. Future Considerations

The framework should be tested through case studies where AM techniques are applied to produce components with predefined requirements, validating the SWOT matrix's utility and highlight improvement areas. Additionally, the following research directions are proposed:

- Material Property Database: Establish comprehensive databases detailing the performance of various AM composites under standardised conditions.
- Experimental Validation: Use the matrix to guide manufacturing decisions and evaluate outcomes against traditional methods.
- Sustainability Metrics: Develop metrics to quantify the environmental benefits of AM technologies compared to subtractive and formative manufacturing.
- Conduct case studies to test and refine the decision-making framework proposed in this study.
- Develop standardised datasets on AM composites to ensure consistent quality and reliability.
- Establish benchmarks to evaluate the environmental impact of AM techniques and promote eco-conscious practices.
- Integrate real-time monitoring and control systems to enhance precision and reduce manufacturing defects.

Establishing material property databases and standards for additive manufacturing is vital for ensuring the consistent quality of additive-manufactured products. Moreover, production efficiency must be optimized to adopt this manufacturing method while balancing productivity and product quality.

Author Contributions

F.J.G.S.: conceptualization; F.J.G.S., R.S.-C., R.L.: methodology; R.S.-C., R.L.: data curation, visualization; A.F.V.P.: writing—original draft preparation; G.G.: investigation; F.J.G.S.: supervision; R.D.S.G.C.: validation; F.J.G.S., R.D.S.G.C.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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