Material extrusion additive manufacturing of Continuous Fibre Reinforced Polymer Matrix Composites: A Review and Outlook⋆

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ABSTRACT

In recent years, three-dimensional printing (3DP) technology has developed to include composite materials. Most of the development to date in this area has involved particulate or short fibre reinforced composites, whilst continuous fibre printing remains a relatively novel research area. This review paper focuses on the state-of-the-art of continuous fibre reinforced 3DP technology (CF-3DP). The materials and devices being used in the current studies are reviewed, and the different processing methods are discussed in detail. A thorough summary of the mechanical properties is provided. Despite improvements compared to 3D printed pure plastics, the performance of current continuous fibre 3D printed composites are not yet in a position to compete with conventionally processed composites due to defects and low fibre volume fraction. Finally, an overview of current potential applications are presented. However, challenges still remain in materials and process development. New design, modelling and analysis methods are needed before these novel composite structures can find their optimal applications.

1. Introduction

3D printing, also known as additive manufacturing (AM), is a manufacturing approach in which a 3D part is built from a digital representation of the required geometry without the need for tooling. Advantages include the ability to create geometrically complex, customized parts without the cost and time penalties that are incurred when attempting this with a process optimised for mass manufacture, whilst also minimising the product development cycle period and material wastage [40]. For this reason, it was first employed as a means of producing prototype parts [167]. Material Extrusion (ME) is one of the AM techniques based on ASTM (American Society of Testing and Materials) standard [150]. Fusion Deposition Modelling (FDM) or Fused Filament Fabrication (FFF) is an ME process, in which a thermoplastic filament is fed into a heated nozzle where the plastic is melted. The melted plastic is then extruded from the nozzle, with the print ahead being controlled to enable the formation of layers by fusing extruded lines, and then to form 3D objects by the fusing of layers. In order to achieve this the temperature must be controlled to enable the fusion of adjacent lines & layers without excessively heating to introduce material degradation and/or loss of geometric control. Owing to this demand, the materials that can be successfully processed by ME are limited. Pure plastic printing by ME has been under development for decades and there is a large array of commercial machines, however, the 3DP of composites using ME techniques is still a relatively new research area. There is significant literature demonstrating the addition of discontinuous fibres and particle reinforcements to the plastic filaments in order to improve the mechanical properties of the printed part or to achieve special functionalities [78, 16, 121, 120, 151, 93, 96, 133, 90, 91, 48]. Although 3D printed short fibre reinforced polymer composites show significant improvements in performance over pure plastics, the mechanical properties are far inferior those achievable with composites of continuous fibre reinforcement. Since fibres are of much higher specific stiffness and specific strength than the matrix, it is weight efficient to design composite parts such that the loads are predominantly sustained and transmitted by the fibres. To facilitate this design philosophy, maintaining the continuity of the fibres is crucial. Therefore, 3DP of continuous fibre reinforced composites has the potential to achieve much improved performance compared with (foreseeable) short fibre composites. Christian et al. (1998) developed a process combining a form of ME with thermoplastic tow placement [21], which was possibly the first CF-3DP technology. Since then, a number of further studies have been carried out in this area and the technology is developing progressively.

Previously, the development of composite materials 3DP has been reviewed by quite a few papers, which covered various printing processes including polymeric, metallic and ceramic based composites with mainly particulate and short fibre reinforcements [78, 69, 119]. Besides mechanical improvements, other functional improvements such as optical, electronic, thermal, and biomedical etc., were achieved by adding these reinforcements. Continuous fibres including prepreg sheets, fibre matts and fibre tows were reported being employed in laminated object manufacturing (LOM) process [77], Stereolithography (SL) process [47, 70], and ME

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process [117, 154]. Other studies reviewed only 3DP of polymer matrix composites including both short and continuous fibre reinforcements [162, 125, 55, 39], in which various processes were described and potential applications of 3D printed composite materials in biomedicine, electronics, and aerospace was discussed. Brenken et al.'s review [12] focused particularly on the ME process for manufacturing polymer matrix composites. The mechanical performance of printed parts in different studies was compared for both short fibre and continuous fibre reinforced composites. Physical phenomena such as flow and fibre orientation, bond formation, solidification behaviour, deformation and residual stresses in the ME process were discussed in depth. Several studies of CF-3DP were briefly reviewed by Luca [94], concluding that the development of optimization design and slicing software would present new challenges for the technology. Frketic et al. [40] compared composite 3DP with conventional automated composites manufacturing processes such as filament winding (FW), automated tape laying (ATL), automated fibre placement (AFP). It was pointed out that composite manufacturing with 3DP had the potential of reducing the product development cycle period and material wastage, and is moving towards the use of continuous fibre to achieve comparable mechanical properties with 3DP compared to conventional composite processing. Additionally, 3DP processes allow the customization of part strength by aligning fibres in designated directions and controlling fibre volume fraction throughout the part, neither of which is feasible with conventional composites manufacturing processes. Chapiro [20] discussed the disadvantage of current composites 3DP in high performance industries such as aerospace. The author pointed out that it would be meaningless to compare composites with metals without considering their anisotropic properties, and CF-3DP could potentially exploit the anisotropic mechanical properties of composites and topology optimization for external geometry and internal fibre paths, and it could be a promising route for realising the full potential of composite materials. Hu et al. [57] reviewed the recent patents in continuous fibre reinforced composite AM, which discussed the current development in continuous fibre ME printers and printhead structures.

Recent review papers on 3D printing of fibre reinforced composite materials are summarized in Table 1, most of which were covering a broad subject of composite materials in AM, including both discontinuous fibre and continuous fibre in all AM processes. One huge advantage of the 3DP continuous fibre reinforced composites is the superior mechanical performance over the discontinuous ones, which has been compared in several reviews [12, 20, 45]. Discontinuous fibre reinforced composite AM might be easier to achieve, but the benefits of using continuous fibres are substantially greater in terms of better mechanical properties especially strength. The ME process is one of the AM techniques capable of achieving continuous fibre composite printing without major modification of the process itself. This is why it has becomes a very fast developing area for research and the majority of the literature on continuous fibre composite AM are related to this subsection of the AM processes. However, few reviews were available focusing on continuous fibre composite ME and the ones available have been found not thorough and up-to-date enough. As a fast developing subsection of the technology, the literature has witnessed various modified ME processes which have been developed for continuous fibre composite printing in recent years [136, 95, 175, 144, 145, 7], and some new mechanical testing results which were not available when the previous reviews were conducted [144, 7, 2]. Kabir et al. [68] provided a very thorough summary of the mechanical properties of continuous fibre 3D printed composites including tensile, compressive, bending, bearing and fatigue properties, but similar to other previous reviews [13, 12, 20, 39, 45, 181], a big part of the mechanical properties summarized was related to a single commercial printer and associated materials by the Markforged company [102]. With the development of the technology, new equipment has become available. There is a need to update the knowledge base so that researchers can better place their efforts and resources in this fast moving subsection of composite AM for more focused development in future. This review is to serve this purpose by focusing exclusively on continuous fibre ME process, from material feedstock preparation, to the manufacturing process itself to how to design with a material of strong anisotropy. It provides the readers a more extensive and in-depth understanding of the state-of-the-art of the continuous fibre composite ME process. A comparison will be made between the current performance of continuous fibre 3D printed composites and conventional manufactured composites. While the AM continuous fibre reinforced composite materials are still finding their way into real-life applications, this review reveals the potential of utilizing the ability of the newly developed process to steer fibre path, which brings new possibilities and challenges to continuous fibre composite AM, as well as to the conventional composite manufacturing and design.

2. Materials

Thermoplastic polymers are commonly used in the ME process, but not all thermoplastics are developed or commercialized to be printable materials. It is reported that commonly seen 3D printable thermoplastic polymers include ABS (acrylonitrile butadiene styrene), PMMA (polymethyl methacrylate), PC (polycarbonates), PEI (polyethylenimine), PA (polyamide), PEEK (polyether ether ketone), PET (polyethylene terephthalate) etc. [27]. However, only a subset of these polymers has been used in conjunction with continuous fibre printing. Table 1 summarizes the reinforcement and matrix materials that have been used, as published in the open literature.

Fibre reinforcements which are commonly used for conventional composite materials have also been used for the continuous fibre printing process, including carbon fibres, glass fibres, Kevlar and natural fibres. Constrained by the

Table 1
Summary of recent review papers on 3D printing of fibre reinforced composite materials (ME: material extrusion; PBF: powder bed fusion; LOM: laminate object manufacturing; SLA: stereolithography; MJ: material jetting; LENS: laser engineered net shaping; UC: ultrasonic consolidation; VP: vat photo-polymerization; FW: filament winding; ATL: automated tape laying; AFP: automated fibre placement; CTS: continuous tow shearing.)

Authors		Reinforcements	Processes	Content
Kumar and Kruth	[78]	particles/ short fibre	PBF/MJ/LENS/LOM/ SLA/ME/UC	materials, processes and applications
Wang et al.	[162]	particles/ short and continuous fibre	ME/PBF/SLA/MJ	processes and applictions
Sönmez et al.	[146]	short and continuous fibre	ME/SLA/LOM/PBF/MJ	processes and applictions
Brenken et al.	[13]	short and continuous fibre	ME	properties and process modeling
Luca	[94]	continuous fibre	ME	materials and process
Parandoush and Lin	[125]	particles/ short and continuous fibre	ME/LOM/SLA/PBF	processes and performance modelling
Hofstätter et al.	[55]	carbon nanotubes/ short and continuous fibre	ME/SLA	materials, processes and applications
Brenken et al.	[12]	short and continuous fibre	ME	properties and physical phenomena of the process
Chapiro	[20]	short and continuous fibre	ME/PBF	current peformance and outlook
Ngo et al.	[119]	particles, short and continuous fibre	ME/LOM/SLA/PBF	materials, processes, applications and challenges
Kalsoom et al.	[69]	particles nad short fibre	PBF/MJ/LOM/SLA/ME/	applications
Fidan et al.	[39]	particles, short and continuous fibre	ME/PBF/SLA	materials and properties
Frketic et al.	[40]	short and continuous fibre	FW/ATL/AFP/Pick and place/ CTS/SLA/MJ/ME/LOM/PBF	processes and properties
Kabir et al.	[68]	continuous fibre	ME	History, mechanism, materials, properties and limitations
Goh et al.	[45]	short and continuous fibre	ME/SLA/LOM/PBF	processes, properties and outlook
Zindani and Kumar	[181]	particles, short and continuous fibre	PBF/LOM/SLA/ME	materials, processes, properties
Moumen et al.	[116]	particles, short and continuous fibre	ME/MJ/SLA/PBF	processes, numerical and analytical modeling
Werken et al.	[166]	short and continuous fibre	ME/DW/SLA/PBF	processes and applications
Tan et al.	[150]	no reinforced polymer/ particles short and continuous fibre	VP/MJ/PBF/ME/BJ/	processes and materials
Currnt authors		continuous fibre	ME	materials, process, properties and applications

size of the nozzle, small fibre tow sizes of 1–3K have mostly been used in CF-3DP. Fibre treatment was reported in a few previously published work. In Li et al.'s study [83], carbon fibres were pre-treated in a PLA and dichloromethane solution, and in Liu et al.'s study [88], carbon fibres were first treated in acetone to remove original epoxy sizing and then dipped in a polyamide solids solution to form new sizing. In Heidari-Rarani et al.'s study, the carbon fibre tow was treated in a Poly vinyl alcohol (PVA) solution at 60°C for 1 hour to remove the sizing for thermoset polymer and to form a new coating for the thermoplastic polymer [53]. A sponge foam infilled with PA845H-PL nylon sizing agent was applied to infiltrate the carbon fibre bundles and improve the bonding strength between fibre and resin matrix in Li et al.'s study [84].

Both thermoplastic and thermoset polymer have been reported in the literature as matrix materials in continuous fibre printing. Thermoplastics are more commonly used in ME because they can be produced as filament type feedstock material and re-melted in the nozzle during the printing process. Thermoplastic polymers that have been used in continuous fibre reinforced printing include PLA (polylactic acid), ABS, PA and PP (polypropylene). PLA and ABS are the two most commonly used feedstock plastics in the ME process for pure plastic printing. PCL (polycaprolactone) has a relatively low melting point of 60°C which makes it easy to process. Nylon is a class of the PA family, including PA6 and PA12. It is an engineering plastic with good mechanical properties, but it absorbs moisture easily. PP also has good mechanical properties and is commonly used as the matrix material in conventional thermoplastic composites. PEI is an amorphous thermoplastic and PEEK is a semi-crystalline thermoplastic, both of which are high temperature and chemical resistant [169]. Thermosetting polymers are usually used in the Stereolithography (SLA) process but not in ME due to their liquid form before curing. However, several studies have attempted to use a thermosetting polymer in a continuous fibre printing process. A fibre tow was pulled through an uncured epoxy resin bath to produce a semi-solid form of fibre filament in Hao et al.'s work [51]. After the fibre filament was printed by ME, the sample was oven cured. A thermosetting polymer was also used by Azarov et al. [8], where dry fibre tows were first impreg-

Table 2
Matrix polymer and reinforcements used in CF-3DP.

Researchers and Institutions	Matrix	Reinforcement	Vf %	Ref.
Markforged USA	PA6	Carbon/Glass/Kevlar	35	[102]
Christian et al. University of Nottingham, UK	PCL	Glass	27	[21]
Matsuzaki et al. Tokyo University of Science, Japan	PLA	Carbon, Jute fibre	6.6	[117]
	ABS	Carbon	21–34	[103]
Tian et al. Xi'an Jiaotong University, China	PLA	Carbon	27	[154]
	ABS	Carbon	5.8	[172]
Li et al. NUAA, China	PLA	Carbon	34	[83]
Mori et al. Toyohashi University of Technology, Japan	ABS	Carbon	-	[115]
Yao et al. Zhejiang University, China	PLA Epoxy	Carbon	-	[174]
Tse et al. University of Michigan, USA	PCL	Carbon	-	[158]
Bettini et al. Politecnico di Milano, Italy	PLA	Kevlar	8.6	[10]
Vaneker et al. University of Twente, Netherlands	PP	Glass	-	[161]
Parandoush et al. Kansas State University, USA	PP	Glass	41	[126]
Baumann et al. Karlsruhe Institute of Technology Germany	ABS	Carbon	-	[9]
Hao et al. Jiangsu University, China	Epoxy	Carbon	-	[51]
Eichenhofer et al. ETH Zürich, Switzerland	PA12	Glass	52	[37]
Hu et al. Shanghai University, China	PLA	Carbon	-	[58]
Azarov et al. Skolkovo, Skolkovo Institute of Science and Technology, Russia	PA Epoxy	Carbon	35	[8]
Yamawaki and Kouno Japan Kure College	PA6	Carbon	50	[171]
Cardon et al. Ghent University, Belgium	PA12	Glass	35	[159]
Zhang et al. Wuhan University of Technology, China	PLA	Carbon	-	[177]
Domm et al. Institut für Verbundwerkstoffe GmbH, Germany	PP	Glass	30	[33]
Backer et al. University of South Carolina, USA	PEI	Carbon	17.4	[28]
Hinchcliffe et al. University of Colorado Boulder, USA	PLA	Jute, Flax	-	[54]
Stepashkin et al. National University of Science and Technology, Russia	PEEK	Carbon	5	[147]
Ranabhat et al. University of South Alabama, USA	Epoxy	Carbon	-	[136]
Luo et al. Xi'an Jiaotong University, China	PEEK	Carbon	38.27	[95]
Ye et al. Jilin University, China	PI	Carbon	-	[175]
Duigou et al. Université de Bretagne Sud, France	PLA	Flax	30.4	[34]

nated with epoxy resin and cured to produce the fibre filament, which was then extruded together with a thermoplastic polymer. A list of polymer and fibres used in the literature is summarized in Table 2.

3. Printers

3.1. Commercial closed-source printers

There are many commercially available pure plastic ME printers in the market. However, to the best knowledge of the authors, there are only a few commercial printers capable of printing continuous fibre reinforced thermoplastics, and the Markforged [102] is one of the most famous ones. There are two nozzles in a Markforged printer, one for pre-impregnated fibre filament and the other for pure plastic filament. The matrix material is Nylon, and fibre reinforcement can be chosen from carbon, glass and aramid. The two separate nozzles are assembled together on the printhead for printing the reinforced and un-reinforced filaments individually. A cutting mechanism is employed on top of the printhead, and a feeding mechanism is used to push the fibre filament into the nozzle. A standard CAD model STL file can be imported into the web based software, called "Eiger" [102], which slices the 3D object into layers for the printing process. Several standard printing parameters for printing the pure plastic can be chosen in the software, such as number of roof and floor layers, number of wall layers, fill pattern, fill density, etc. As for fibre composite printing, the printer provides three types of fill patterns, namely: isotropic (the Markforged terminology), concentric rings and a combination of the two. A schematic of the controllable fibre path design is shown in Fig.1, where the fibre paths are indicated as the blue lines. In the 'isotropic' fill pattern, all fibres are laid down at a designated angle along a straight path. When the nozzle reaches the edge of the print part, it turns around, going back and forth until the full layer is filled. The fibre tow is cut automatically to complete a layer of printing. This isotropic fill pattern is similar to a unidirectional layer in the conventional lay-up of laminates, where fibres are all in the same direction in the layer. It should be pointed out that the fibre continuity at the point of turning will hardly have any strength benefit. In the concentric ring pattern, the fibres are laid along the contour of the outer or inner edges of the print part to fill the layer. For multiply connected areas, once the paths have filled up a side, it will automatically form a new ring path in the area yet to be filled. The Markforged printer is a successful product, which is capable of printing continuous fibre reinforced plastics that have significantly better mechanical properties than any other standard ME material.

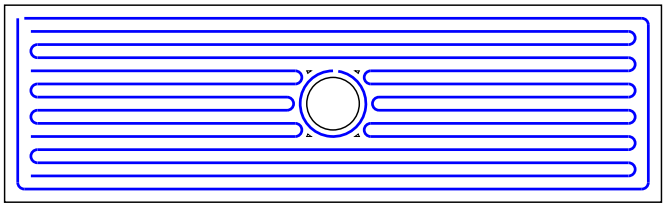


Figure 1: Closed-source printer fibre path design schematic.

However, it currently only provides a limited number of design options for the user to change the fibre patterns. Due to this limitation, the products printed using the Markforged printer generally consist of a relatively simple continuous fibre structural element within a more complex, lower performance nylon outer casing. Given its closed-source nature, users have limited capability to alter the design in order to suit specific applications. Furthermore, only a limited range of composite materials are available for use with the Markforged machine and only a single matrix material (nylon).

The CEAD company [99] developed an industrial level CF-3DP printer. This printer is a gantry-based machine with a $4m \times 2m \times 1.5m$ build volume, as shown in Fig. 2(a). Pre-impregnated fibre and thermoplastic polymer are extruded from the printhead at the same time, and the fibre weight fraction is about 40%. Fibre reinforcements can be chosen from carbon and glass fibre, and a wide range of thermoplastic polymers can be used as the matrix material, including ABS, PC, PEEK, PET, PLA and PP. The 9T Labs company [81] developed the Additive Fusion Technology (AFT), which used continuous carbon fibre reinforced PA12 as the feedstock material. The feedstock material with a desktop ME printer is shown in Fig. 2(b). It is claimed that the fibre volume fraction can reach up to 60% and void content can be lower than 2%.

Anisoprint company [3] has launched the ProM IS 500 as shown in Fig. 2(c). It is designed to print high-temperature thermoplastics with continuous fibre reinforcement. The high temperature printhead can be heated up to $400^{o}C$, which is capable of using PEEK and PEI as the matrix material. The Continuous Composites company [23] developed the CF3D® solution in which a UV fast curing thermosetting resin pre-impregnated continuous fibre prepreg material was used as the feedstock material and a robotic arm was utilised for depositing and curing the prepreg material at the same time. The printer is shown in Fig. 2(d). The reinforcement fibre can be chosen from carbon, glass, aramid for structural applications and optical, metallic for functional usage.

3.2. Open-source ME printers

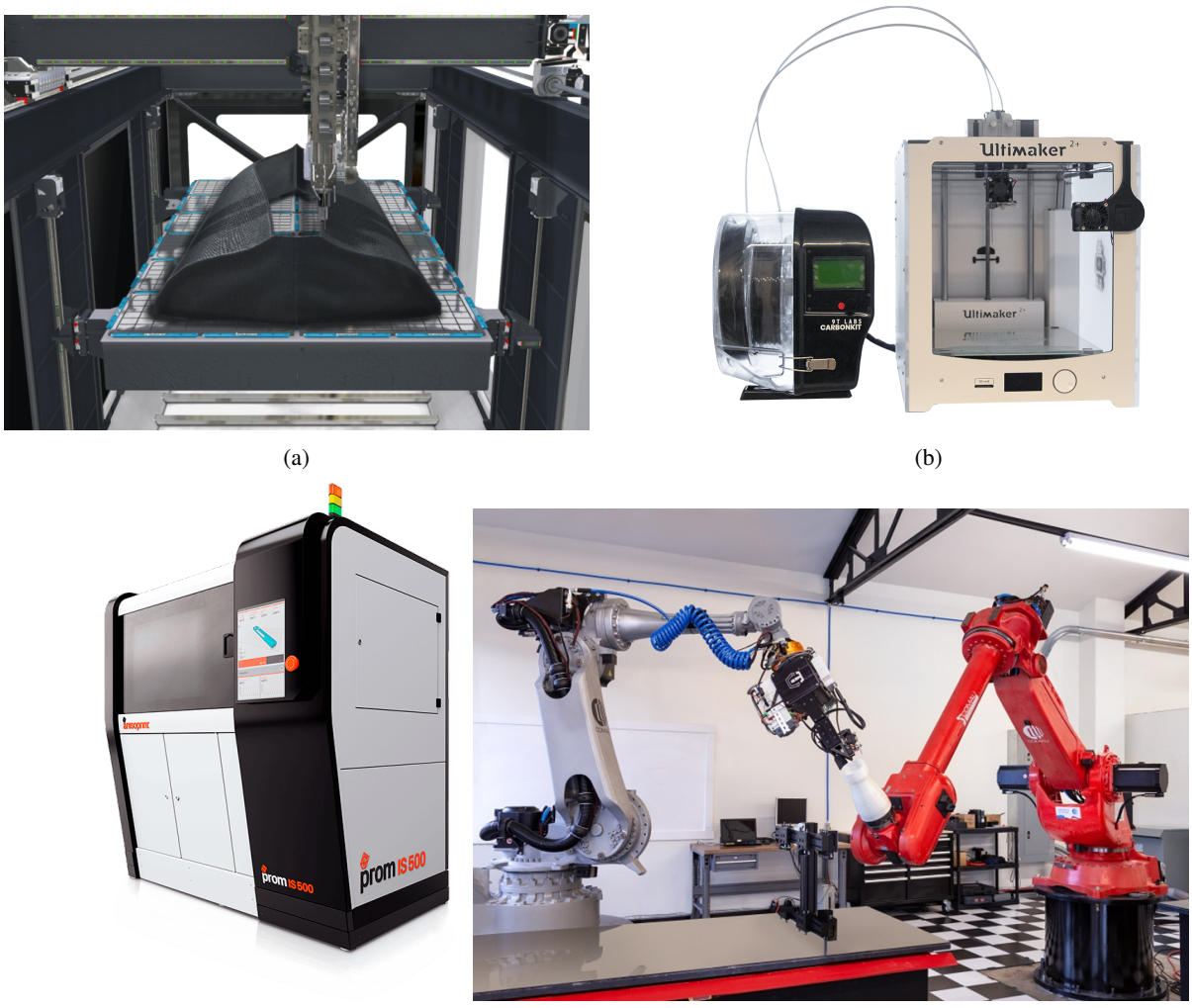
Due to the limitations and restrictions of closed-source printers and their high cost, researchers have tended to develop their own printers from available open-source printers for printing continuous fibre reinforced plastic. The RepRap open-source printers are mostly used for such applications. The word RepRap is the abbreviation for Replicating Rapid-prototyper. As an open-source design, the RepRap printers allow developers to use the free license software and to build their own printers without excessive investment [137]. Some researchers have adapted the RepRap plastic printer for printing continuous fibre composites, by modifying the printhead and changing the feedstock material. In addition, open-source printers allow users to design the fibre path freely by controlling the printer using a user programmable facility, such as G-code [39]. As a result, they provide more flexibility for using different kinds of materials and producing more complex fibre paths, thus providing a possible route for printed parts or components to be manufactured with properties tailored to specific applications.

Open source printers also enable additional functions to be added to suit the purpose of continuous fibre composite printing. For example, a cutting mechanism was implemented on a RepRap printer to cut the fibres as required [158, 161, 33]. Omuro et al. [123] added a compaction roller to the printer to apply compressive force on the printed continuous fibre composite, which showed improved mechanical properties for the material printed. A tilted printhead was introduced by Tse et al. [158] and a rotary cylinder print bed was employed in Fang et al.'s work [51], which enabled continuous fibres to be printed out of plane (curved in z axis) to produce more complex shapes in the parts to be printed.

3.3. Robotic arm

In addition to the desktop ME printers, robotic arms are also being applied to the ME process. An extrusion printhead can be mounted on a robotic arm to enhance the 3DP process, greatly increasing the build volume and number of degrees of freedom of the printhead. Full sized houses and complex shaped aesthetic architectures can be printed with the help of robotic arms using concrete paste and pure plastic materials [119]. Stratasys® developed a robotic composite 3D demonstrator, which uses a robotic arm to deposit short fibre reinforced plastics, as shown in Fig.3 [110]. In some other attempts [28, 152, 38], robotic arms were employed to produce continuous fibre reinforced plastics, as shown in Fig.3 (b) and (c).

Ranabhat et al. developed a Magnetic Compaction Force Assisted-Additive Manufacturing (MCFA-AM) 3D printing head, as shown in Fig.4, which was attached to a robotic arm [136]. A magnetic roller and a magnetic backing article were used to apply $0.21MPa$ compaction force during printing, which gave the advantage of printing free-form composite structures without moulds. Although robotic arms have the advantages of high build volume and non-planar printing, the investment for a robotic arm will be much higher than for a desktop printer.



(a) (b) (c) (d)

Figure 2: (a) CEAD printer [99]; (b) 9T labs printer [81]; (c) Anisoprint PROM IS 500 printer [3]; (d) Continuous Composites robotic arm printer [23].

4. Processes and Apparatus

Unlike the feedstock for the ME printing of pure plastics, the fibre reinforcement needs to be impregnated with the matrix material for use in continuous fibre printing. Thus, various processes and apparatus were developed by many researchers aiming at impregnating and printing the fibres. Various impregnation methods and forms of material have been used. The state-of-art of these processes and apparatus for CF-3DP is described briefly in this section.

4.1. In-nozzle impregnation method

A direct way of impregnating continuous fibres for use in ME is through an extrusion process to impregnate dry fibres with thermoplastic polymer. An in-nozzle impregnation was developed by Namiki et al. [117] and Matsuzaki et al. [105], where continuous dry fibres and the thermoplastic matrix filament are fed into the print head simultaneously in designated proportions. The thermoplastic polymer is heated above its melting point in the nozzle, while the dry fibres are pre-heated before entering the nozzle and then impregnated by the molten thermoplastic within the nozzle. The impregnated fibre tow and the plastic are extruded from the nozzle together and deposited directly for a 3DP process. The schematic of the print head is shown in Fig. 5(a). Two types of reinforcements were used in this study, namely 1K carbon fibre tow and twisted jute-fibre yarns, with PLA filament employed as the matrix material.

Similar in-nozzle impregnation ME processes were also used by Tian et al. [154, 172, 153], Bettini et al. [10], Stepashkin et al. [147] and Akhoundi et al. [2], where carbon fibres with PLA or ABS, aramid fibres with PLA, carbon fibres with PEEK and glass fibres with PLA, were used respectively as reinforcement and matrix material. However, in all cases, a significant number of voids were observed between the printed fibre tows and there was poor polymer impregnation within the fibre tows. Ye et al. [175] designed a separated printing method, where a concentric

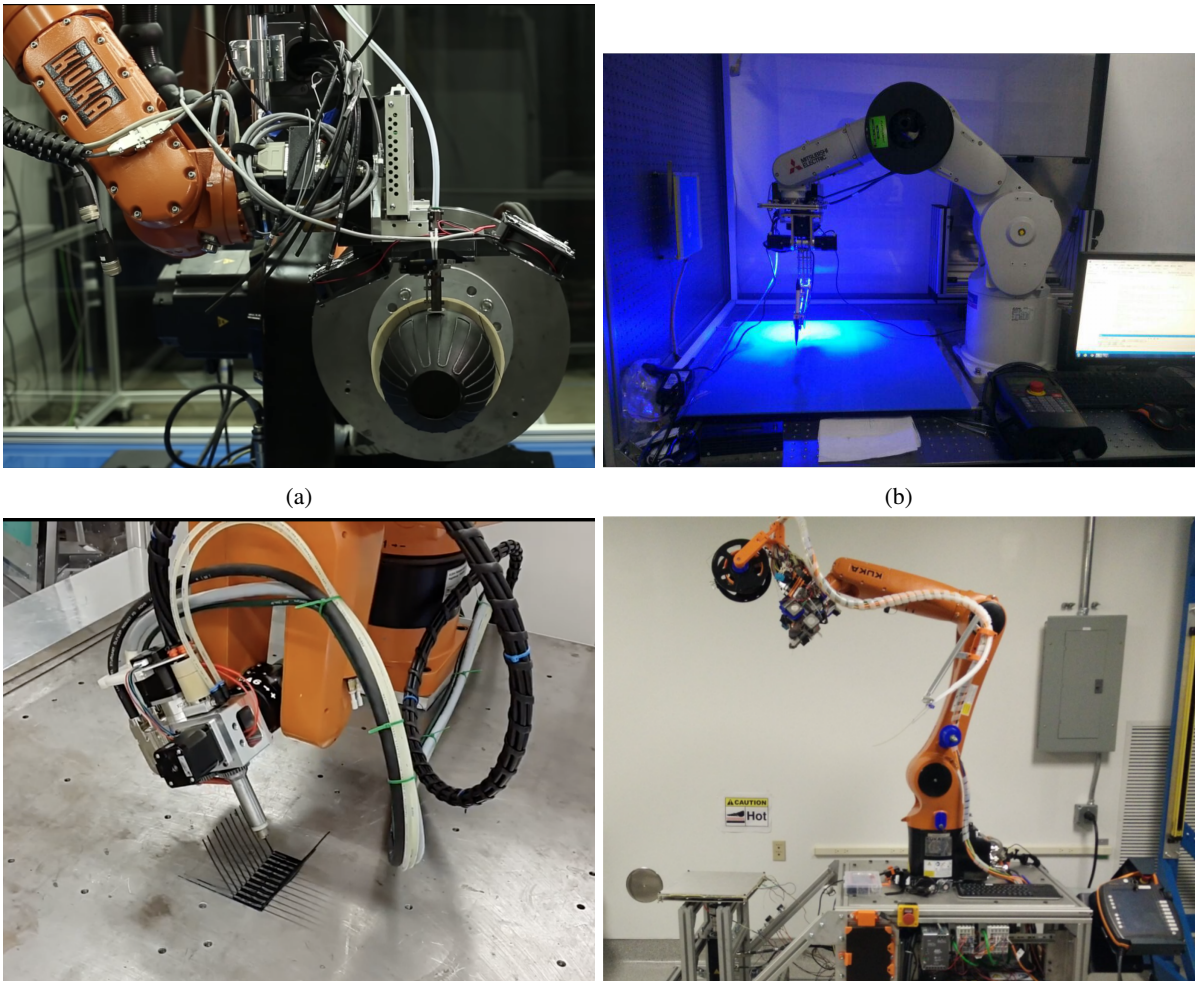


Figure 3: Robotic arms for composites 3DP: (a)Stratasys printer [110], (b) Robotic arm printer from Xi'an Jiaotong University[152], (c) Robotic arm printer from ETH university [38], (d) Robotic arm printer from USC university[28].

tube was placed in the heat block for continuous fibre feeding as shown in Fig. 5(c). An adapted ME print head was developed by Prüß and Vietor [128], as shown in Fig. 5(d). The prototype print head includes a heated mixing chamber and three ports. The dry fibre tow is fed into the middle one, while thermoplastic filaments are fed via the other two ports, with the aim that the dry fibre tow will be more uniformly infiltrated by the thermoplastic polymer. However, the prototype is still under development, and no results have been published regarding the fibre impregnation quality. In Luo et al.'s study, dry carbon fibre tow was first fed into the heated nozzle and mixed with the molten PEEK plastic [95]. Then a laser beam was used to pre-heat the previously printed layer before the carbon fibres and the PEEK plastic extruded from the nozzle, as shown in Fig. 6. The test results showed that the interlaminar shear strength was improved with in-situ preheating using the laser.

A very low fibre volume fraction (lower than 10% [117, 154, 172, 10]) has been achieved through the in-nozzle impregnation process, with voids and dry fibres also common. These defects are probably caused by the difficulty in impregnating the dry fibre tow, due to the high viscosity of the molten thermoplastics, the extremely short impregnation times and a lack of compressive force during the printing process. The typical melt viscosity of a thermoplastic polymer such as PA6 is around 200-1100 Pa·s, whilst a thermoset resin, such as an epoxy used in Resin Transfer Moulding (RTM), is less than 1 Pa·s at the infusion temperature [169]. In general, the viscosities of thermoplastics are several orders of magnitude higher than those for thermoset resins while processing [15]. The viscous molten polymer therefore finds it difficult to travel through the fibre bundle, especially when this impregnation process happens in the nozzle for only a few seconds depending on the printing speed. Pre-treating the carbon fibre in a PLA and methylene dichloromethane solution [83] have been proposed to improve the adhesion between the fibres and PLA plastic. Mechanical testing results showed 13.8% and 164% improvement in tensile strength and flexural strength respectively compared to untreated carbon fibre samples, and Scanning Electron Microscope (SEM) scan results suggested better

Figure 4: Magnetic Compaction Force Assisted-Additive Manufacturing (MCFA-AM) 3D printing head where magnetic force was used to apply compaction during the printing process [136].

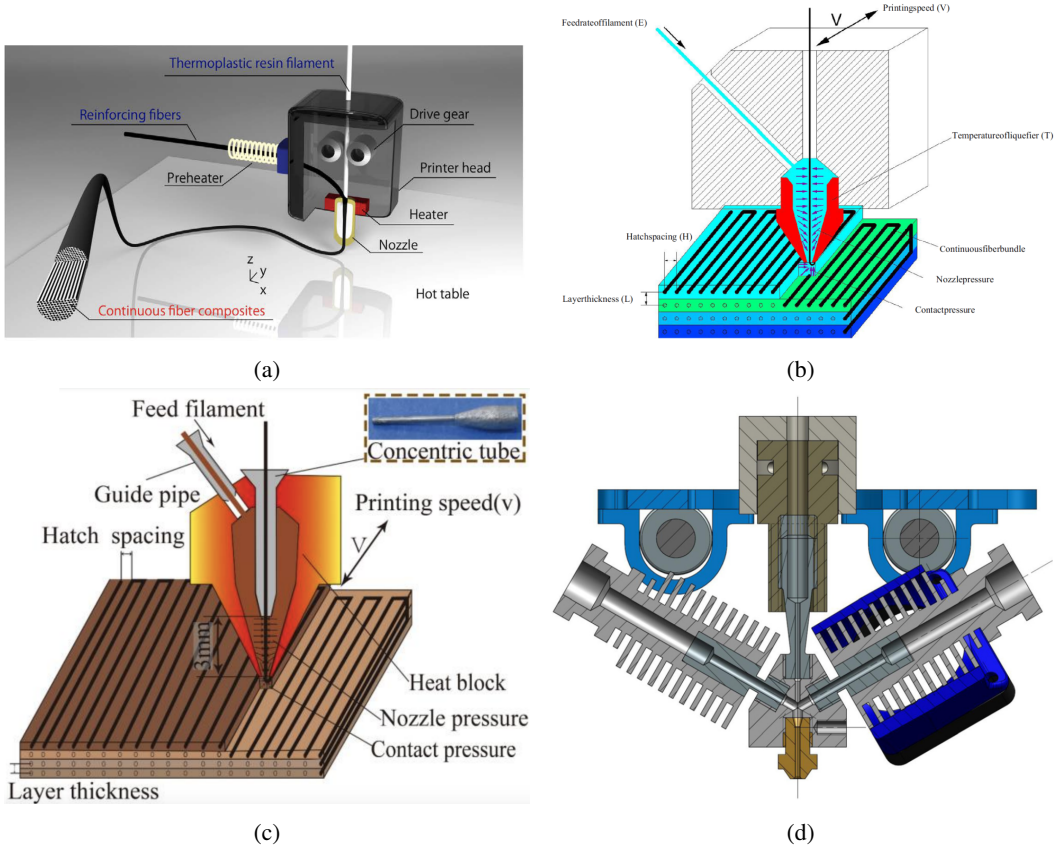


Figure 5: Schematic of different print head designs of in-nozzle impregnation method in different literature where fibre filament (indicated as black lines) was fed through one pipe and the thermoplastic filament (indicated as white (a) Namiki et al. [117]; blue (b) Tian et al. [154]; red (c) Ye et al. [175];) was fed through another pipe as ((a), (b), and (c)), or two other pipes on the left and right sides as (d) Prüß and Vietor [128].

bonding between fibres and PLA matrix. Similarly,with fibre pre-treated in polyamide solids solution, the flexural strength and modulus of printed specimens improved by 82% and 246% respectively [88]

4.2. Prepreg materials as feedstock

Since it is difficult to impregnate the fibres in an in-situ printing process, the printing of pre-impregnated filament (prepreg) materials has also been investigated. A technology called Materials Deposition Modelling (MDM) was de-

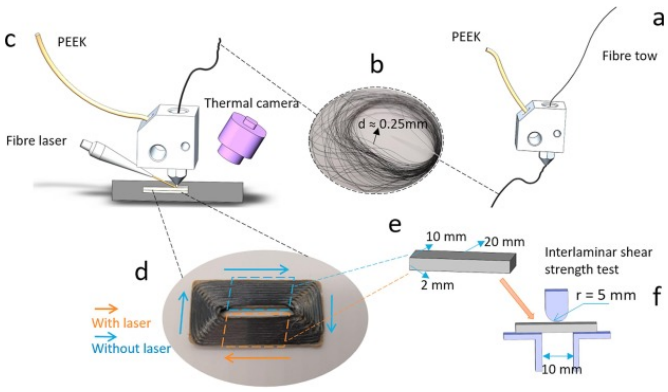
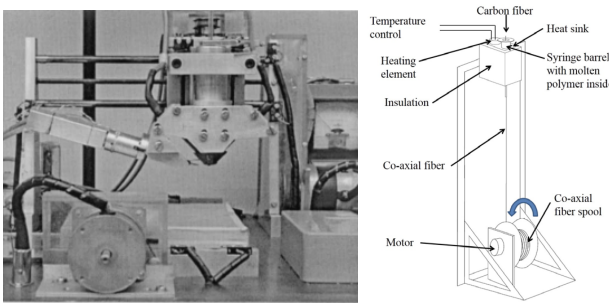


Figure 6: Diagram of preparation and test of carbon fibre/PEEK composite components [95].



(a) (b)

Figure 7: (a) Deposition Modelling (MDM) which combined a form of ME with thermoplastic tow placement [21]; (b) schematic of a filament fabrication method developed by Tse et al. [158].

veloped, as shown in Fig.7(a), which combined a form of ME with thermoplastic tow placement [21]. A continuous glass fibre tow was passed through a molten PCL bath to form a tow-preg, and then the prepreg filament was fed into the MDM machine to produce biodegradable polymer composites for potential application in human bone replacement. Similarly, Tse et al. [158] developed a filament fabrication method, as shown in Fig.7(b), where carbon fibres were fed through a heated syringe barrel with molten PCL polymer, before being used as the feedstock material in a modified ME printer.

In Zhang et al.'s study [58], an extrusion device for manufacturing carbon fibre reinforced PLA filament was developed, as shown in Fig. 8(a). PLA pellets were fed into the single screw extruder, where they were heated up and mixed with the 1K carbon fibre tow. However, it was observed from the prepreg cross sections that PLA polymer was mostly adhered to the surface of the fibre tow and dry fibres were found within the fibre tow. Matsuzaki et al.[103] used an ABS resin tank with three rollers to achieve better impregnation quality of the dry fibre bundles, as shown in Fig. 8(b). Full impregnation was observed in the 1K filament. In Qiao et al's study [131], an ultrasonic transducer was sued in the thermoplastic resin tank to improve the impregnation of the dry carbon fibre tow, as shown in Fig. 8(c). The tensile and flexural strength of printed specimens were improved by 34% and 29%, respectively, compared with those without the ultrasonic treatment.

A more complex prepreg filament manufacturing device was designed by Van de Steene et al. [159] using a fibre impregnation technology called "ActivePin", as schematically shown in Fig. 9(a). During the "ActivePin" impregnation process, the dry glass fibre bundle was wrapped over a cylindrical surface of the spreader pin, and a continuous flow of polymer was drawn between the fibre bundle and the surface in the melt chamber. An outward radial flow of molten PA12 polymer was generated by the build-up pressure generated, which caused the liquid polymer to pass through the fibre bundle. In addition, liquid PA12 polymer was continuously added in the contact region through small holes on the spreader pin. The result showed significant improvement in fibre impregnation and fibre distribution compared to pultruding dry fibres and thermoplastic polymer together. Similarly, Liu et al. [89] developed a high-pressure impregnation method as schematically shown in Fig. 9(b) . 1K and 3K dry fibre tows were used in the study and they were fed into the impregnation mould individually. Tension was applied on the fibre tow and molten PA12 plastic was extruded from the holes in the middle pin to impregnate the fibre tow. Fibre volume fractions of 31.9% and 50.2% were achieved for the 1K and 3K fibre tow respectively.

As well as in-house manufactured feedstock prepreg materials, researchers have utilized conventional thermoplastic prepreg sheets and cut them into small width tapes for 3DP. Parandoush et al. [126] used both unidirectional and woven glass fibre reinforced PP prepreg in their study. The prepreg sheets were cut into tapes with 5mm width. A CO_2 laser was used to heat up the prepreg tapes during deposition and to trim off the extra material to form the final shape. In addition, a compaction roller was employed while laying down prepreg tapes, as shown in Fig.10. Yamawaki and Kouno [171] used carbon fibre reinforced PA6 prepreg sheets cut into 1.2mm wide and about 1m long tapes. They were fed into a heated metal mould and consolidated to form a fine rod-shaped (needle-shaped termed by the author) filament. After consolidation, the filament was used as the feedstock material for the printing process in a RepRap 3D printer. In addition to the prepreg filament, supplementary unreinforced PA6 plastic was extruded with the prepreg filament in the aim of flattening an uneven surface and filling gaps. After the printing was finished, the printed part was put into a hot press for post processing to form the final part.

4.3. Commingled fibres as feedstock

Besides in-nozzle impregnation and the use of prepregs, commingled fibres, which is commonly used in textile composites, have also been utilized for continuous fibre print-

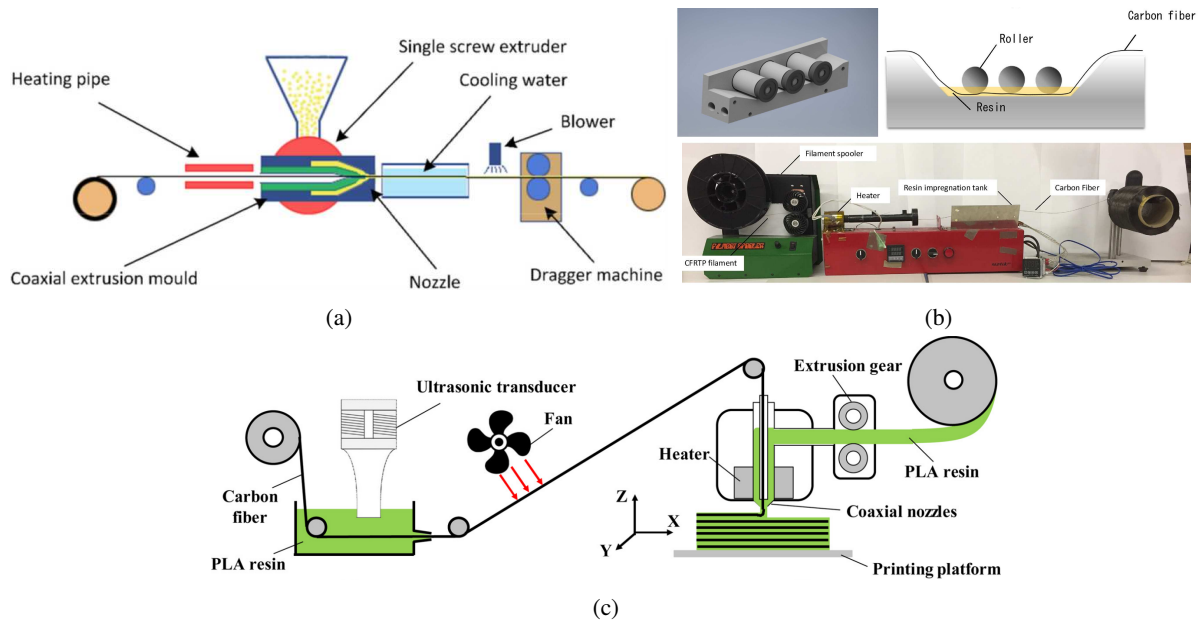


Figure 8: (a) Schematic for manufacturing 3D printable CCF prepreg filament [58]; (b) Schematic of the manufacturing process of resin impregnated carbon fibre bundles [103]; (c) A schematic diagram of the ultrasonic assisted additive manufacturing device [131].

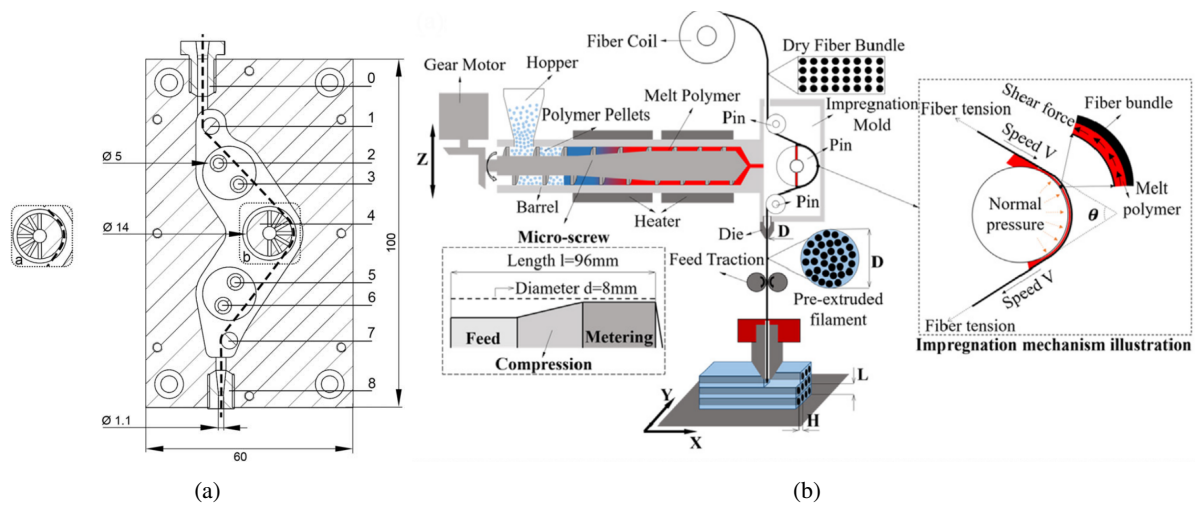


Figure 9: (a) ActivePin melt impregnation device where fibres bundles were wrapped over several pins to achieve full fibre impregnation [159]; (b) High-pressure interfacial impregnation method where fibre bundles impregnated in the impregnation mould [89].

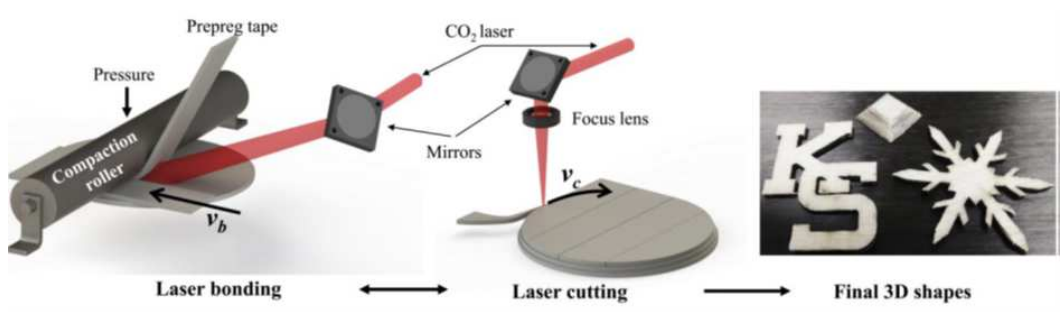


Figure 10: Schematic of laser assisted additive manufacturing of continuous thermoplastic composites [126].

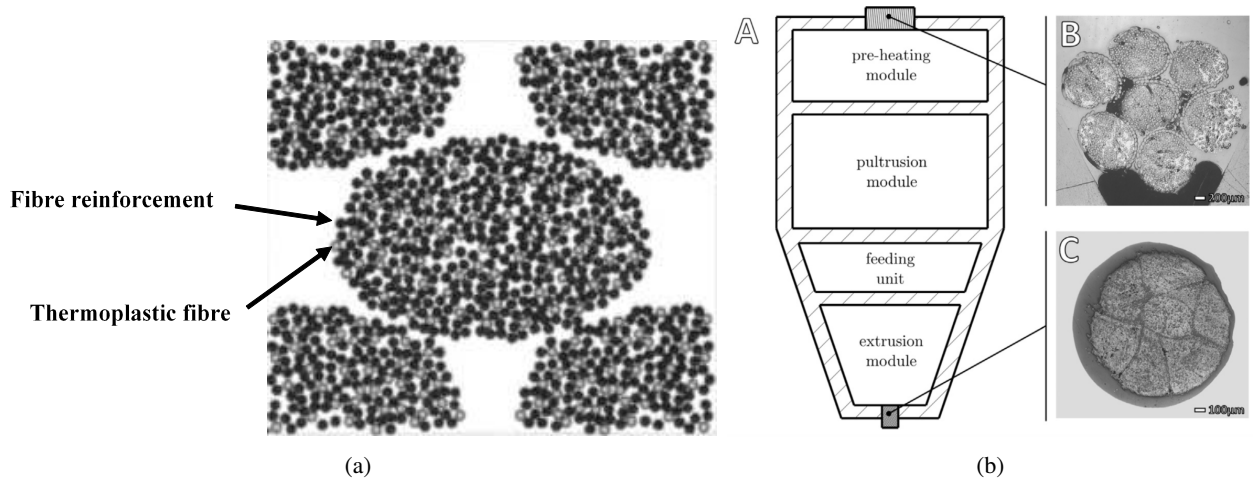


Figure 11: (a) Commingled fibre [15]; (b) Schematic of a two stages printing process using commingled fibres where A indicates the commingled fibre bundles fed through the printhead, B is the cross-section of the commingled fibre bundles before feeding through the printhead and C is the cross-section of the commingled fibre bundles after feeding through the printhead [38].

ing. As illustrated in Fig.11(a), commingled fibres consist of both thermoplastic fibres and reinforcement fibres. Since the fibres are commingled with each other, the impregnation distance is much shorter. Thus, there is a potential of achieving good impregnation.

In Vaneker et al.'s study [161], a glass and PP commingled yarn with 35% fibre volume fraction was pultruded through a heated die to produce the feedstock material. Various pultruding speeds and temperatures were investigated to obtain the optimal process parameters. A RepRap ME printer was used for extruding the fibre filament, and the printer was fitted with a cutting device. A well impregnated filament was manufactured, but a high void content of 19% was found in the printed specimens. Similarly, carbon fibres and PA12 commingled yarns were used for producing additively manufactured composites in Eichenhofer et al.'s study [37, 38]. A two-stage printing process was designed, as shown in Fig. 11(b). In the first stage, 7 yarns of commingled fibres were pultruded from a heated metal die and consolidated into a rod. In the second stage, the pultruded rod was extruded from a robotic arm to produce an ultra-lightweight lattice sandwich structure. Various process parameters were investigated with the aim of achieving good fibre impregnation and low void content. In Silva et al.'s study, the carbon/PA12 commingled fibres with a 55% fibre volume fraction were co-extruded with the 1.75*mm* PA12 plastic filament [144]. 1K and 3K carbon fibres were used, and the resultant fibre volume fraction of the printed composites were 3.45% and 11.73% respectively due to different amount of co-extruded PA12 plastic.

4.4. Thermosetting polymer CF-3DP

Due to the fact that it is difficult to impregnate fibre tow with a thermoplastic polymer, Azarov et al. developed a printing process using two matrix materials [8]. In this study, a carbon fibre tow was first impregnated with an epoxy resin based binder, which was fully cured. After that, the pre-impregnated fibre tow was extruded together with unreinforced polyamide plastic using a 3D printer, where the fibre tow was wrapped by the molten thermoplastic polymer, as shown in Fig. 12(a). Although there is no difficulty in fully impregnating the fibre tow, there could be some drawbacks for this method, such as low fibre volume fraction (only 35%) because of two-stage impregnation, uneven fibre distribution with resin rich areas as shown in Fig. 12(a), difficulty in bonding cured thermoset matrix and thermoplastic matrix, and the lack of fibre flexibility due to the rigidness of the cured thermoset matrix. In Hao et al.'s work [51], a 3DP process was developed using only thermoset material as the matrix material. A 3K carbon fibre tow was passed through a low viscosity epoxy resin pool (5-10 Pa·s at 25°C) and was fed into the printer, as shown in Fig. 12(b). The impregnated fibre was heated up, soften and laid down on the print bed. After the part was printed, it was moved to a high temperature chamber for curing. Similarly in Ming et al.'s study [111, 112], 3K carbon fibre tow firstly passed through an epoxy resin tank at 130°C, where a thermally induced latent hardener agent (DICY) is added. Then it was cooled down rapidly and re-winded for the printing process. A carbon/epoxy mesh preform was printed onto of an glass fibre reinforced prepreg as shown in Fig. 12(c), then it was vacuum bagged and transferred into a heated oven at 170°C for curing. Continuous fiber-reinforced thermosetting polymer composites (CFRTPCs) fabrication process is schematically shown in Fig.12(d). In Ranabhat et al.'s study [136], a two-part epoxy resin was first mixed and then poured on top of a preheated unidirectional fabric to manufacture the prepreg material for printing. The prepreg was heated at 60°C for 8-10 minutes to achieve B-stage curing level and then cut into 300*mm* by 15*mm* strips for the MCFA-AM printing process as mentioned in section 3.3.

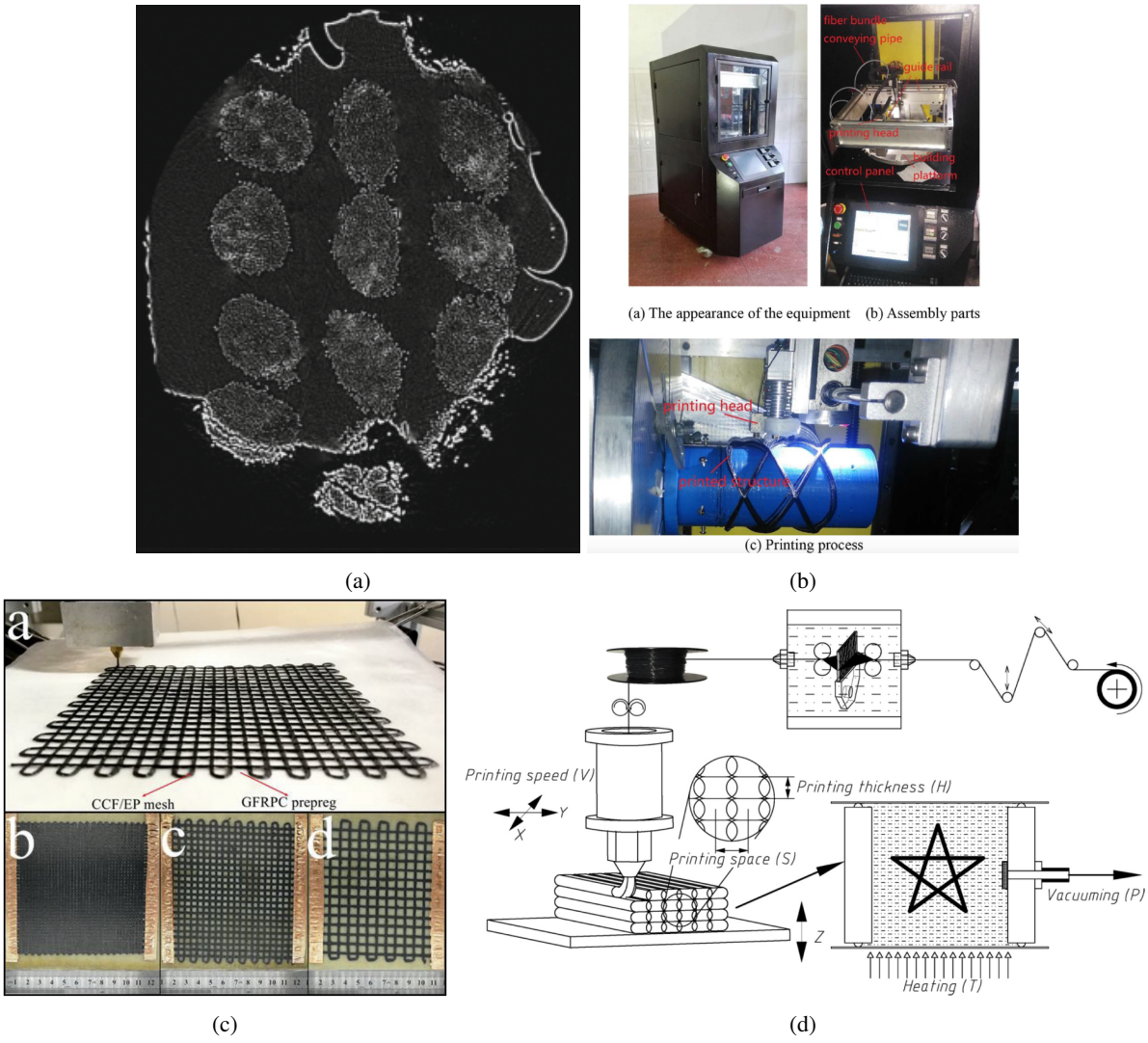


Figure 12: (a) optical microscopy of two matrix material where epoxy resin impregnated carbon fibre bundles are seen as the circular shapes and the rest is thermoplastic matrix material [8]; (b) equipment for 3DP continuous fibre reinforced thermosetting composites and printing ona tube surface [51]; (c) 3D printed continuous carbon fibre/epoxy mesh with different printing spaces for wind turbine blade de-icing application [111]; (d) Schematic illustration of the 3D printing process for CFRTPCs [112]

In these studies, thermoset polymer was used to bypass the impregnation difficulties of using a thermoplastic matrix. However, the method introduces an extra curing step to consolidate the printed part. Since only ovens were used to consolidate the printed parts instead of an autoclave, the quality of the printed parts cannot be guaranteed. Void content was reported to be 2.84% with vacuum applied [112]. Furthermore, if parts with complex shapes such as over-hang were to be printed using uncured thermosetting feedstock materials, how to maintain the printed shape without moulds during curing process would be a potential problem.

4.5. Other apparatus

Other, more direct ways, of applying continuous fibre in ME were explored by Yao et al. [174], Baumann et al. [9], Mori et al. [115] and Jahangir et al.[63]. In these studies, the bottom half of the test specimen was first printed with pure thermoplastic materials. Then the continuous carbon fibre tow was placed manually on top of the bottom part. The dry fibres were glued to the bottom substrate using thermosetting resin [174], or an ultrasonic embedding tool was used to bond the fibre with the bottom plastic substrate [63], or the dry fibre tows were only fixed at both ends [115, 9]. Finally, the fibre tow was covered with the printed top half of pure thermoplastic. The mechanical properties showed some improvement compared with pure plastic printed specimens, however, the impregnation quality of the fibre tow was poor, even at very low fibre volume fraction (below 10%).

5. Mechanical performance

The achievement of high strength and modulus are the main aims of 3DP composite materials, as the continuous

fibre reinforcement is aimed specifically at improving mechanical performance beyond that seen with standard 3D printed materials. Unidirectional tensile and 3-point-bending tests are most commonly performed to evaluate mechanical performance with these materials. In previous reviews [40, 55, 12, 45, 19, 68], the mechanical performance of printed parts was summarized, including all the AM processes with both continuous and discontinuous fibre reinforcements. Improvements were observed compared with pure plastic printed parts. However, the majority of the continuous fibre printing data were obtained by various users of the commercial Markforged printer with the associated limitations in terms of material and process. Investigations have been conducted on the performance of 3D printed continuous fibre reinforced nylon parts produced by the Markforged printer using the Markforged supplied prepregs alone [160, 29, 109, 44, 67, 80, 1, 11, 14, 36, 35, 127, 130, 46, 107, 113, 32, 108, 165, 17, 124, 118, 176, 61, 114, 52, 4]. By changing the number of fibre layers, fibre types and the infill patterns, different mechanical properties were obtained. Some recent research using other materials and processes, as mentioned above, was not included in the previous reviews.

The tensile properties are chosen to be discussed in this review to represent the current mechanical performance of the CF-3DP composites. The tensile strengths and tensile moduli of 3D printed continuous fibre reinforced composites in the fibre direction are summarized in Fig. 13. The carbon fibre reinforced feedstock materials are labelled using triangular symbols; glass fibre reinforced feedstock materials are labelled using circular symbols; squared symbols are used to label other reinforcement feedstock materials and other not 3D printing materials. Data points of in-nozzle impregnation method are shown in colour blue; data points of using prepreg as feedstock materials are shown in colour yellow; data points of other apparatus are shown in colour green; conventional composite materials are shown in colour grey. The type of reinforcements and feedstock materials, fibre volume content and processes are different in each research, which influences the mechanical properties of the printed parts.

As expected, the 3D printed parts with carbon fibre reinforcement mostly yield higher tensile properties than those with glass and aramid fibres. However, the data for 3D printed carbon fibre composites covers a wide range of values, from 147MPa [172] to 1400MPa [171] for tensile strength and from 4GPa [172] to 160GPa [51] for tensile modulus. Besides the difference in matrix materials, different printing processes and different fibre volume fractions can result in diverse mechanical properties. All the results from in-nozzle impregnation processes appear at the lower left hand corner where tensile strength and modulus are lower than 250MPa and 20GPa respectively. The data where prepreg feedstock materials were used show better performance than those of in-nozzle impregnation process. The highest tensile modulus (161GPa) was obtained in Hao et al.'s research [51], where carbon fibre and thermosetting resin were used. The highest tensile strength (1400MPa) was found in Yamawaki et al.'s study [171] where a conventional thermoplastic prepreg material was used and the printed samples were post-processed using a hot-press. When comparing the tensile strength and modulus of the continuous fibre 3D printed composites (the yellow region) with the conventional composites manufactured using unidirectional prepreg tape materials processed in a hot-press or cured in an autoclave (the blue region), they are mostly less than half depending on the type of reinforcements. Meanwhile, some of the values are comparable with the typical aluminium and titanium alloys the red region, which are considered to be the competitors as they are commonly used in aerospace applications.

Since fibres are the main component for load bearing, fibre volume fraction has a significant influence on the composites' mechanical properties. Higher fibre volume content is preferable for conventional composite materials and a fibre volume content can commonly reach 50-60% for high performance applications. However, such high fibre content in AM composite material is not common due to process limitations and the relatively early stage of development of composite materials for 3DP. The tensile strength of current 3D printed continuous fibre reinforced composites is plotted against the fibre volume content in Fig. 14. The rule of mixtures might not be clearly observed here due to the various processes and process parameters used, however, it can be seen that the tensile strengths of 3D printed parts with higher fibre contents are generally higher than those for lower fibre contents. In most studies, fibre volume contents were below 50%, the exceptions being those which used conventional prepregs or commingled fibres as the feedstock materials. The fibre volume fractions of the composite specimens printed by the in-nozzle impregnation process are generally very low (below 10%). An estimate of the upper limit of fibre volume fraction in this in-nozzle impregnation ME 3DP has been proposed to be 40-50% [105], because, with a higher fibre volume fraction, fully impregnating the fibre tow and extruding fibres through the printer nozzle becomes difficult. However, by using conventional prepreg materials or commingled fibres, fibre volume contents of 50% or higher have been achieved in some of the studies [171, 38]. But the tensile strength of those 3D printed composites with relatively high fibre volume fraction is still lower than those of conventional composite materials (the blue region).

Insufficient impregnation of fibres, high void content and uneven fibre distribution have been observed in many CF-3D printed specimens [21, 154, 8, 161, 58, 171, 159, 147, 38, 105]. Lack of compaction force during the printing process can be one of the reasons for such defects occurring in the printed parts, resulting in low tensile properties. In He et al's study [52], the specimens produced using the Markforged printer were compression moulded before being tested. The 0° tensile strength, 90° tensile strength, flexural strength and the Mode I interlaminar fracture toughness were improved

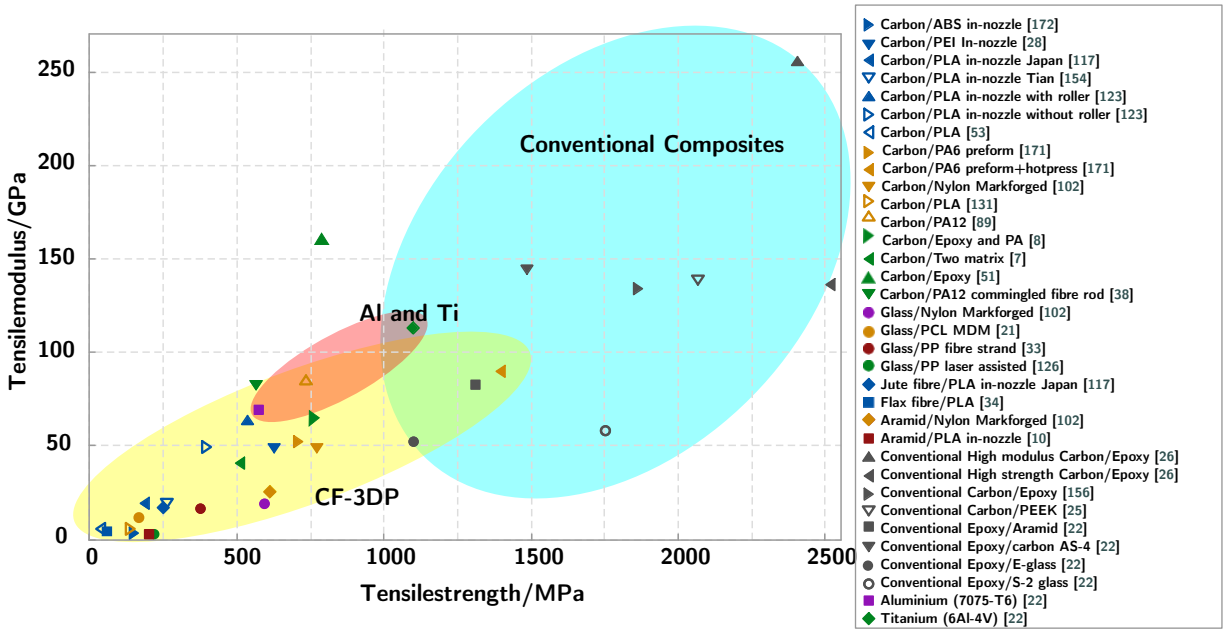


Figure 13: Tensile strength and tensile modulus of 3D printed continuous fibre reinforced composites.

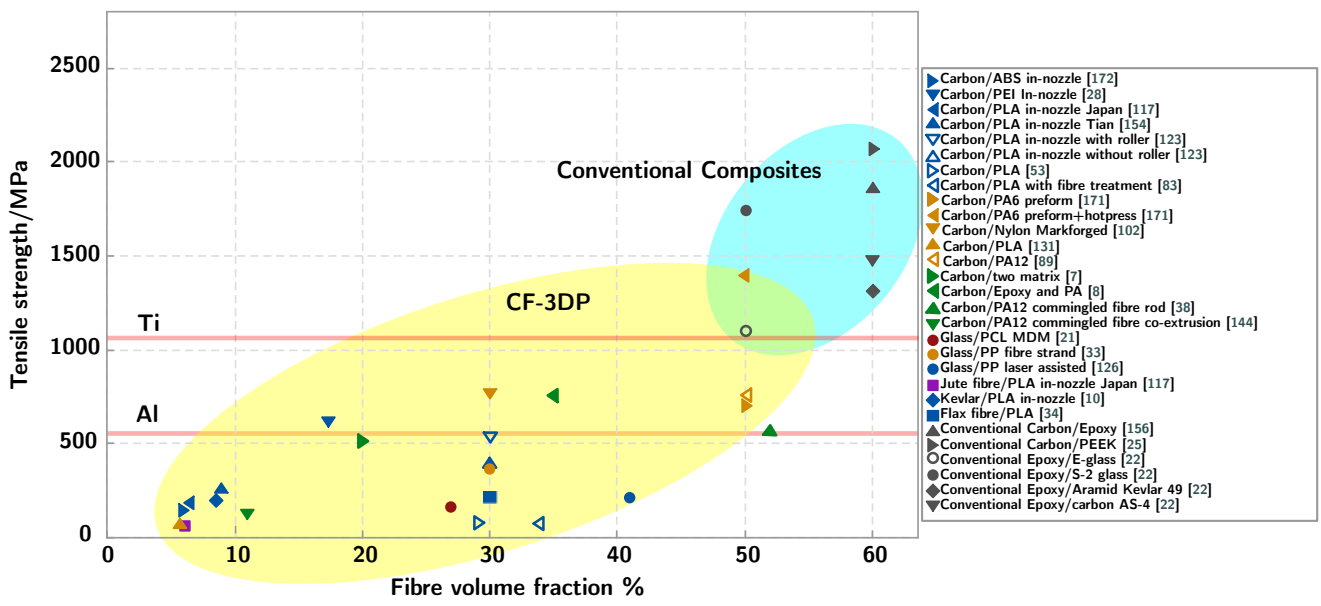


Figure 14: Tensile strength and fibre volume fraction of 3D printed continuous fibre reinforced composites.

by 22%, 78%, 93% and 90% respectively. It was claimed that the improvement was caused by the reduce of void content from 12% to 5%, and thickness reduced 15% after compression moulding. A compaction roller was utilized in the printing of continuous fibre was printing in Omuro et al.'s study [123], and a 30% improvement in tensile strength and modulus was found compared to specimens printed without the use of the compaction roller. Post-processing was performed using a hot press to compress the 3D printed 3 point bending specimens. The flexural strength after post-processing improved by a factor of three and the modulus was doubled via the post-processing. Similarly, post-processing was also performed using a hot press in Yamawaki et al.'s study [171]. The result showed doubling of the tensile strength from 700MPa to 1400MPa. In these two studies, the specimens thickness had a substantial reduce (nearly 50%) due to matrix leakage, and voids contents were also largely reduced, which could be the reason for such big improvement in mechanical properties. O'Connor and Dowling[122] produced the continuous fibre specimens in a $1Pa$ chamber, and the void content reduced from 6.8% to 1.1%. Considering failure modes, fibre pull-out was commonly observed in the fracture surface of failure specimens [117, 154, 10, 126, 58], which indicates poor wetting of the thermoplastic matrix on

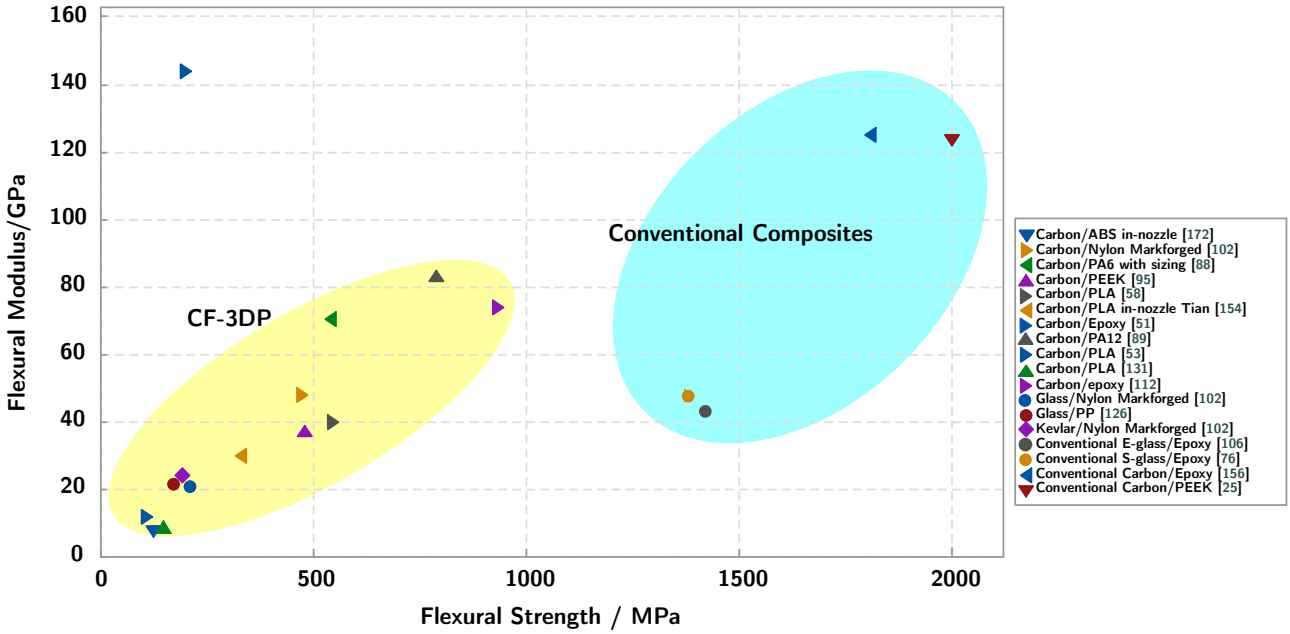


Figure 15: Flexural strength and modulus of 3D printed continuous fibre reinforced composites.

the fibres. By contrast, the dominant failure mode of fibre breakage at the fracture surface was found in the study which used thermoset resin as the matrix material [51]. This failure mode suggests strong bonding between the fibres and the matrix, and it is not commonly reported in literature in which thermoplastic matrix is used. This indicates that it is still challenging to achieve full fibre impregnation and strong fibre/matrix bonding when printing with thermoplastic matrix in CF-3DP.

The defects discussed above would be expected to have a higher impact on the composite matrix properties than the properties in the direction of the continuous fibres, and hence, would be most usefully investigated by measurement of the transverse properties of the composite. However, in most studies of continuous fibre 3D printed composites, only the tensile properties in the fibre direction are reported. In Bettini et al.'s study, a 90° tensile test was performed on the aramid fibre reinforced PLA specimens [10]. The tensile modulus in the transverse direction was 1530MPa, which was only half of that seen in pure plastic PLA specimens. It was suggested that the decrease in tensile modulus was caused by the observable voids and poor adhesion between aramid fibres and PLA. Justo et al. investigated the 90° tensile properties of the glass fibre reinforced nylon samples manufactured by the Markforged printer [67]. The tensile strength and modulus were $9.84MPa$ and $1.13GPa$, which were only 30% and 12%, respectively, of the values attained in conventional E-glass/epoxy composites (65% fibre volume content). In Iragi et al.'s study [61], transverse tensile strength and modulus of the carbon fibre reinforced PA6 specimens produced by the MarkTwo printer, which were $17.9MPa$ and $3.5GPa$. The tensile strength was less than half of injection moulding PA6. A high void content (17%), lower fibre volume fraction (15% lower) and lack of compaction during printing process were indicated to be the reasons for the low values. It is obvious from the limited studies to date that transverse property measurement is highly useful at highlighting defects in CF-3DP and it is to be hoped that such testing is seen more in future if the challenges in improving the process to minimise such defects is to be seriously addressed. It is also to be expected that such defects would have some effect on the flexural properties of the CF-3DP composites, and these are compared with conventional manufactured composites in Fig. 15. The flexural properties of the 3D printed composites were much lower in both strength and modulus. A much bigger different can be seen in the flexural properties than the tensile properties. Delamination and de-bonding between fibre and matrix were observed in the failed specimens [154, 88, 172, 58, 95]. This result shows a very poor mechanical performance of the CF-3DP composites in the matrix sensitive properties. The difficulties of CF-3DP lay in how to improve bonding between fibre and thermoplastic matrix and between layers. For example, a proper fibre sizing is required for the fibre and the thermoplastic matrix to be bonded, and introducing compressive force during printing would be beneficial for improving layers bonding. There is still a big mountain to climb for the CF-3DP composites to reach a comparable level with conventional composites in terms of mechanical performance.

6. New designs and Applications

Significant development has been achieved in composite ME in the last few years, especially for discontinuous fibre or particulate reinforced composites. Instead of toys and prototypes, real functional end use products are being developed

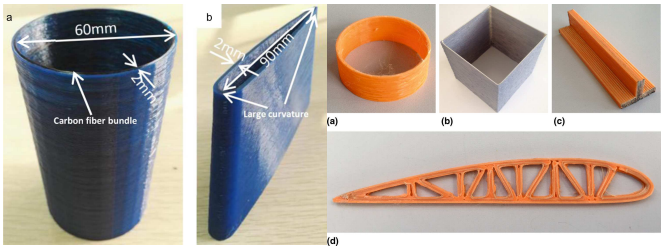


Figure 16: Demonstration parts of CF-3DP [154, 10].

in biomedical [79, 140], electronics [82, 42] and aerospace applications [154, 162, 145]. However, applications of continuous fibre reinforced composites manufactured by ME are rarely seen due to their early stage of development. Currently, no real end use product has been reported as being produced by the technology. A few parts with simple aerofoil geometry have been produced to demonstrate the capability of the technology [154, 10], as shown in Fig. 16. Aerofoil shaped parts such as ribs and wings are often used to demonstrate the continuous fibre printing technology, probably for the reason that conventional fibre reinforced composite materials are widely found in aerospace applications. However, in these demonstration cases especially for wings, fibres are all in the aerofoil section plane, and there is no fibre in the wing span direction. In real life situations, however, the main load a wing structure has to bear is bending moment caused by lift. The bottom surface of the wing is under tension while the upper surface is under compression. Since composite materials are much stronger in the fibre direction, therefore, fibres should be placed along the wing span direction for any meaningful application instead of in the transverse plane of the aerofoil section. Continuous fibre printing technology has been used in manufacturing Unmanned Aerial Vehicles (UAV) frame [145]. A hexacopter was produced to demonstrate the manufacturing capability. A small size Unmanned Aerial Vehicle composite frame structure was produced using the two-matrix (thermoset and thermoplastic) continuous fibre 3D printing process [7], as shown in Fig. 17. Anisoprint company produced a continuous fibre 3D printed aircraft seat support, which achieved a 40% weight reduction compared to the conventional aluminium one [3].

A bicycle lug was successfully produced with continuous carbon fibre reinforced nylon material using the Markforged printer in Gerguri et al.'s study [43]. There are several holes in the lug, to which the bicycle frame tubes are connected, as shown in Fig. 19(a). Fibres are placed around the holes on the top and bottom, but they are truncated at the edge of the side holes within the part and some of the holes are left without any circumferential reinforcement, which is similar to the schematic shown in Fig. 1. This design diminishes the load bearing effectiveness of the fibre reinforcement. Fibres should be placed following loads and surfaces. Due to the physical constraint of the printer, fibres can only be placed in the x,y plane not vertically around the

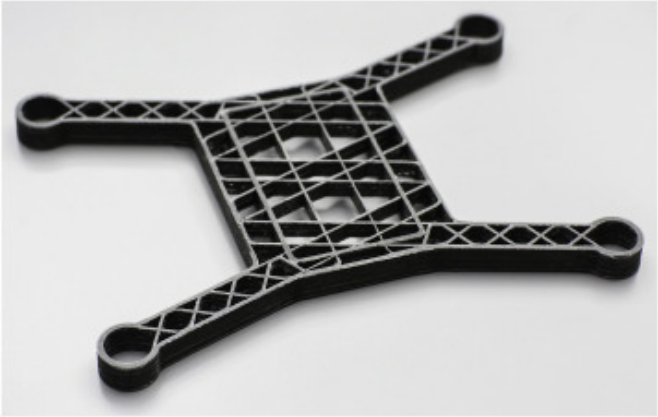
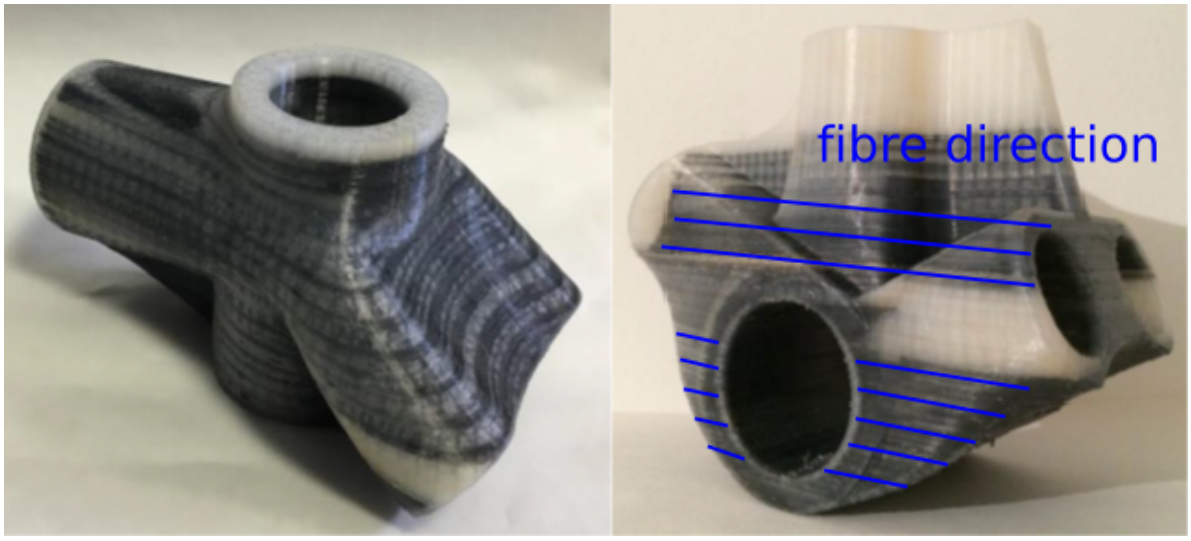


Figure 17: Small size UAV frame manufactured via continuous fibre composite 3D printing [7].

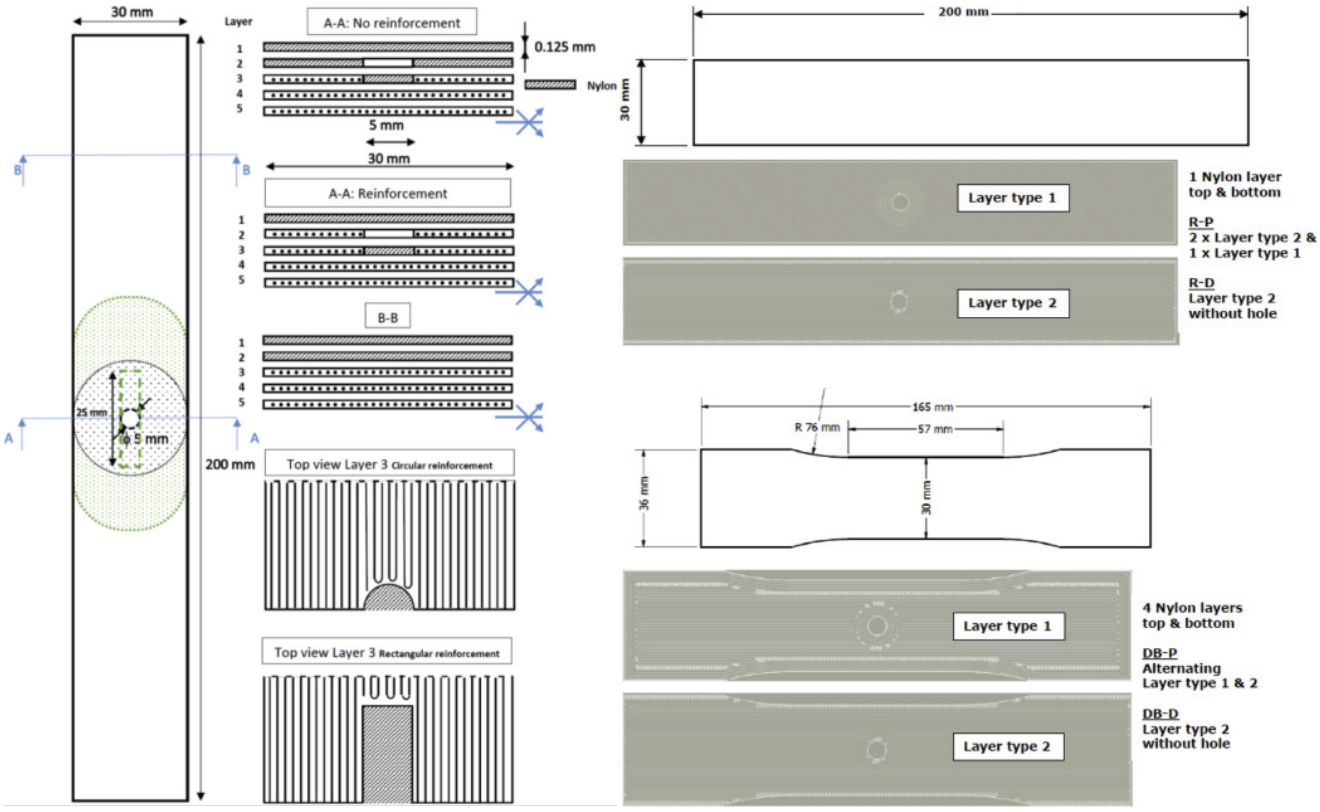
Figure 18: Aircraft seat support printed by Anisoprint company [3].

side holes, and such a design therefore fails to exploit the potential of the reinforcement by placing them to resist the mechanical loads. Similarly, Pyl et al. investigated the 3D printed composites' open-hole tensile properties and compared specimens with printed holes and drilled holes, but the fibres were placed in the conventional way where they were terminated or cut at the hole [129], as shown in Fig. 19(b). The test results showed that the specimens with drilled hole resulted in a higher load capacity than those with printed hole. Fibre breakage was found when the fibre making a U-turn in the specimens with printed hole, which was claimed to be the reason of the reduction of tensile strength. However, it should be pointed out that, although the fibres were continuously laid down, they were turning back at the hole edge, which would not be any better than drilling the fibre at the hole. To address this issue, the continuous fibre printing technology provides an opportunity for fibre steering and part strength tailoring with curvilinear fibres being possible. Part strength can be tailored by changing the local fibre orientation and fibre volume fraction. The greatest challenge in CF-3DP, therefore, lies in placing the fibres to maximize the parts' mechanical properties.

Curvilinear fibre or fibre steering within composites design is not a new concept. Automated processes such as au-



(a)



(b)

Figure 19: (a) Bicycle lug printed by Markforged printer [43]; (b) Schematics of fibre path design of open-hole tensile test specimens with printed holes, where layer type 1 has concentric circles around the hole edge while fibres turned around at the hole edge in layer type 2 [129].

tomated fibre placement (AFP) and automated tape laying (ATL) have been adapted to produce composite structures with curvilinear fibres. These areas of research were focused on improving buckling properties of cylindrical structures such as fuselages and stiffened panel with cut-outs by making use of fibre steering [49, 50, 168, 64, 65, 143, 141, 142, 92]. However, these automated processes have limitations in manufacturing curvilinear fibre structures, such as leaving gaps or overlaps, and following a minimum steering radius [73]. Rakhshbahar and Sinapius [135] proposed using continuous fibre printing technology to fill the gaps left in the AFP process in order to overcome the drawback of mechanical properties reduction. A continuous tow shearing process (CTS) was also developed to ease such limitations

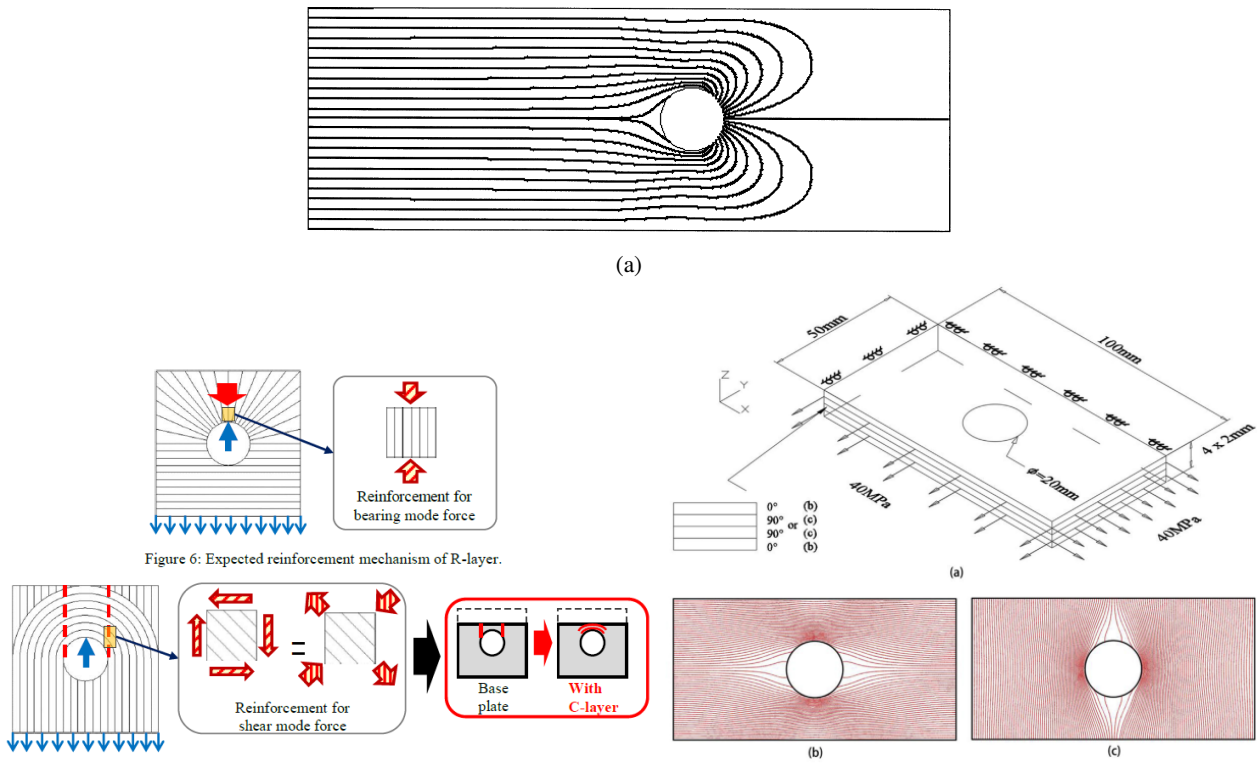
and to improve buckling performance [164, 75, 74].

Other research has focused on how to improve the performance of structures with holes or notches. When conventional laminated construction is used, fibres have to be cut when there are holes and notches in the part concerned. As the fibres are the load carrying component in composites, the strength of the structure is compromised when fibres are cut, in terms of both the elimination of continuous reinforcement and the damage to the composite material due to cutting. In addition, cutting fibres around the hole may cause stress concentrations at the edge due to the high stiffness of the straight fibres, which can lead to premature failure. More importantly, fibres missing could cause resin rich area or voids which would be a weak area for the structure. Therefore, placing the fibres in a structurally appropriate way around the hole or notch can potentially reduce stress concentration at the hole edge, creating an opportunity for optimizing composite structures with holes or notches. In some previous studies [59, 60, 98, 97, 139, 138, 101, 100], researchers suggested that placing fibres along the stress trajectories or principal stress direction could improve mechanical properties. In Kelly et al.'s study [71, 72, 157, 85, 24, 86], a load path design was proposed with the aim of improving open hole tensile strength and pin-load bearing strength, as shown in Fig. 20(a). The bearing load of the pin-load tensile test specimen was improved by replacing the 0° ply with the steered fibre ply. Fujii et al. [41] proposed a design involving radial and circular reinforcements for a bolted joint application, as shown in Fig. 20(b). Straight fibres were aligned radially around the hole to withstand the compressive force, and curvilinear fibres were circumferentially aligned around the hole to withstand the shear and tensile forces. In these studies, the specimens with curvilinear plies were produced by manually laying down the dry fibres on resin films and curing them in an autoclave or manually placing the dry fibres in an RTM mould, then injecting and curing the resin in-situ via the RTM process. Although the composite specimens with the curvilinear plies were manufactured without precise fibre placement, both numerical modelling and experimental testing results indicated that the load capacity of the composite specimens with curvilinear fibre increased compared to specimens with conventional quasi-isotropic layup design.

With the development of CF-3DP technologies, realizing precise fibre placement with such fibre paths becomes possible, and new design concepts have been proposed using this new technology to produce unconventional composite structures. Zhang et al. [179] investigated fibre laying patterns which were designed to be produced by CF-3DP technology. In this study, fibres were suggested to be placed along the principal stress trajectories in an open-hole laminate under three different loading conditions. The stress trajectories were generated through finite element analysis and curvilinear fibres were placed along the first or second stress trajectories in each ply to build up the laminate to resist bi-axial tensile load, as illustrated in Fig. 20(c). The numerical results show that the stress concentration factor is reduced compared to a unidirectional fibre laminate with the same fibre volume fraction. Sugiyama et al. placed fibre along the principal stress direction in a bolt joint specimen, as shown in Fig. 21(a) [148]. In the bolted-joint tensile test, the variable fibre volume fraction specimen with curvilinear fibres resulted in 9.4 and 1.2 times higher stiffness and maximum load respectively compared to the straight fibre design specimen. In Li's study [84], fibre paths were generated according to topological analysis results for the open hole tensile test specimens, 3-point bending test specimens and a suspension plate as shown in Fig. 21(b). Specimens with steered fibre paths were produced and compared with specimens with straight fibre design and drilled hole. The test results showed that the printed specimens with steered fibre paths were 67.5% and 62.4% higher in tensile and flexural strength respectively compared to those with drilled hole.

In Yamanaka et al.'s study [170], fibres were proposed to be placed along the stream lines of perfect flow in an open hole specimen, as shown in Fig. 22(a). A genetic algorithm was used to optimize the parameters in order to achieve improvement in the fracture strength. The simulation results predicted that the fracture strength of an open-hole ply would be higher than unidirectional ply. It was pointed out that this ply of curved fibres without any intersection could potentially be manufactured by the composite 3DP process. Dickson et al. [31, 30, 178] utilized the CF-3DP to produce a woven laminate in which a 6mm diameter hole is created by steering the fibre path, as shown in Fig. 22(b). The steered fibre laminates showed improvement in both open hole tensile strength and pin load bearing strength along $o°$ direction, compared with equivalent specimens in which the hole had been drilled. However, the stiffness of the specimens with steered fibre was lower than that of the drilled specimens in the bearing test. . Another new design concept was proposed by the present team for a composite lug structure, as shown in Fig.22(c) [180]. Fibres were designed to go around the top of the hole where fibres were loaded in tension to sustain the pulling load. In the area under the hole, arch shape supports were designed to resist the pin load under compressive loading. A lug sample with the new design patterns was produced using CF-3DP. Mechanical testing will be perform to validate the new design.

Another area of application for CF-3DP is to produce ultra-light weight sandwich structures. Hou et al. [56] produced a composite sandwich structure with a corrugated core as shown in Fig. 23(a). An ultra-light weight sandwich structure with pyramidal truss core was produced by Eichenhofer et al. using a Continuous Lattice Fabrication(CLF) process [38], as shown in Fig. 23(b). The compressive strength of the sandwich structures in both cases was found to be promising compared to state-of-the-art ultra-low density structures made from various other metallic and ceramic materials. Similarly, a novel free-hanging 3DP method was developed by Liu et al. [87] for manufacturing continuous carbon



(b) (c)

Figure 20: (a) Dominant or X-direction load paths for a pin-loaded plate with anisotropic material properties [157]; (b) Radial and circular reinforcements design for bolted joints [41]; (c)Stress trajectories under biaxial tensile loading [179].

fibre reinforced thermoplastic lattice truss core structures, as shown in Fig. 23(c). Sugiyama et al.[149] investigated the effect of different core shapes on the flexural properties of the sandwich structures. Quan et al. used continuous fibre 3D printing technology to fabricate auxetic honeycomb structures [132], as shown in Fig. 23(d). The in-plane compressive test showed 86.3% and 100% increase in compressive stiffness and energy absorption respectively. 3D printing smart continuous carbon fibre thermoplastic lattice truss sandwich structure was produced in Wang et al.'s study[163] as shown in Fig. 23(e). These novel sandwich structures might out-perform conventional sandwich structures with lower density, but since fibres are not parallel with the loading direction, the strength of the fibres in the core would not be able to be fully utilized.

7. Development outlook

The continuous fibre 3D printing based on the ME process has been developing rapidly. However, most of current work is still based in laboratory environment. The Technology Readiness Levels(TRLs) of CF-3DP is still low due to its early stage of development. Investments are needed in materials, printers, printing process and fibre path design before the technology can grow into its maturity. These challenges are elaborated in the following sections.

7.1. Materials development and mechanical properties improvement

The fibre types commonly used in conventional composite materials can be applied in the CF-3DP technology, while thermoplastic polymers are mostly used as the matrix materials, which represents a relatively underdeveloped area in the field of composite research in general, even for the conventional composite manufacturing. Most of these thermoplastic polymers employed so far have relatively low or moderate melting points, which make them easy to process but leads to relatively low performances. Those polymers with high melting points such as PEEK, PEI, PPS, etc. normally come with a better mechanical properties but are more difficult to process. At the current stage, the Markforged materials are mostly found as the commercial continuous fibre feedstock materials for ME process in the literature. They have a limited choices for matrix materials (PA6 and short fibre reinforced PA6 only) which is of relatively low performance and even further undermined by their low fibre volume fractions. They are designated to the use with the Markforged printers and hence not available for general applications. Most of the studies in the literature employed self-developed feedstock materials, which suffer from a low fibre content and poor fibre impregnation. A melt-impregnating process for continuous fibre reinforcements has been used in the majority of available studies, and the melted thermoplastics usually have a very high viscosity which makes the

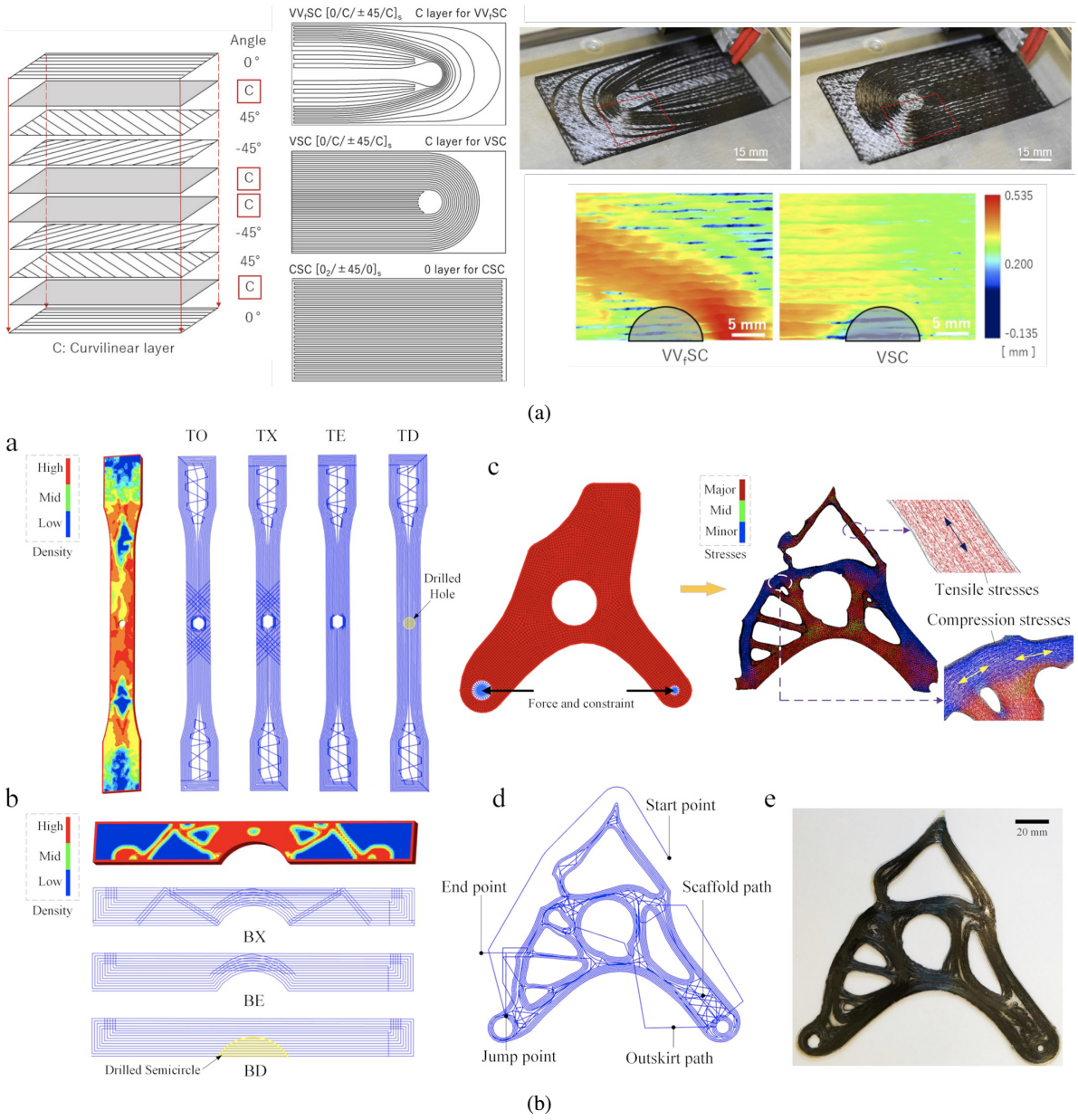


Figure 21: (a) 3D printing of optimized composites with variable fibre volume fraction and stiffness using continuous fibre [148]; (b) Topological calculation and printing path design of the testing specimens and the suspension plate [84].

fibres impregnation very difficult. Poor wetting of fibres and high void content were commonly found in the literature.

As a small minority or the work found in the literature, epoxy was reported as being used as the thermoset matrix material in the CF-3DP in a few studies [136, 7, 51, 8, 174]. However, thermoset matrix requires an extra curing process. It might be easier for the fibres impregnation, but moulding would be required, especially if an autoclave is involved for the curing process. If an oven is used instead as an out-of-autoclave process, it is well-known that it is difficult to control the defects even in conventional process of composites [5], let alone the newly developed CF-3DP.

As can be seen in the summary of the mechanical properties of continuous fibre 3D printed composites in the most recent studies in Section 5 of this review, the mechanical properties are usually too poor to be considered as suitable replacement for traditionally processed continuous fibre composites, despite improvements compared to printed pure plastics or short fibre reinforced plastics. The low mechanical properties of AM products have always been a major barrier to their applicability in load bearing parts. Adding continuous fibre reinforcement is expected to improve mechanical properties but a lot are yet to be done before the potential can be realised. Fibre volume fraction needs to be sufficiently high and defect to be sufficiently low before the printed products can be used in real engineering structures. For example,

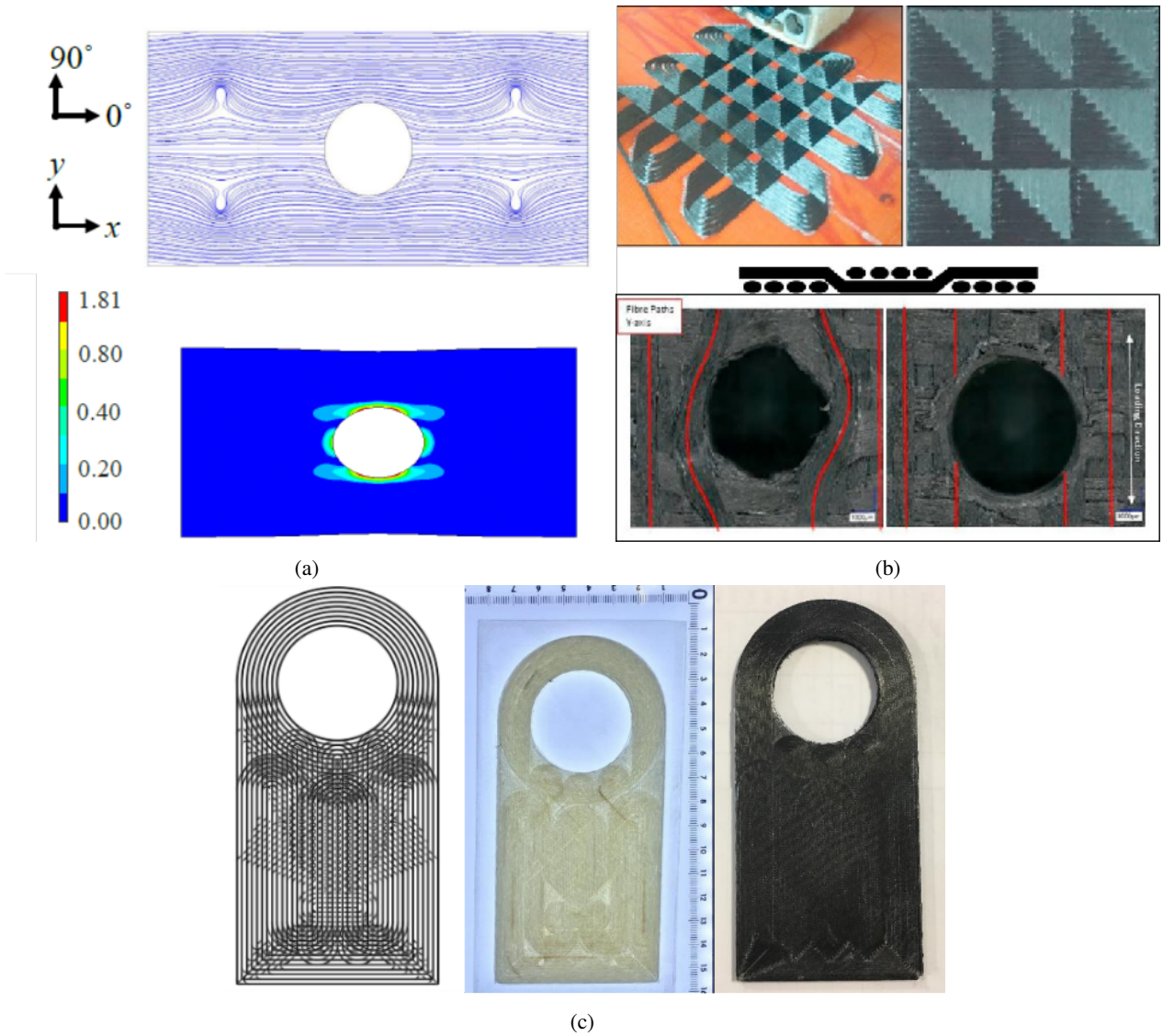


Figure 22: (a) Fibre line optimization in a single ply [170]; (b) Carbon fibre laminate produced through tailored fibre placement and fibre path around the 6mm hole comparing with fibre path in straight woven sections (red lines indicate fibre path and placement) [31]; (c) Continuous fibre 3D printed lug conceptual design and printed lug samples [180].

for aerospace applications, fibre volume content for unidirectional plies should be higher than 58% and void content should be lower than 1% [6].

7.2. Printing process development

The conventional desktop plastic ME printers are conventionally used for printing non-load carrying models and prototypes. Thus, the surface quality is more important than the inner quality. However, it is the opposite for CF-3DP parts because the main reason for having fibre reinforcement is to sustain loads and to serve as structural components. Therefore, the print quality inside the printed parts is crucial, but current desktop printers are not yet up to the state for industrial production. The process parameters, such as printing temperature, speed, compaction, environment temperature, etc., need to be accurately monitored and controlled in order to achieve high product quality, and yet the current specifications of desktop ME/FFF printers are far from meeting these requirements.

Besides the defects from the feedstock materials themselves, more can be induced during the printing process. Cavities and poor bonding between layers were reported in several studies. Lack of compaction during the continuous fibre printing process could be one of the reasons causing these defects. Adding a compaction system developed in some of the studies [123, 135] or having a post-processing process, e.g. using a hot-press [171] showed improvement in the quality and mechanical performance of the part. However, having a post-process like hot-press requires moulds, which eliminates the advantages of AM. Improvement of the print quality and better understanding of the mechanism of the continuous fibre printing process are required. Many publi-

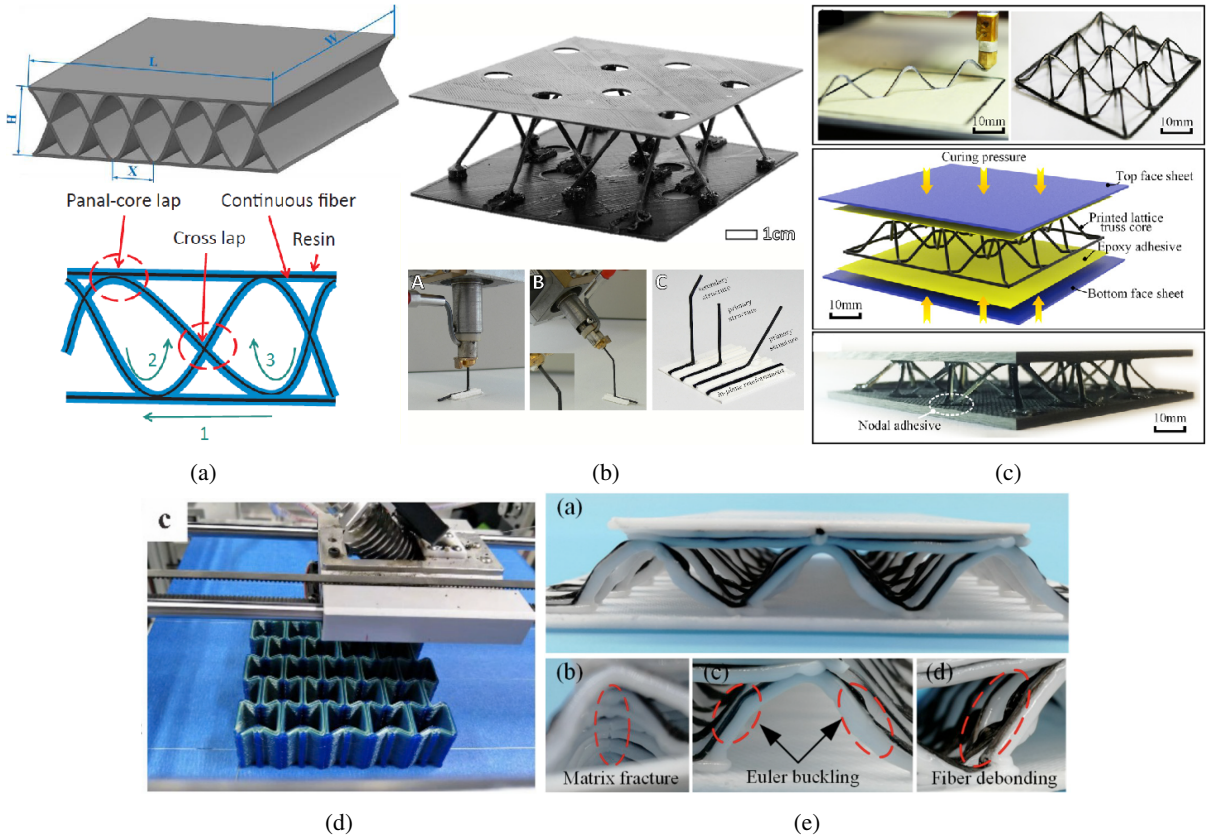


Figure 23: (a) Corrugated core sandwich structure [56]; (b) An ultra-light weight sandwich structure with pyramidal truss core [38]; (c) Continuous carbon fibre reinforced thermoplastic lattice truss core structures [87]; (d) 3d printed continuous fibre reinforced composite auxetic honeycomb structures [132]; (e) 3D printing smart continuous carbon fibre thermoplastic lattice truss sandwich structure [163].

cations in the literature can be found simulating the printing process of pure plastic and short fibre reinforced plastic materials, as reviewed by Brenken et al. [12], but very limited amount of similar studies are available on the 3D printing of continuous fibre [66, 173]. There are some similarities in short and continuous fibre printing process, such as melt plastic flow, bonding, residual stresses, etc., but significant differences are expected in other respects such as fibre shearing during printing, fibre deformation [62, 104], etc. Appropriate studies need to be carried out to better understand the process so that the process parameters can be optimized in order to achieve acceptable printing quality for purpose-driven applications.

On the other hand, the conventional software for CF-3DP, i.e. the plastic ME slicing, is not suitable for continuous fibre composites since it does not consider the anisotropy of the fibres [137]. The software for commercial printers allows the users to change the fibre fill type in each layer [102], but the limited fibre options restrict fully utilizing the strength of the fibre reinforcement. Other researchers have developed their own facilities by adapting commercially available open-source printers or by utilizing robotic arms for continuous fibre printing as discussed in Section 3 and 4. The studies using the open-source ME printers to produce printed parts were controlling the printers by writing their own G-codes [144, 145, 7, 2, 83, 171, 31, 30, 180, 87, 149]. This process can be labour intensive and time consuming as each customized structural part has different loading conditions and each layer could have different fibre paths. An automated layer slicing software needs to be developed, especially for CF-3DP. This does not only require a software developer for software development but also composite designers for stress analysis of the structural parts and fibre paths design according to the specific loading condition and part geometry.

7.3. Fibre path design, modelling and optimization

New designs for composite materials via CF-3DP have been proposed as discussed in Section 6. Researchers are exploring the advantage of the new technology to overcome the limitations of conventional composite materials, which show good mechanical performances but are difficult to form complex geometries. On the other hand, the current AM technology is able to achieve high geometric complexity, but its performance is unsatisfactory. Achieve both advantages would be the goal for CF-3DP. This will involve optimization for the topology, external dimension and internal fibre paths [20]. However, to facilitate the new design is the key

challenge for the new technology.

CF-3DP creates an opportunity to increase the capability of composite materials by expanding the design envelope. However, conventional design rules might not be sufficient to sustain such development because available means of analysis, such as the Classical Laminate Theory(CLT), are mostly applicable to composites of piece-wise homogeneity. CF-3DP provides an opportunity for fibre steering and part strength tailoring with curvilinear fibres paths. Along such a fibre path, the material can no longer be considered homogeneous in its conventional sense as the principal axes of the material dictated by the fibre orientation could vary from point to point. A more appropriate category for such material is functionally graded materials which are demanding to analyse, let alone to design. CF-3DP creates new opportunities to tailor the performances of the part to be printed but at the same time poses a major challenge to designers and analysts. Design and simulation software needs to be developed for shape topology and fibre path optimization in order to achieve weight reduction as the goal of employing composites in most applications. The existing analysis tools, such as the finite element method (FEM), need to be broadened in order to be better adapted the needs in modelling and simulating the behaviour of such unconventional composite materials and structures, which are highly heterogeneous and anisotropic. Many research aspects are still waiting to be invested and developed in modelling, analysis and optimization before these novel composite structures can find their niche applications.

7.4. Mass production and potential applications

While significant technical achievements have been made in recent years, there is still a long way to go before printed products find their way into engineering applications. A further but crucial potential of CF-3DP for structural applications lies in its mass production capability.

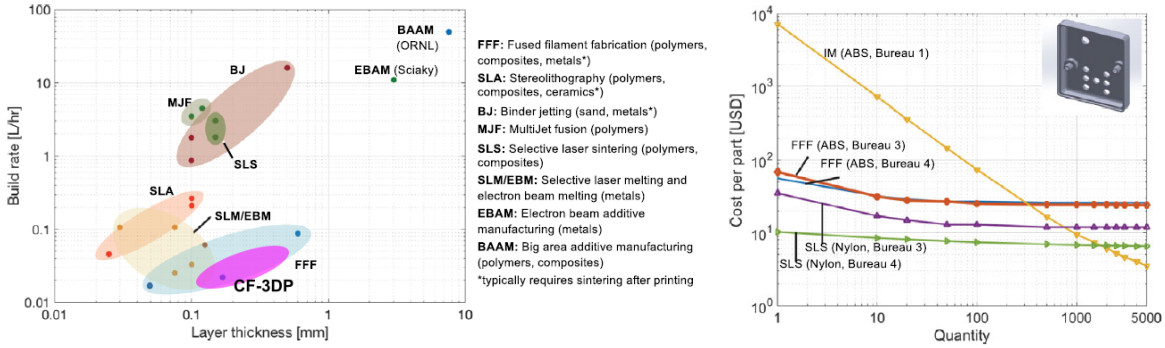
Quinlan et al. [134] compared the build rate and layer thickness of mainstream AM processes, as shown in Fig. 24(a). The processes at the top right corner would have a higher build rate but low resolution, and those at the bottom left corner have a higher print resolution but lower build rate. ME process has a relatively low build rate and moderate print resolution. CF-3DP will fall within the domain of the ME process as the purple region depicted by the present authors. The layer thickness of CF-3DP is between $0.1 \sim 1.0mm$ depending on the tow size of the fibre reinforcement, while the build rate is between $0.01 \sim 0.05L/hr$ depending on the amount of fibres used in each layer. Fig. 24(b) shows the cost versus quantity for an exemplary plastic component, comparing different AM processes and injection moulding (IM). The cost per part of the FFF process is lower compared to that of IM when the quantity is below 200, since AM processes save from the investment in tooling. For CF-3DP, the cost per part versus quantity would follow the similar trend but with higher cost per part value, since the fibre reinforcements are higher cost than the plastics.

With the low build rate and lower cost at small quantity, CF-3DP would be more suitable for low volume but high value applications, such as aerospace and super cars. Fig. 24(c) shows the current and future development of AM in defence, aerospace and automotive industry [18]. CF-3DP could be found viable in some of these niches. For example, with the proper design, continuous fibre 3D printed part could achieve better performance than that of conventional laminated composite materials, realizing weight reduction. Aircraft structures like joints and lugs are commonly made by metal. However, this usually came with significant penalties, such as bolted joint design complexity and additional weight. With CF-3DP manufactured composite parts, if their quality could be assured, such metallic parts could be replaced by composites to achieve substantial weight reduction and eliminating other issues, such as galvanic corrosion. For aircraft of small wing spans, there would be probable reason for printing the complete spar, eliminating the need for such joints, bearing in mind that spars are not simple to manufacture with conventional manufacturing routes, while with CF-3DP they might not introduce much further complication except for increased thickness.

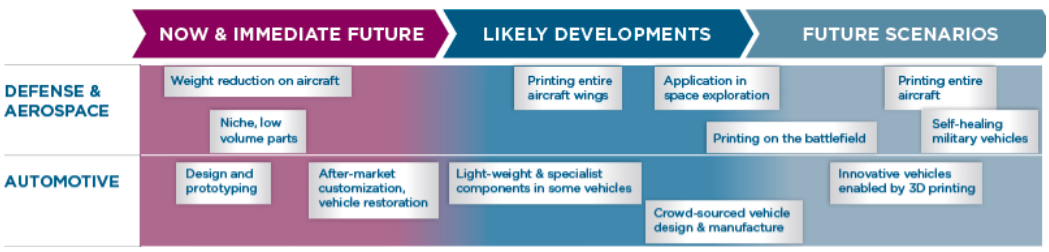
8. Conclusions

The state-of-the-art of CF-3DP based on the ME process has been reviewed. The materials used so far are summarized in Section 2. Carbon and glass fibres are mostly used as the reinforcing material in the printing process, as with conventional composite materials. Both thermoset and thermoplastic polymers have been used as matrix materials, with thermoplastics being more commonly used. The melting temperature of these thermoplastic polymers are relatively low or moderate, which makes them easy to process. However, the high viscosity can mean poor wetting of fibres and voids and the mechanical properties are usually too poor to be considered as suitable replacement for traditionally processed continuous fibre composites.

The printers or devices for continuous fibre printing are discussed in Section 3. There is a commercially available printer in the market and, compared to pure plastic printers, it is able to produce much stronger and stiffer parts but with limitations such as its closed-source nature and materials restrictions. Other researchers have been developing their own facilities by adapting commercially available open-source printers or by utilizing robotic arms for continuous fibre printing. Since the technology is in its early stage of development, the various apparatus have mainly been used to demonstrate the feasibility of continuous fibre printing. In order to achieve the print quality necessary for high load application, full impregnation for the feedstock materials for high volume fractions of fibre is a key objective for future



(a) (b)



(c)

Figure 24: (a) Comparison of build rate and layer thickness (a measure of resolution) of mainstream AM processes, drawn from specifications of industrial equipment [134]; (b) cost versus quantity for an exemplary polymer component, comparing injection moulding (IM), fused filament fabrication (FFF), and selective laser sintering (SLS). ABS = acrylonitrile butadiene styrene; AM = additive manufacturing; L/hr = litres per hour; mm = millimetres; USD = U.S. dollars [134]; (c) AM facts and future development [18].

research. In addition, both the commercial printer and the self-developed printers are not yet satisfied for industrial production. CF-3PD is a newly developed process, and the process mechanisms such as melt plastic flow, bonding, residual stresses, etc. have not yet been fully studied. Research has been carried out on pure plastic and short fibre reinforced plastic ME printing process, but very few studies were found relating to continuous fibre printing. Appropriate studies need to be carried out to understand and improve the process better in order to achieve acceptable print quality for purpose driven applications.

The mechanical properties of continuous fibre 3D printed composites in the most recent studies are summarized in this chapter. Despite improvements compared to pure printed plastic, the performance of current 3D printed continuous fibre reinforced composites is not yet in a position to compete with conventionally processed composites. The low mechanical properties of AM products have always been a major barrier to their load bearing applications. By adding continuous fibre reinforcement, mechanical properties are improved but at a price of increased complexity and cost. Fibre volume fraction needs to be sufficiently high and defect content to be sufficiently low before the printed products can be used in real engineering structures.

Before the newly developed CF-3DP technology can be applied in industry, improvement needs to be achieved in materials, process, properties and design.

- Since fibre steering can be achieved, fibre paths can tailored according to the applied load. Fibre directions need to be designed and optimized in order to improve the structural performance compared to conventional composites.
- Fibre wetting and impregnation need to be improved especially for thermoplastic matrix printing. The current approaches using untreated fibres for thermoplastic matrix would certainly reduce the mechanical performance of the printed composites.
- A compaction process needs to be introduced during the CF-3DP process to achieve better bonding, better fibre distribution and lower void content. In addition to in-situ compaction during printing, high compaction pressure might be required (post-processing) in order to achieve the desirable fibre volume fraction for structural composites.
- The current mechanical properties such as 0° tensile strength and modulus achieved in some of the literature are already higher than long fibre reinforced compound ($290MPa$ for tensile strength and $29.66GPa$ for tensile modulus of long carbon fibre reinforced PA6 compound with 40% fibre volume fraction [106]), but they are still much lower than UD tapes prepreg materials manufactured by conventional process ($1900MPa$

and $100GPa$ for 0° tensile strength and modulus respectively of carbon/PA6 with 48% fibre volume fraction [155]). The CF-3DP composites should achieve even higher fibre volume fraction (60%) and reach even higher properties ($2000MPa$ and $120GPa$ respectively for 0° tensile strength and modulus) in order to be used as aircraft structural components.

- In addition, the process needs to be carefully monitored and controlled to eliminate process induced defects such as gaps, overlaps, and fibre twisting etc. in the printed parts in order to meet the industrial manufacturing requirements.

While significant technical achievements have been made in recent years, there is still a long way to go before end-use printed products find their way into industrial applications. Many research aspects are still waiting to be invested and developed, for instance, using stronger polymers, such as PEEK, which are more suitable for aerospace applications but come with higher processing temperatures, and associated processing difficulties. CF-3DP creates an opportunity to increase the capability of composite materials by expanding the design envelope. However, conventional design rules might not be sufficient for designing the composites with steered fibre paths cause fibre direction could be changing at each location. It could create massive amount of design variables that would raise major challenges to designers and analysts. One common design idea currently is that fibres should be placed along the load paths, in the meantime removing material which dose not contribute much. In addition, design and simulation software needs to be developed for shape topology and fibre path optimization. The existing analysis tools, such as the finite element method (FEM), need to be better adapted in order to face the challenges of modelling and simulating the behaviour of such unconventional composite materials and structures, which are highly heterogeneous and anisotropic.

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