Chapter 7

Additive Manufacturing of Polymer Matrix Composites

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Additional information is available at the end of the chapter

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Abstract

Due to the developments and the interest of leading aerospace companies, additive manufacturing (AM) has become a highly discussed topic in the last decades. This is mainly due to its capability of producing parts with high geometrical complexity, short manufacturing lead times, and suitability for customization as well as for low-volume production. As is the case with aircraft fuselage body where weight reduction while keeping the demanding mechanical properties is of uttermost importance, modern technology applications sometimes need materials with unusual combinations of properties that cannot be solely provided by metals, polymers, or ceramics. In this case, composite materials combining two or more materials allow having the preferred properties in one material. Thus, AM of composites is becoming more and more important for critical applications. Fiber reinforcement can significantly enhance the properties of resins/polymeric matrix materials. Although continuous fiber composites even present higher mechanical performance, the manufacturing methods for chopped fibers are more commercially available. This chapter reviews the studies in the field involving many aspects spanning from design, process technology, and applications to available equipment.

Keywords: additive manufacturing, polymer matrix composites, layered manufacturing, carbon fiber-reinforced polymers, rapid manufacturing

1. Introduction

Due to the developments and the interest of leading aerospace companies, AM, also known as 3D printing, became a highly discussed topic in the last decades. Due to its capability of producing parts with a high geometrical complexity and short manufacturing lead times, AM has been utilized more especially in aerospace and motorsports. Revenues from the production of end use parts, as a proportion of total AM production, have risen from under 4% in 2003 to 34.7% in 2013 [1]. The first step of applying AM technology was historically producing

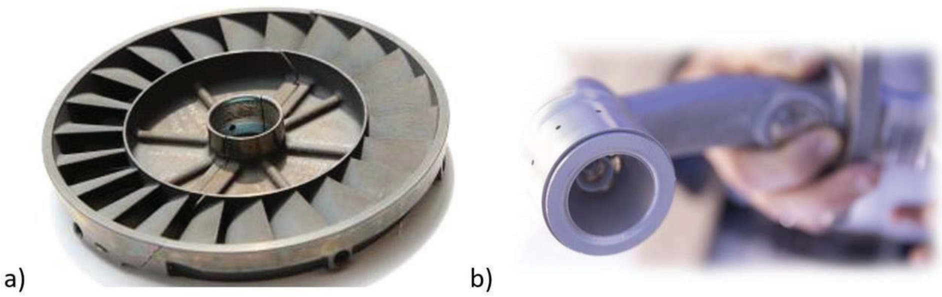

Figure 1. (a) Safran obtains the first certification for a 3D-printed gas turbine engine major part in the auxiliary power unit (APU) from Hastelloy X: conventionally machined by Inconel casting, the 3D-printed part is now 35% lighter and is now comprised of only four versus eight components prior to the new manufacturing technique [3]. (b) GE LEAP engine fuel nozzle: the 3D-printed nozzle combined all 20 parts into a single unit, but it also weighed 25% less [4].

plastic prototypes using various AM processes such as fused deposition modeling (FDM), stereolithography (SLA), and other processes. Producing complex net-shaped materials including metals, ceramics, and composites as functional parts later became available [2]. Today, polymers and metals are considered as commercially available materials for AM processes (see **Figure 1**). Meanwhile, ceramics and composites are rather considered still under research and development. **Table 1** shows various properties of AM processes including the state of

State of the starting material	Process	Material preparation	Layer creation method	Typical materials	Applications
Filament	FDM	Melted in nozzle	Continuous extrusion and deposition	Thermoplastics, waxes	Prototypes, casting patterns
	Robocasting	Paste in nozzle	Continuous extrusion	Ceramic paste	Functional parts
Liquid	SLA	Resin in a vat	Laser scanning	UV curable resin, ceramic suspension	Prototypes, casting patterns
	MJM	Polymer in jet	Ink-jet printing	Acrylic plastic, wax	Prototypes, casting patterns
Powder	SLS	Powder in bed	Laser scanning	Thermoplastics, waxes, metal powder, ceramic powder	Prototypes, casting patterns
	SLM	Powder in bed	Laser scanning	Metal	Tooling, functional parts
	EBM	Powder in bed	E-Beam scanning	Metal	Tooling, functional parts
	3DP	Powder in bed	Drop-on-demand binder printing	Polymer, metal, ceramic, and other materials	Prototypes, casting shells, tooling
Solid sheet	LOM	Laser cutting	Feeding and binding of sheets with adhesives	Paper, plastic, metal	Prototypes, casting models

Table 1. Analysis of the state of starting material working principle for AM processes [5].

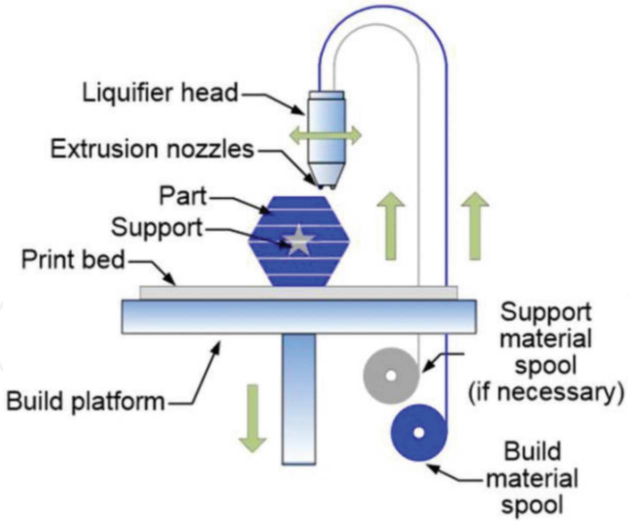

Figure 2. Schematic of fused deposition modeling [7].

starting material, material preparation, layer creation method, typical materials, as well as applications [5]. As is the case with aircraft fuselage body where weight reduction while keeping the demanding mechanical properties is of uttermost importance, modern technology applications sometimes need materials with unusual combinations of properties which cannot be solely provided by metals, polymers, or ceramics. In this case, composite materials combining two or more materials allow us to have the preferred properties in one material [2].

Fused deposition modeling (FDM) (see **Figure 2**) is one of the AM technologies and a widely used method for fabricating thermoplastic parts with advantages of low cost, minimal waste, and ease of material change [7]. In order to improve the mechanical properties of pure thermoplastic materials, one of the methods is to reinforce plastic matrix by different materials like carbon fibers to produce CFRPs (carbon fiber-reinforced polymers) composites which can be directly used as functional end parts. FDM is an advantageous process for producing polymer matrix composites because of the possibility to use multiple nozzles with loading of different materials. Moreover, being low-cost and high-speed, simplicity makes FDM a suitable process for composite manufacturing. One drawback of the FDM process for producing PMCs is that the input material has to be in filament form to enable the extrusion. Additionally, the usable matrix material is limited to thermoplastic materials due to needed melt viscosity (high enough for structural rigidity and low enough for extrusion) [6].

2. AM composites: literature review

Producing CFRPs (carbon fiber-reinforced polymers) by AM is quite a new research topic, and therefore there are a very limited number of studies that can be found in the literature as the summary in **Table 2** presents. Zhong et al. have studied the processability of glass fiber-reinforced ABS matrix composites with three different glass contents used as feedstock filaments in FDM leading to the result that the reinforcement could improve the tensile strength and surface rigidity at the expense of flexibility and handleability [8]. These limits were overcome

	Reinforced by	Matrix material	Investigated properties	Limitations
Zhong et al. [8]	Glass fibers	ABS	Tensile strength and surface rigidity	Flexibility and handleability
Gray et al. [9]	Thermotropic liquid crystalline polymer	Polypropylene	Tensile strength	Poor adhesion and delamination
Shofner et al. [10]	Vapor-grown carbon fibers	ABS	Tensile strength and tensile modulus	Interlayer and intralayer fusion; change behavior from ductile to brittle
Tekinalp et al. [11]	Carbon fiber	ABS	Tensile strength and tensile modulus	Porosity, weak interfacial adhesion between the fibers and the matrix, and fiber breakage
Ning et al. [7]	Carbon fiber	ABS	Tensile strength, Young's modulus, flexural properties	Decrease in toughness, yield strength, and ductility; increase of porosity with an increased level of carbon fiber
Love et al. [12]	Carbon fiber	ABS	Strength, stiffness, thermal properties, and distortion and geometric tolerances	—

Table 2. A summary of studies in FDM of chopped fibers.

by adding a small amount of plasticizer and compatibilizer. Gray et al. reinforced polypropylene with thermotropic liquid crystalline polymer fibers and provided a significantly increased tensile strength, whereas they encountered some problems of poor adhesion and delamination [9]. Shofner et al. studied reinforcing ABS matrix with vapor-grown carbon fibers at nanoscale. Although the tensile properties were improved, the amount of improvement depended on built parameters as well as the degree of interlayer and intralayer fusion [10]. Tekinalp et al. [11] have studied carbon fiber-reinforced ABS polymers in order to evaluate the potential for load-bearing components leading to the result that composites with highly dispersed and highly oriented carbon fibers can be printed by FDM process (see **Figure 3**) [11]. Ning et al. have provided a more comprehensive study on the effect of fiber content on mechanical properties. Carbon fiber content varying between 0 and 15% was studied on tensile and flexural properties of carbon fiber-reinforced ABS plastics. Some limitations such as decrease in toughness and ductility as well as encountered porosity were identified [7]. Love et al. have addressed reinforcement of ABS material with carbon fibers regarding the thermal deformations and leading geometrical tolerances in addition to strength and stiffness achieved (see **Figure 4**). They have concluded that carbon fiber additions can significantly reduce the distortion and warping of the material during processing allowing large-scale, out-of-the-oven, high deposition rate manufacturing [12].

The effect of fiber content on the mechanical properties is also another interesting research topic. Tekinalp et al. [11] have investigated the fiber loading on the tensile strength and modulus as shown in **Figure 5**. Some interesting results were obtained in this study. The results

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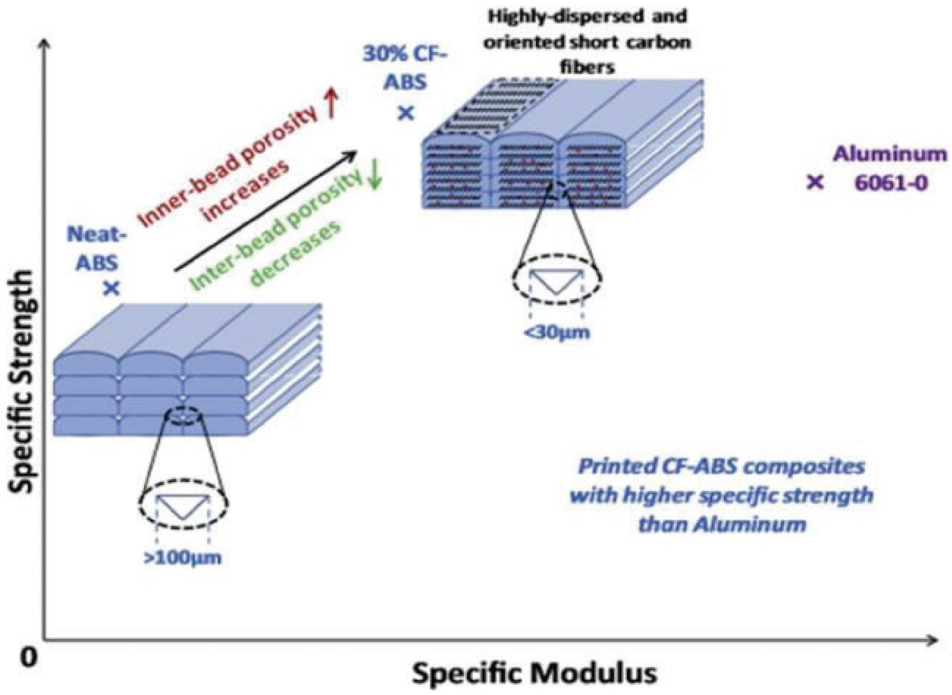

Figure 3. Schematic presentation of 3D-printed fiber-reinforced composite by fused deposition modeling [11].

Figure 4. Tensile test specimens produced along z-axis and deformation coupons showing the difference between carbon fiber-reinforced ABS and no reinforcement part in terms of deformation [12].

leading to the fact that modification/optimization of the mixing process to minimize fiber breakage and modification of the FDM process to minimize inner-pore formation may result in a much more optimized process are summarized as follows [11]:

- An increase in fiber length and fiber orientation improves the tensile properties, whereas an increase in void fraction reduces the strength of a composite by both creating stress concentration points and lowering the fiber-matrix interface and bonding.
- Tensile strength increases with increasing fiber content in both CM and FDM processes.
- The ABS samples with 0% fiber loading prepared by the FDM process have higher tensile strength, while the standard deviations in tensile strength measurements for the FDM samples were significantly lower than those for the CM samples.

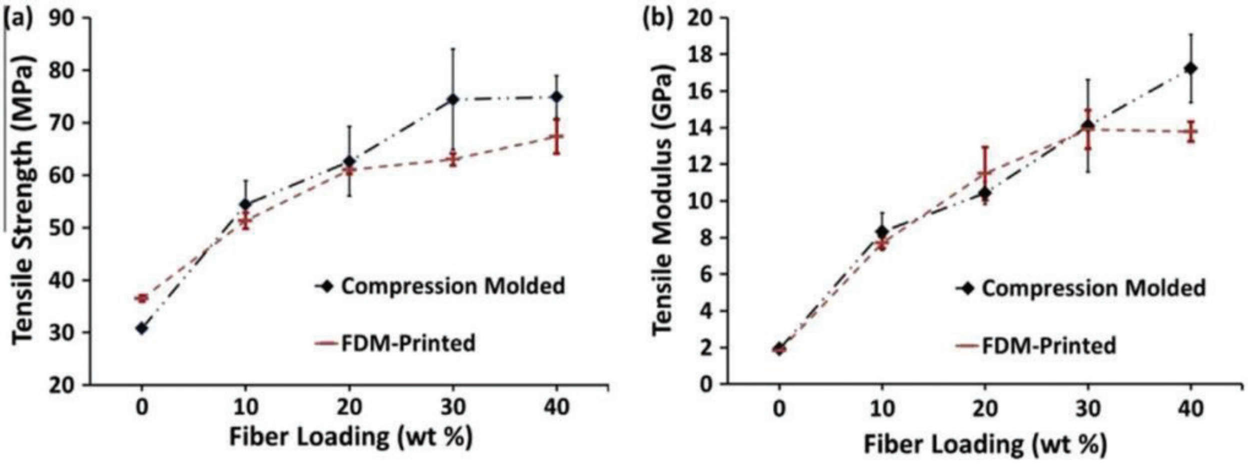

Figure 5. Effect of fiber loading on tensile strength and modulus in comparison to compression molded specimens [11].

- The FDM process increases the orientation of the polymer molecules in addition to improving fiber dispersion and uniformity since the parts are manufactured in a layer-wise and line-wise manner.
- The FDM samples can compensate the negative effect of porosity/weak fiber bonding by the strongly enhanced fiber and thus still reach strength values close to CM samples.
- For both processes, the tensile strength increase with the increase of the fiber content becomes less obvious at higher fiber loadings. This can be attributed to the decrease in average fiber length with increasing fiber content.
- At 40 wt% fiber loading, the modulus value of the CM composites is increased by nearly an order of magnitude. However, the FDM samples could not be fully fabricated due to the repeated nozzle clogging at this high fiber loading. These samples could only be printed to a few layers of thickness. This thickness difference possibly caused the difference in moduli between the FDM and CM specimens [11].

However, the optimum fiber loading obtained in [11] is not in line with the results of Ning et al. [7] due to differences in the material in terms of fiber distribution and interfacial bonding strength which leads to the conclusion that a basic standard for design and processing needs to be established as is the case with many other AM processes. Ning et al. concluded that the best performance of the produced parts was obtained with 5% fiber loading and higher loading of fiber reduced the performance. The studies found in the literature have tested up to 40 wt%, and the composites with higher loading could not be produced due to nozzle clogging issues. In addition, it is difficult to make filaments with such high fiber content due to the loss of toughness. As a solution to improve feedstock processability, plasticizers are added as already mentioned [8]. To eliminate the voids impairing the mechanical properties of FDM parts, a novel solution was found by [13]. Thermally expandable microspheres are added to the matrix, and a thermal treatment is combined with FDM. The results show that tensile and compressive strength of treated specimens increase 25.4 and 52.2%, respectively, in comparison to the untreated ones when 2 wt% microspheres are added [13].

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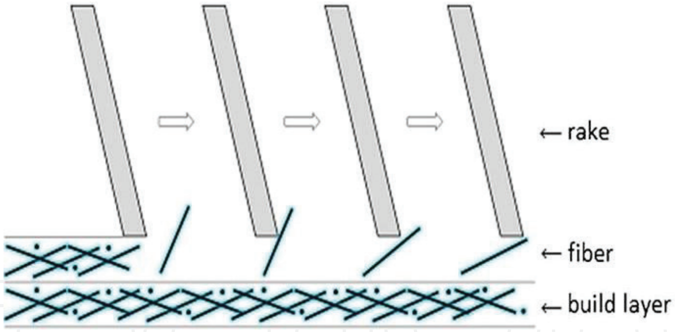


Figure 6. Illustration of the rake spreading a powder layer in the build chamber [14].

Fused deposition modeling is not the only method to produce polymer matrix composites by additive manufacturing. Selective laser sintering, a powder-bed AM technology, is also investigated in this field. Jansson and Pejryd have characterized carbon fiber-reinforced polyamide manufactured by this technology using the CarbonMide® (CF/PA12) material provided by EOS [14]. The material in its raw form is a powder consisting of polyamide spherical particles and carbon fibers of diameter 10 μm and length 100–200 μm. However, porosity is a significant problem as is the case with other studies [15–17]. The study given in [14] also has confirmed that porosity was concentrated in between the layers produced weakening the material in the direction normal to the layered structure. They also obtained different mechanical properties along different build directions mainly due to fiber orientation and porosity. They also concluded that the fiber orientation is linked to the powder rake mechanisms (see **Figure 6**). Some sample products produced by CarbonMide® material are demonstrated in **Figure 7**.

More recently, studies on embedding continuous fiber in the plastic materials are realized mainly using fused deposition modeling (FDM) for different applications [20–27]. Yao et al. have investigated embedding carbon fiber tows which provided a tensile strength increase of 70% and flexural strength increase of 18.7% compared to non-reinforced specimens. As seen in **Figure 8**, an artificial hand printed by FDM with embedded carbon fibers is manufactured

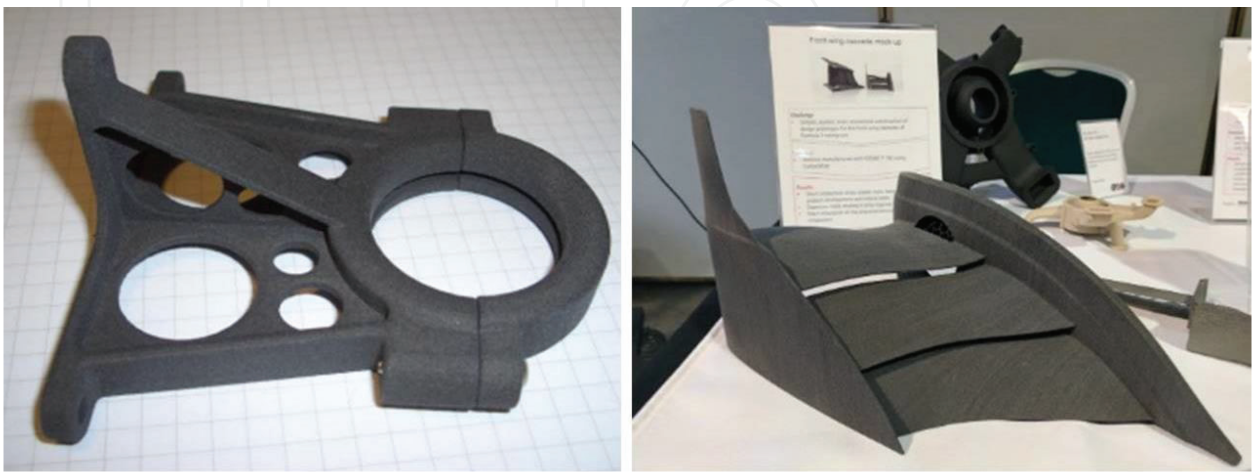


Figure 7. Sample products produced from CarbonMide® material [18, 19].

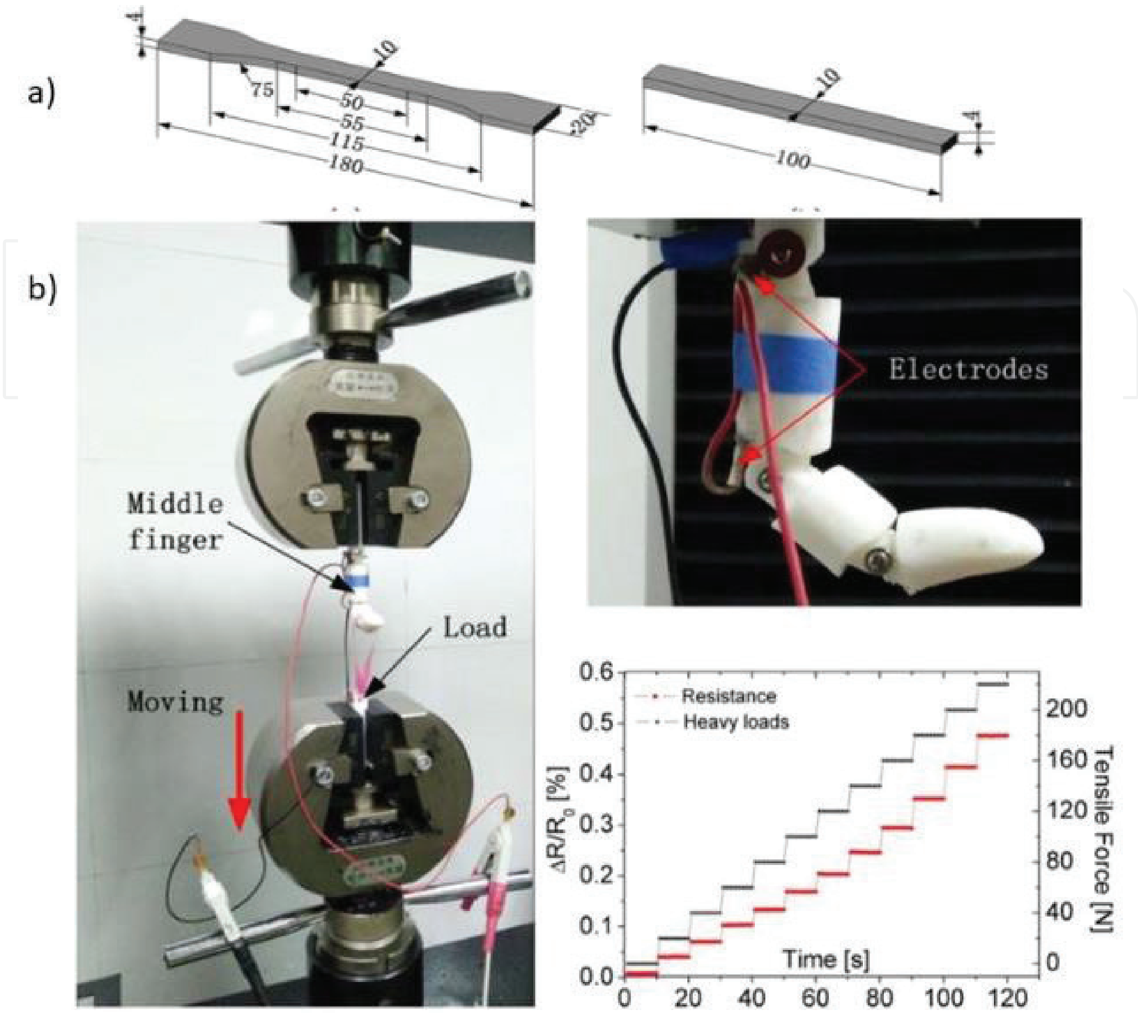


Figure 8. (a) Test specimen geometries per ISO 527-4:1997 for tensile and ISO 14125:1998 for flexural tests and (b) demonstration part [20].

as a demonstration part [20]. Dickson et al. have utilized a Mark One 3D printer in order to reinforce glass, carbon, and Kevlar fibers into nylon material (see **Figure 9**). For each of the printed composites relative to that obtained for the nylon samples with no reinforcement, up

Figure 9. Schematic description of the process (left) and produced specimens with different types of reinforcement fibers (right) [21].

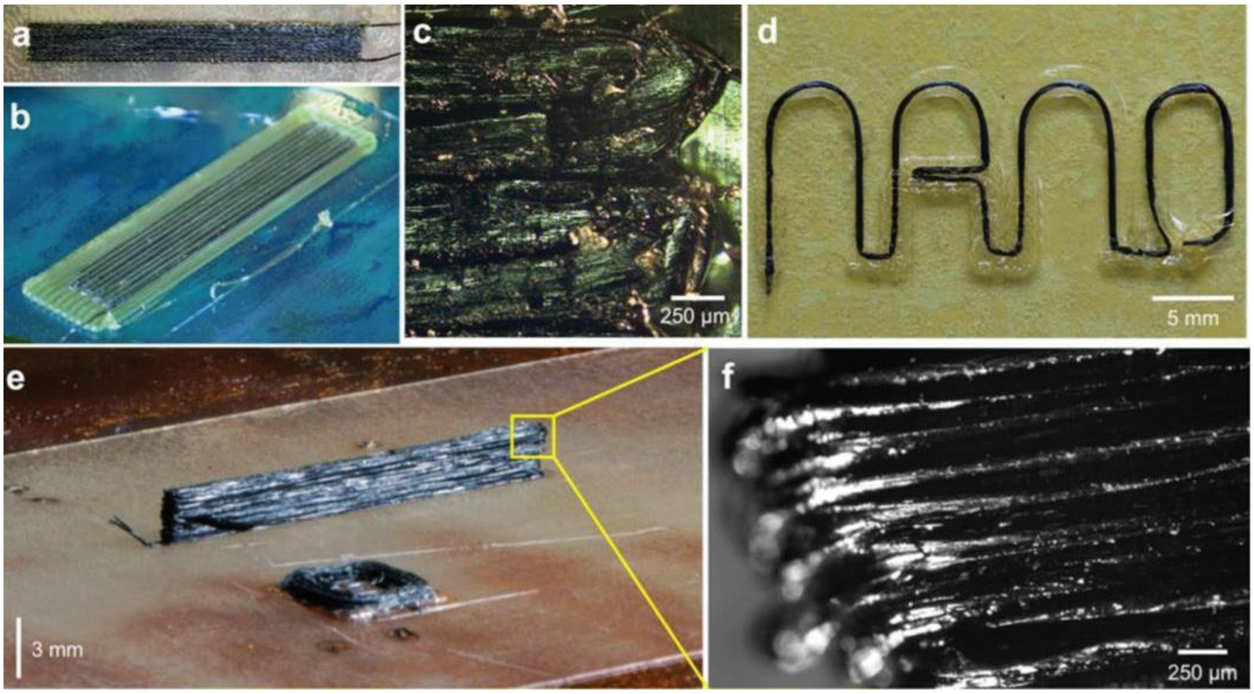


Figure 10. Samples produced: (a) Uniaxial CNT yarn filament layer (b) embedded electrical signal (c) at higher magnification (d) Letters nAno printed (e) printed thin walls (f) at higher magnification [22].

to a 6.3- and 5-fold enhancement in the tensile and flexural strengths were obtained, respectively, and the fiber type superior to others was observed to be carbon fiber [21]. Some studies did not only look into material but also equipment development as is the case with [22].

Gardner et al. have investigated reinforcing ULTEM® material with carbon nano-yarn filaments leading to better tensile and electrical conductivity properties (see **Figure 10**) [22]. Rather than FDM or selective laser sintering, some new techniques are proposed by some researchers. For example, Parandoush et al. proposed a novel method for AM of fiber composites by using prepreg composite. A laser is used to heat successive layers of prepreg tapes, and a compaction roller is utilized to bond these layers (see **Figure 11**) [23]. Moreover, Tian et al. also proposed a new methodology for continuous fiber reinforcement in AM (see **Figure 12** for

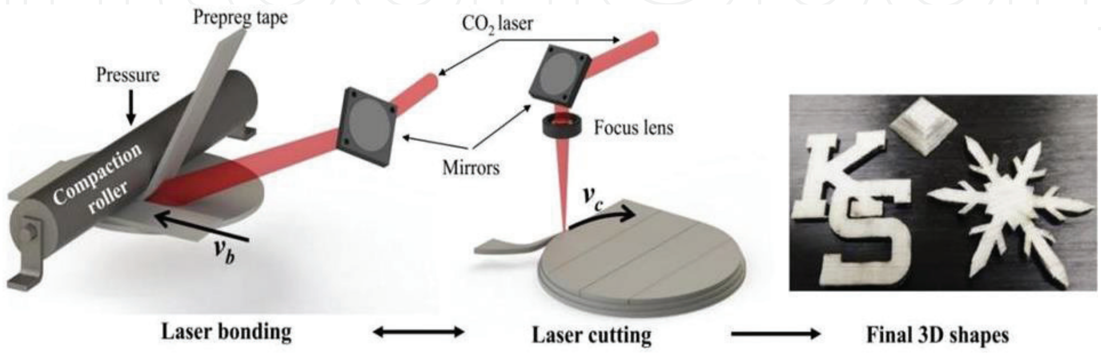


Figure 11. Schematic demonstration of the process [23].

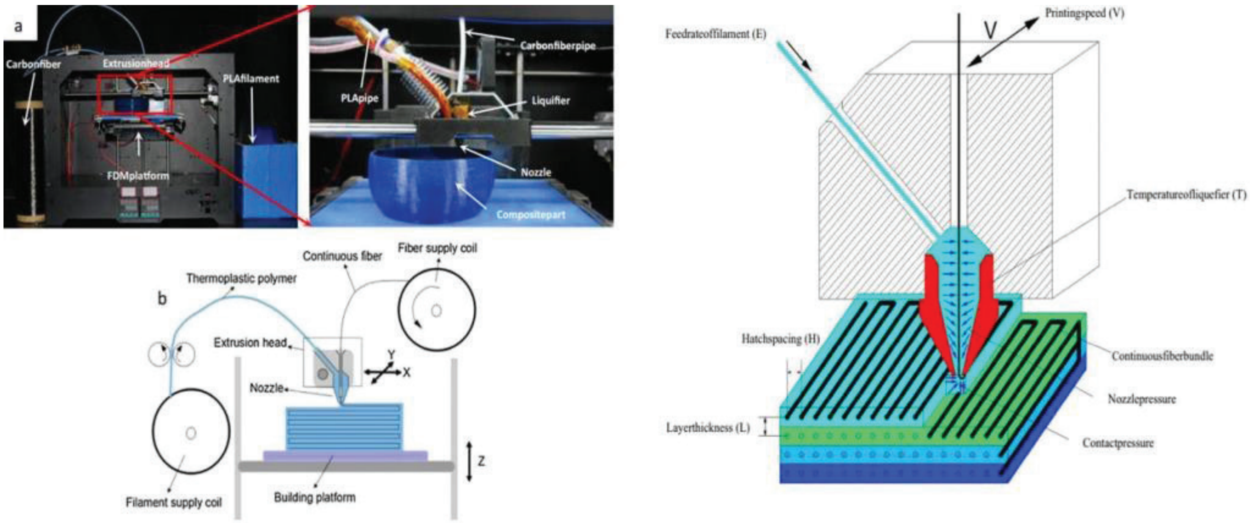


Figure 12. (a) Equipment for 3D printing for CFR PLA composites (b) Schematic printing process [24].

schematic demonstration of the process). In their study, the influence of process parameters on the interfaces and performance of printed composites have been investigated. With the optimized parameters, a fiber content of about 27% could achieve the maximum flexural strength of 335 MPa and flexural modulus of 30 GPa [24].

A similar technology is presented by Matsuzaki in [25], while another study conducted by Matsuzaki et al. [26] reports a very significant mechanical improvement by reinforcing continuous carbon fibers by FDM. Their results show that the tensile modulus and strength of 3D-printed continuous carbon fiber-reinforced PLA composites are 19.5 ± 2.08 GPa and 185.2 ± 24.6 MPa, respectively, which are 599 and 435% of the tensile modulus and strength

	Reinforced by	Matrix material	Investigated properties	Limitations
Yao et al. [20]	Carbon fiber	Epoxy resin + polyamide	Flexural and tensile properties, weight reduction	Adhesion between fibers and matrix and carbon fiber placement
Dickson et al. [21]	Carbon, glass, and Kevlar fiber	Nylon	Tensile and flexural properties	Weak bonding and porosity
Gardner et al. [22]	Carbon nanotube yarn	ULTEM®	Tensile strength, specific modulus, and electrical conductivity	Cutting mechanism
Parandoush et al. [23]	Continuous glass fiber	Polypropylene	Tensile and flexural properties	Adhesion
Tian et al. [24]	Carbon fiber	PLA (polylactic acid)	Flexural strength and modulus	None reported
Matsuzaki et al. [25, 26]	Carbon fiber	PLA (polylactic acid)	Tensile modulus and strength	Irregularity and discontinuity of fiber

Table 3. A summary of studies in FDM of continuous fibers.

of the pure PLA specimens. This mechanical improvement is much larger compared to that of short fiber-reinforced PLA composites [25]. **Table 3** gives a summary of studies involving continuous fiber reinforcement by FDM technology.

3. AM equipment for processing composites

The commercial machines available in the market for producing composite materials by AM are limited as given in **Table 4**. As seen, only MarkForged equipment (Mark X and Mark Two) can build composites with continuous fibers. Some examples of parts produced on a Mark Two machine are demonstrated in **Figure 13**. It is crucial to note that the MarkForged company producing Mark series for 3D printing of continuous fiber-reinforced plastics holds a patent for this technology [27]. The fiber replacement in Eiger software, which is compatible with MarkForged equipment, can be done in different ways as shown in **Figure 14**. Concentric fill strategy involves following the outer profile of the part and fitting a single strand of fiber inward in rings from that boundary. The other option is isotropic fill where the whole layer is covered with a single strand where the angle of filling can be changed from in 45° changes. Moreover, a combination of two fill options is also possible.

Another company working on commercializing continuous fiber-reinforced polymers is based in Russia and entitled as Anisoprint [30]. Their equipment named as Composer is shown in **Figure 15** with sample products. However, the technology is not yet fully commercialized, and thus sufficiently detailed information cannot be found in open literature about the technology.

The other machines available in the market for producing composites give the only option of using chopped fiber (generally of about 20–35%) in combination with a plastic matrix. For example, Roboze offers a material called Carbon PA including 20% chopped carbon fiber in nylon combining chemical resistance of nylon and mechanical properties of carbon fiber. Some examples of products manufactured on Roboze are shown in **Figure 16**. Some companies like GE are also investigating this technology, as entitled "fused filament fabrication (FFF)" for lightweight structures from other materials like PEEK [31, 32]. Processing high-temperature materials like PEEK and PEI are advantages of Roboze One+400 compared to Roboze One (see **Table 4**).

Stratasys also offers equipment for processing a composite material FDM Nylon 12CF. The material comprises of a blend of Nylon 12 resin and chopped carbon fiber, at a loading of 35% by weight. Some sample parts are shown in **Figure 17** [33]. Some mechanical properties of Nylon 12CF and Carbon PA are given in **Table 5** to give a general understanding. However, they are not comparable due to the fact that the tested specimens are produced along different axes.

At the moment, the easiest method to reinforce carbon fiber in the AM is considered to be the use of a filament which typically combines chopped fiber with a thermoplastic polymer for FDM processes which are simple and cheap as described above [34]. The manufacturers of the filaments are various. It can be either a machine vendor, as is the case with MarkForged

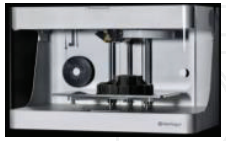
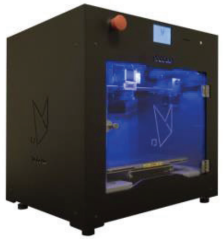
MarkForged Mark X	MarkForged Mark Two	Stratasys Fortus 450	Roboze ONE	Roboze One + 400
				
50 μm resolution	100 μm resolution	Minimum layer thickness 0.127 mm	Not specified	25 μm resolution
330 x 250 x 200 mm	320 × 132 × 154 mm	406 × 355 × 406 mm	280 × 220 × 200 mm	200 × 200 × 200 mm
Dimensional accuracy online measurement		Parts are produced within an accuracy of ±0.127 mm or ±0.0015 mm/mm whichever is greater	The X and Y motion is provided by helical racks and pinions, enabling positioning precision of 0.025 mm. A C7 ball screw with flexible motor coupling, enabling precision of up to 0.025 mm for z axis	Extruders over 400 C designed for reaching very high temperatures and to print high viscosity materials (patent pending)
Plastic materials: nylon and onyx Fiber materials: carbon, fiberglass, Kevlar, high-strength high-temperature fiberglass CW fiber	Plastic materials: nylon and onyx Fiber materials: carbon, fiberglass, Kevlar, high-strength high-temperature fiberglass CW fiber	No CW fiber-chopped fiber ABS, PC, nylon, ULTEM, nylon 12CF	Carbon PA (20% chopped fiber, no CW), ABS, nylon, ASA	Carbon PA (20% chopped fiber, no CW), ABS, nylon, ASA + PEEK, PEI

Table 4. The commercially available machines for producing composites by AM.

Figure 13. Holder with Kevlar reinforcement (left), head support for go-cart cars with carbon reinforcement (middle), and a structural part made of nylon and carbon fiber (right) [28].

[29], or material supplier. colorFabb, based in the Netherlands, produces XT-CF20 combining polyethylene terephthalate glycol-modified (PETG) copolyester with 20% chopped carbon fiber (see **Figure 18** (left)) [35]. Proto-pasta's Carbon Fiber PLA is a mix of PLA and chopped carbon fiber [36]. 3DXTECH makes a variety of carbon fiber filaments ranging from PLA to ABS, nylon, ULTEM®, and PEEK having different characteristics [37]. A PLA composite may be the easiest to print with, whereas ABS may be a bit stronger. Nylon may be even tougher and more wear resistant. PEEK may be the ultimate choice for functional applications requiring resistance to higher temperatures and chemical attack [34]. Fuel intake runners printed from PEEK filament are demonstrated in **Figure 18** [38]. Although these filaments give superior strength compared to non-reinforced polymers, due to their chopped nature of the carbon fibers, the enhancement is limited. Therefore, Arevo Labs has worked on 6-Axis Composite Part Additive Manufacturing Platform [39]. Arevo Labs has developed filaments with chopped carbon fiber, in addition to continuous carbon fiber filament as well as materials with carbon nanotubes/nanofibers. In order to overcome the problem of delamination with AM of chopped fiber-reinforced polymers, in collaboration with ABB, they have worked on a robotic solution for AM of polymer matrix composites [34]. Instead of stacking 2D layers on top of each other, the robot can deposit material on a 3D surface, which is not limited to XY plane only as demonstrated in **Figure 19** [39].

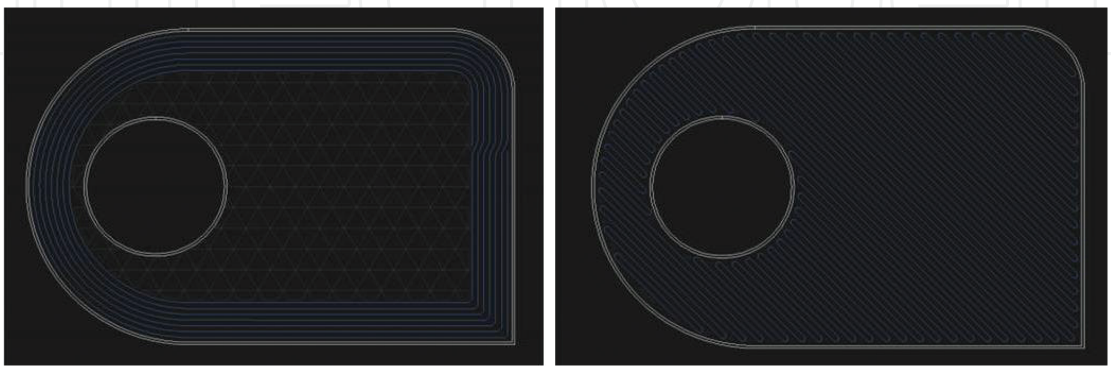


Figure 14. Different infill properties for the reinforcement of fibers [29]: left- concentric fiber replacement and right-isotropic fiber replacement.

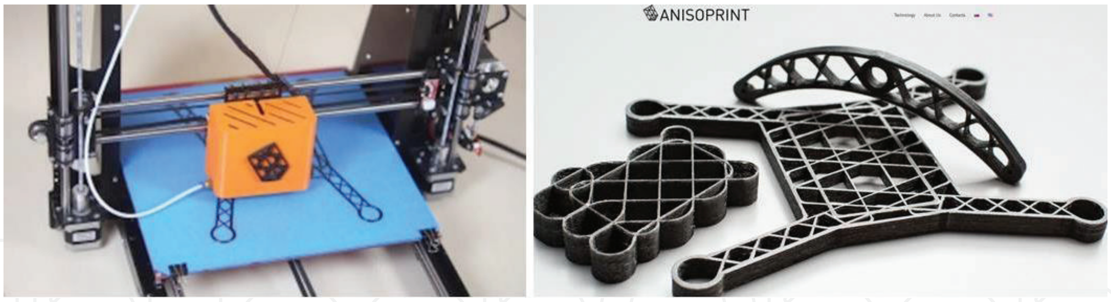


Figure 15. Anisoprint's composer (left) and sample products (right) [30].

Impossible objects' composite-based AM (CBAM) technology may overcome some limitations of AM of composites by combining fiber reinforcement with any number of matrix materials potentially at high speeds and at scalable sizes. In this process, namely, CBAM, a CAD file has been sliced into layers, which are converted into individual bitmaps. Then, for every layer, the printer leaves an aqueous solution into the shape of that bitmap onto a substrate sheet made from a given reinforcement material [40]. The substrate sheet is subsequently poured with the thermoplastic matrix material in powder form, which sticks only to the wet from deposited aqueous solution. The excessive powder is then removed, leaving only the plastic powder adhering to the liquid (see **Figure 20** for process steps). This cycle is repeated with each layer of the part to be produced. After all the substrate sheets are layered on top of each other, they are heated to the melting temperature and compressed to the final height. After the object is then taken out of the oven, the excess un-bonded portions of the reinforcement material are removed. The result is a thermoplastic print reinforced with a wide variety of options ranging from carbon fiber to silk and cotton [40]. **Figure 21** depicts some samples produced by CBAM. While the technology as a whole is very promising in terms of unlimited geometric complexity, every 3D printing process has its limitations when it comes to the exact shapes a system can produce. In CBAM, the geometry is partially determined by the chosen substrate material which brings a restriction on the design. Removing carbon fiber requires sand blasting, creating similar limitations faced by SLS due to the fact that the sand must be able to access the interior of the part to remove excess carbon fiber. This is a limitation regarding internal features. However, a chemical process is

Figure 16. Products from Carbon PA on Roboze equipment [31].

Figure 17. Products made of Nylon 12CF [33].

used to remove other reinforcement materials, such as Kevlar and polyester. In those cases, the geometric complexity is more similar to that possible with FDM, when using soluble supports [40].

Another company on the horizon of developing new composite AM methods is EnvisionTEC with their first and only industrial thermoplastic reinforced woven composite printer, SLCOM (Selective Lamination Composite Object Manufacturing) [42]. SLCOM allows building composite parts using thermoplastic composite fabric sheets from a roll in a layer-wise manner. This technology utilizes a wide range of matrix materials such as PEEK (polyetherketoneketone), PEKK (polyetherketoneketone), PC (polycarbonate), PPS (polyphenylene sulfide), PEI (polyetherimide), PE (polyethylene), and polyamides (Nylon 6, Nylon 11, or Nylon 12), whereas the possible fiber reinforcements include carbon fiber, fiberglass, and aramid fiber along with metal fibers (see **Figure 22**) [42]. The supply roll is fed into the print bed. Later, the thermoplastic within the roll is melted and compressed with a heated roller passing over. At the same time, a mechanism similar to an ink-jet head deposits a waxlike substance and a binding agent to the metal. A carbon blade with an attached ultrasonic emitter cleanly cuts away any area with wax. However, the price tag of 1 M USD makes it an expensive option.

Material	Vendor	Machine model	Build plane	Yield tensile stress (MPa)	Ultimate tensile strength (MPa)	Tensile modulus (MPa)	Tensile elongation at break (%)	Tensile elongation at yield (%)	Melting point (°C)
Nylon 12 CF	Stratasys	Fortus	*XZ*	63.4	75.6	7515	1.9	0.9	233
			ZX	28.8	34.4	2300	1.2	1.1	233
Carbon PA	Roboze	ONE	*XZ*		98.0	7850			178
			XY		94.0	6400			178

Table 5. Comparison of mechanical properties provided by Nylon 12CF produced on a Fortus equipment from Stratasys and by carbon PA produced on a one equipment from Roboze.

Figure 18. 3D-printed car from XT-CF20 material (left) [34]; fuel intake runners 3D printed with Arevo Labs' PEEK filament (right) [38].

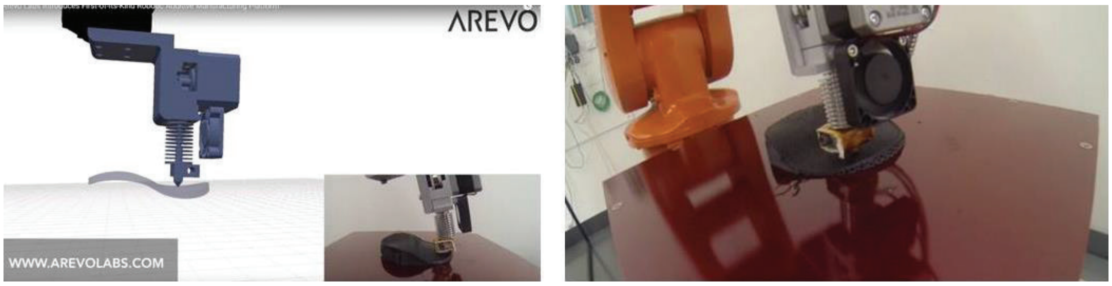


Figure 19. Six-axis composite part additive manufacturing platform from Arevo Labs [39].

Another interesting development in the field of AM of composites is BAAM (Big Area Additive Manufacturing) technology [43, 44]. The Oak Ridge National Laboratory has developed this technology, which is a large scale out of the oven extrusion-based 3D printer that enables faster and cheaper fabrication of large parts. Cincinnati Incorporated has commercialized the

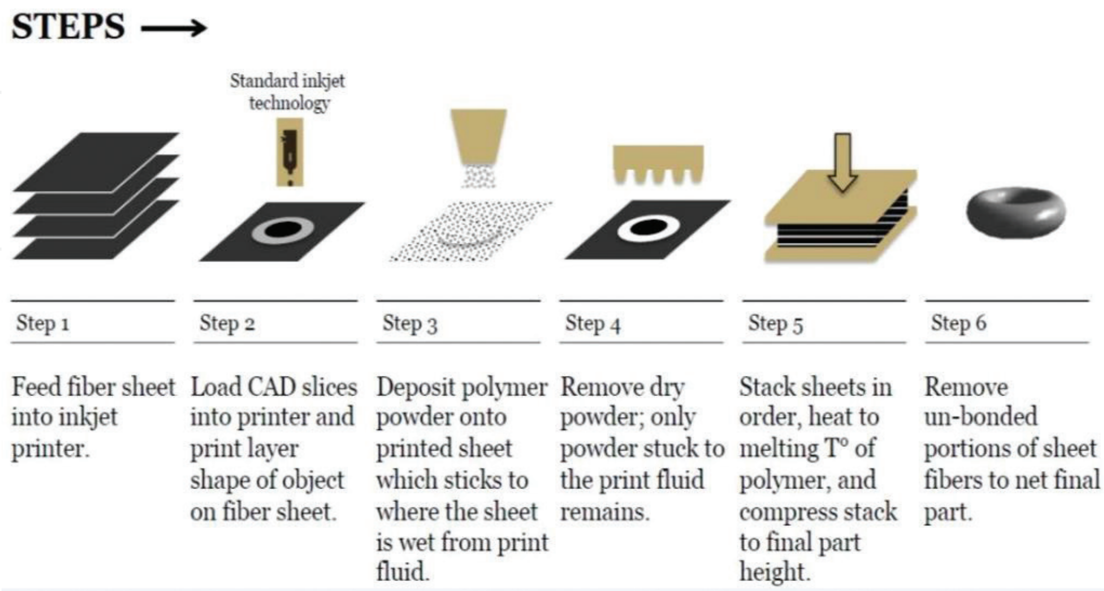


Figure 20. Process steps of CBAM [41].

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Figure 21. Sample products produced by Impossible Objects' CBAM technology [34].

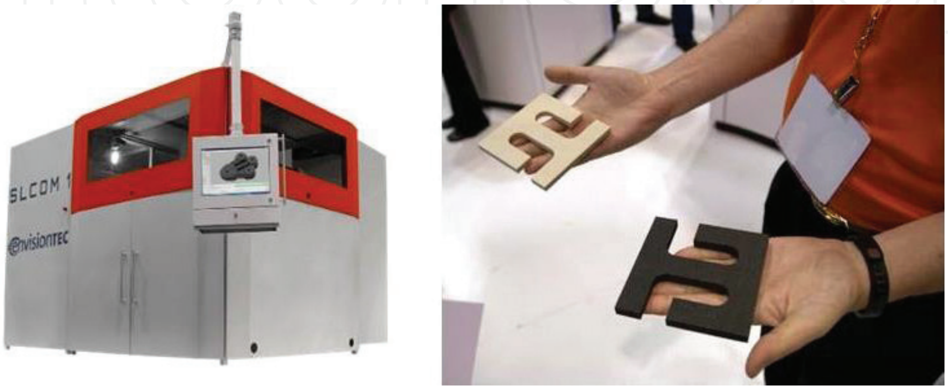

Figure 22. EnvisionTEC's SLCOM process demonstration (left) and sample parts (right) [34, 42].

Figure 23. Large parts produced by BAAM technology [45].

system for ABS, PPS, PEEK, and ULTEM® materials. By adding carbon fiber and glass fiber, it is possible to increase the strength and thermal stability. It is possible to have built volumes up to 6096 × 2286 × 864 mm which allows making huge parts as shown in **Figure 23** [45].

Despite the dominance of polymer matrix composites by carbon fiber, graphene is also considered as an interesting reinforcement material. With a thickness of a single carbon atom, graphene is about 100 times stronger than steel, incredibly lightweight, and electrically and thermally conductive. The difficulty of 3D printing with graphene is the inability to deposit this hydrophobic wonder material from a print head. PLA-based graphene filaments are commercially available from Graphene 3D Lab [46], but no commercial application seems to have created impact other than at laboratory scale [47, 48] in open literature.

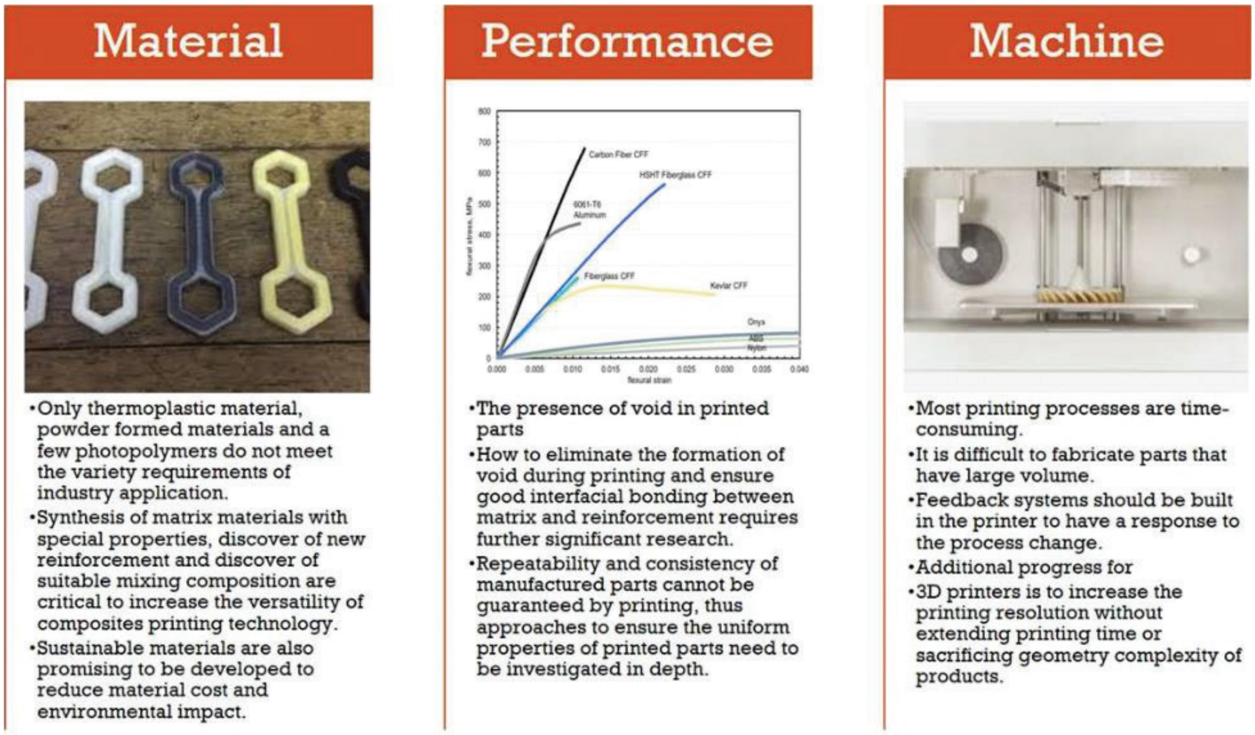

Figure 24. Limitations of the AM of polymer matrix composites similar to other materials in their development phases adapted from [6].

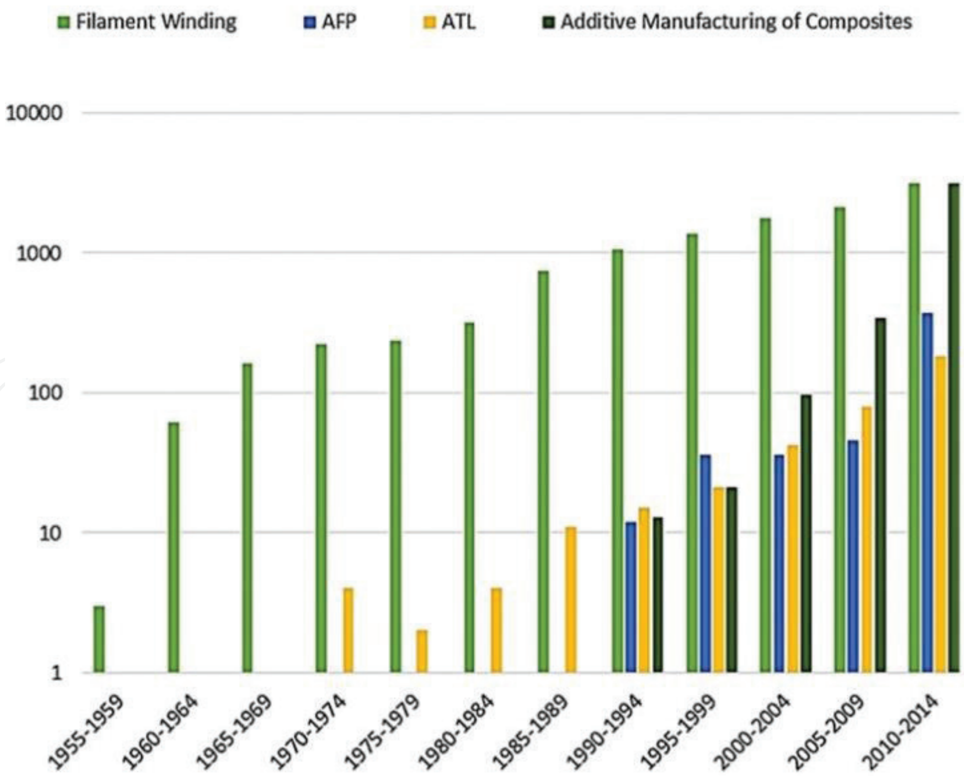

Figure 25. The number of papers considering filament winding, AFP (automated fiber placement), ATL (automated tape layup), and AM (data from Google Scholar) [49].

4. Summary

Although additive manufacturing of polymer matrix composites has gone through a significant improvement in the last years (see the dates of publications in the references list), it is still not widely adopted by various industrial sectors for functional applications. Several limitations that need to be overcome are demonstrated in **Figure 24**. These problems are very similar to other AM techniques, such as direct metal laser sintering, which are more mature and overcome these restrictions for a wider infusion into industry. As seen in **Figure 25**, the interest of the industry and academia in AM for producing polymer matrix composites has been growing significantly, and this seems to continue exponentially in the coming years.

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