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REVIEW ARTICLE

Recent Patents in Additive Manufacturing of Continuous Fiber Reinforced Composites

Chao Hu, Zeyu Sun, Yi Xiao and Qinghua Qin*

Research School of Engineering, College of Engineering and Computer Science, Australian National University, Canberra, ACT 2601, Australia

Abstract: ***Background***: Additive Manufacturing (AM) enables the accurate fabrication of designed parts in a short time without the need for specific molds and tools. Although polymers are the most widely used raw materials for AM, the products printed by them are inherently weak, unable to sustain large tension or bending stresses. A need for the manufacturing of fiber reinforced composites, especially continuous fiber as reinforcement, has attracted great attention in recent years

Objective: Identifying the progress of the AM of continuous carbon fiber reinforced composites over time and therefore establishing a foundation on which current research can be based

Methods: Elaborating the most related patents regarding the AM techniques for fabricating continuous fiber reinforced composites in the top three institutions, including Markforged company, Xi'an Jiaotong University and President and Fellows of Harvard College.

Results: The recent patents in AM of continuous fiber reinforced composites are classified into two aspects: patents related to novel technique methods and patents related to novel structures. The current issues and future development of AM-based composites are given.

Conclusion: New structures and techniques have been introduced into conventional 3D printers to enable the printing of continuous fiber reinforced composites. However, until now, Markforged is the only company commercializing the fabrication of this kind of composites based on AM technique. Numerous challenges and issues need to be solved so that AM of continuous fiber reinforced composites can be a new manufacturing method.

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1. INTRODUCTION

Additive manufacturing, also known as Rapid Prototyping (RP), Solid-Freeform (SFF) or 3D printing, is a process where complex parts can be fabricated by adding materials, layer by layer from three-dimensional (3D) models, opposite to conventional subtractive manufacturing methods [1]. It starts with a meshed 3D computer model that can be developed by using Computer-Aided Design (CAD) softwares (e.g. Solidworks) and converted into a standard AM file format such as Surface Tessellation Language (STL) file or Material Template Library (MTL) file. The file with sliced 2D layers is then sent to the AM machine for further manipulation, such as setting the infill density and pattern, altering the position and scaling the part, so as to fulfill the product printing [2]. Based on the ISO/ASTM standard, AM processes can be classified into following types: binder jetting, material jetting, material extrusion, directed energy deposition, sheet lamination and vat photopolymerization [3]. First proposed by Hull in 1986, this technique has received wide attention and research, and is expected to revolutionize the contemporary manufacturing modes of objects [4].

As a promising technology, the product fabricated via AM has numerous distinct advantages. Compared to conventional manufacturing techniques (e.g. machining and stamping) that need to remove materials from the block of raw materials, AM can make the most use of raw materials to create the final product with desired geometric accuracy by simply adding materials without waste [5]. The designed product can be directly fabricated from the computerized 3D model without the use of other tools (e.g. jigs, fixtures, cutting units, etc.). Parts with intricate internal structures which are normally hard or impossible to be prepared by conventional methods can also be fabricated by 3D printing technique. It, to a certain extent, promotes the product design innovation by eliminating the extra consideration of manufacturing and assembly (DFM/DFA) principles [6]. Besides,

*Address correspondence to this author at the Research School of Engineering, College of Engineering and Computer Science, Australian National University, Canberra, ACT 2601, Australia; Tel: +61 2 6125 8274; E-mail: qinghua.qin@anu.edu.au

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the lean production with less waste and more complex geometries endows AM technique with the capability of designing and manufacturing environmental friendly products. Moreover, with the topological optimization of structural design, exotic functionalities can be inputted into the printed parts such as negative Poisson's ratios existing in auxetic structures [7]. Meanwhile, the consumption of energy and natural resources is able to be minimalized during the AM operation [8].

Currently, the materials employed in 3D printing are largely focused on thermoplastics (e.g. Polylactic Acid (PLA), polyamide (PA) and polypropylene (PP)) and thermosetting (e.g. epoxy) [9-11]. The former is suitable for the heat-assisted printing process since they can be repeatedly melted and cooled down into the designed geometries, while the later normally requires UV-assisted curing to increase the viscosity to complete the solidification process from liquid state [12, 13]. Combined with the specific selection of these materials, AM processes have been involved into various applications, such as construction industry for structure support, aerospace industry for complex lightweight parts, art and education industries for prototype demonstration, and biomedical industry for tissue and organ repairs [14-17]. However, it is challenging to most of these pure polymer-based products fabricated by 3D printing for high-performance engineering applications due to their low strength and stiffness. These drawbacks, to a large extent, hamper the manufacturing of fully functional and load bearing components by 3D printing. Thus, the development of composite materials by AM technique for better mechanical properties has been increasingly advanced in recent years [18].

As the materials of the future, composites consist of two or more constituents with significantly different mechanical, physical or chemical properties. By integrating these distinctive characteristics, these materials exhibit remarkable overall performance with respect to their individual components [19-26]. Apart from the above-mentioned polymers as matrices, reinforcers used in composite 3D printing are usually discontinuous fillers, such as nanoparticles, carbon nanotubes, carbon black, reinforcing platelets, graphene and short fibers [27]. Up to now, most studies on 3D printed composites centered on short fibers as reinforcements for these materials by virtue of their better mechanical performance compared to other discontinuous fillers [28-30]. Nevertheless, a big gap in mechanical properties still exists between additively manufactured composites and fiber reinforced composites fabricated by conventional manufacturing methods, in which continuous fibers are mainly adopted [31]. For instance, the tensile strengths of conventionally manufactured fiber reinforced composites can reach up to 1500MPa while those of additively manufactured ones are merely around 70MPa [32, 33]. Therefore, to enhance the mechanical performance, 3D printing of Continuous Fiber-Reinforced Composites (CFRC) becomes a must for the development of AM composite materials.

Due to the difficulty of adding continuous fibers to polymer matrix, 3D printing of composites with continuous fiber reinforcement is currently the biggest challenge. Only a few researches are reported in the last five years, leading to a lack of robust and standard paradigm developed for 3D printing of CFRC [34-36]. Until now, only two AM techniques have the capacity for the printing of CFRC: Stereolithography (SL) and Fused Deposition Modelling (FDM) [37, 38]. Of both, FDM is more promising in additively manufacturing CFRC compared to SL since it not only has a technologically simpler configuration with more flexible printing capacities via a slight modification of extrusion nozzles but employs more durable feedstock materials with less susceptibility to degrade [31]. In general, the fabrication of CFRC via FDM technique can be realized by two approaches: *in situ* fusion and pre-impregnated fiber extrusion [39-41]. For *in situ* fusion, the reinforced fiber will be fused with the melted thermoplastic polymer when they are simultaneously delivered to the extruding nozzle. Based on this approach, hierarchical composites with graded parts can be printed via altering the extruded amount of thermoplastics to achieve the change of fiber volume content. However, poor interfacial bonding between fiber and polymer matrix is still a big issue existing in this method. Although functionally graded CFRC is difficult to be printed in pre-impregnated fiber extrusion, it can provide strong adhesion between fiber-matrix interfaces. It is attributed to the initial fabrication of pre-impregnated fibers, which can be finely regulated and controlled [27].

As an infant field, the 3D printing of CFRC will usher in a bright future in smart manufacturing of complex composites with continuous fiber reinforcement since it can solve many issues in conventional manufacturing (e.g. hand lay-up and resin transfer molding) of CFRC, such as high cost, limited design of fiber pattern geometries and lack of manufacturing reliability and repeatability [42-44]. In this review, the recent patents in 3D printing of CRFC will be discussed and analysed by embracing three most influential institutions in this area: Mark forged company, Xi'an Jiao Tong University, and Resident and Fellow of Harvard College. These patents invented by above institutions can be divided into two categories: patents protecting the ideas related to structure innovation in 3D printing and patents protecting the ideas related to 3D printing method innovation. The common goal is to effectively produce CFRC by AM technique at a high rate of speed with decreasing hazards.

2. MARKFORGED COMPANY

Markforged Company has the most patents in 3D printing of CFRC based on their numerous innovation plans. Some of the innovation lies in printing techniques while others lie in the invention of the mechanical structure itself.

2.1. Patents Related to Novel Technique Methods

In one technique innovation plan, a void-less reinforced filament is introduced into the nozzle of a conduit, which is shown in Figs. (**1** & **2**) [45]. The reinforced filament consists of a core and the host material surrounding the core [46, 47]. The core can be either continuous or semi-continuous. Before inserting the filament into the nozzle of the conduit, the reinforced filament is heated up to a temperature that is higher than the melting temperature of the host material and lower than the melting temperature of the core [48, 49].

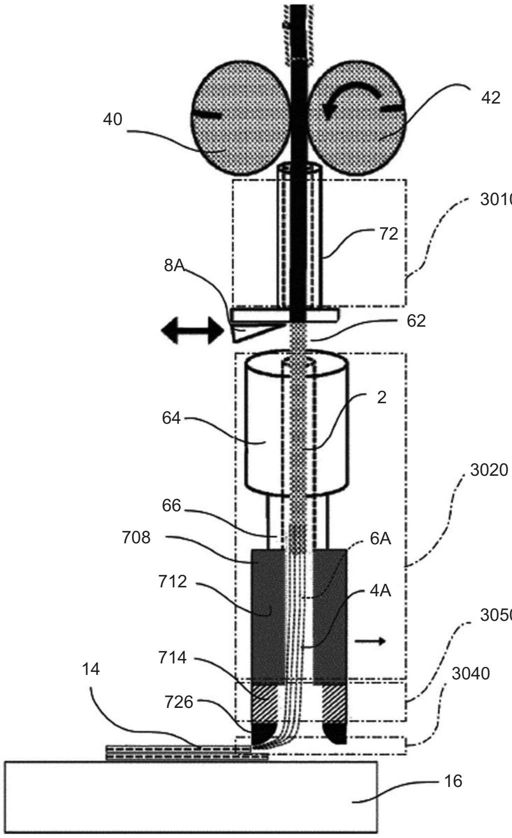

Fig. (1). A design drawing graph for the 3D printer [45].

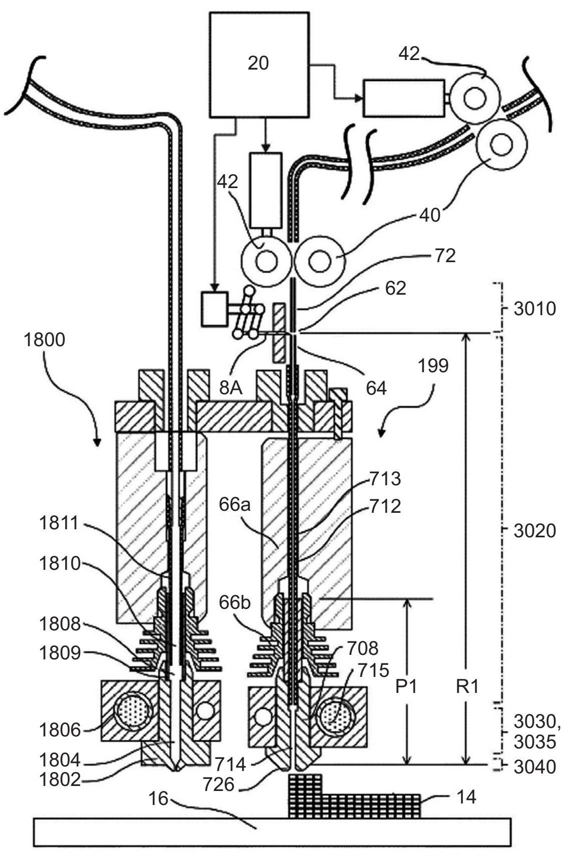

Fig. (2). A plane design drawing for the 3D printer [45].

Another patented printing technique innovation initiated by Mark forged Company is related to the 3D printer for composite fabrication. As can be seen in Fig. (**3**), a 3D composite printer receives tool paths that define the filling shell, as well as tool paths that define the supporting shell [50, 51]. It also receives 3D tool paths that define the bending shell made of long fiber reinforced composite materials. The deposition head tracks the tool paths to, at least partially, deposit some filling shell or supporting shell in a position that is unparalleled to the printing substrate [52, 53]. The long fiber deposition head tracks 3D tool paths in a position that is at least partially unparalleled to the printing substrate so as to deposit long fiber composites, which has been presented in Fig. (**4**). Shells with bending, concave, annular, tubular or winding shapes are used to enclose the filling shell or the supporting shell or at least part of it [45, 54].

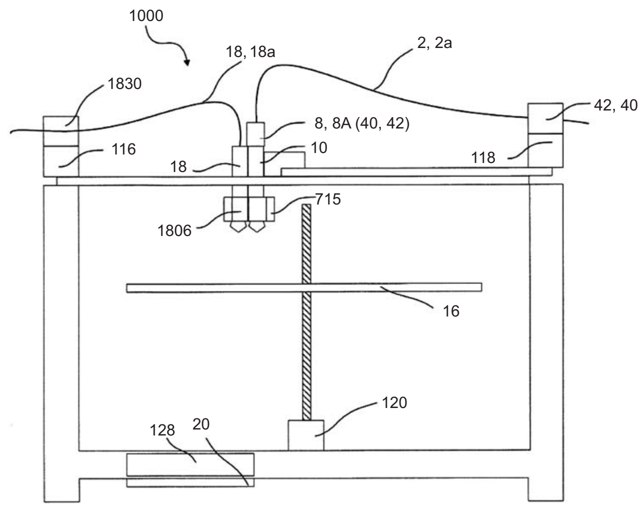

Fig. (3). A plane design drawing for multiaxis fiber reinforcement for 3D printing [50].

One more patented printing technique innovation created by Mark forged Company involves the supply of reinforced multi-core structure filaments including flowable matrix and near-continuous reinforced strands. The strands extend parallel to the direction of the length of the filament during the production of reinforced materials [55, 56]. First, a consolidated composite material whose height is less than half of the filament width deposits in the first reinforced structure. This first reinforced structure consists of at least one straight path and at least one bending path abutting on the deposition surface, as well a second consolidated height composite wideband in the second reinforced structure relative to the first consolidated composite swath, which is more than half of the filament width [57]. Each deposition enables the host material to flow and exerts the ironing and pressing force to unfold the reinforced strands within the filament so that it abuts on the surface beneath and/or the strip deposited previously [58, 59]. Related SEM images are exhibited in Fig. (**5**) [56].

2.2. Patents Related to Novel Structures

In terms of mechanical structural innovation, Markforged Company has come up with two patented inventions. One of them involves the combined continuous/random reinforced

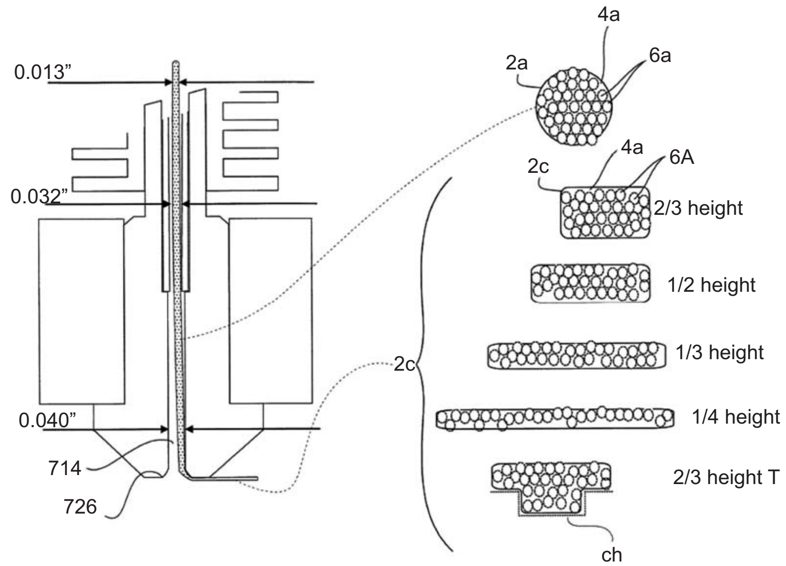

Fig. (4). A complex plane graph for multiaxis fiber reinforcement for 3D printing [50].

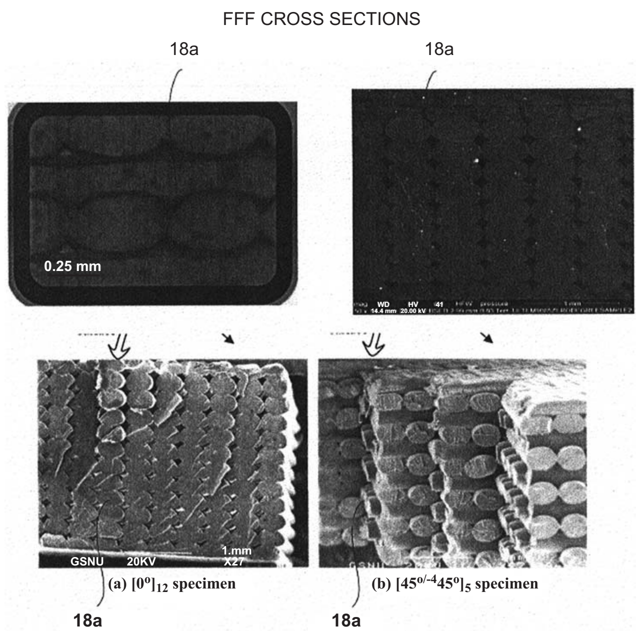

Fig. (5). Some real photos for composite filament 3D printing [56].

fiber composite filaments in multiple fiber strands along the axial direction. The filaments continuously extend within the host material of the reinforced fiber composite filament as well as in multiple short-cut fiber rods that at least partially extend in a random form within the same host material. 3D printer extrudes the filament through the deposition head that consists of a conduit, continuously extending to an outlet with a circular shape. The outlet has an ironing and pressing edge, which is driven to adhere to the reinforced fiber composite filament onto the previously deposited part of the mentioned component [60]. The first part of short-cut fiber rods which are the mentioned as a host material and also included in it flow intermittently within the axial fiber strands that extend from the ironing and pressing edge. The second part of short-cut fiber rods is forced to abut the previously deposited part of this component [61, 62]. Schematics including the design principle and fiber reinforcement can be found in Figs. (**6 & 7**) [60].

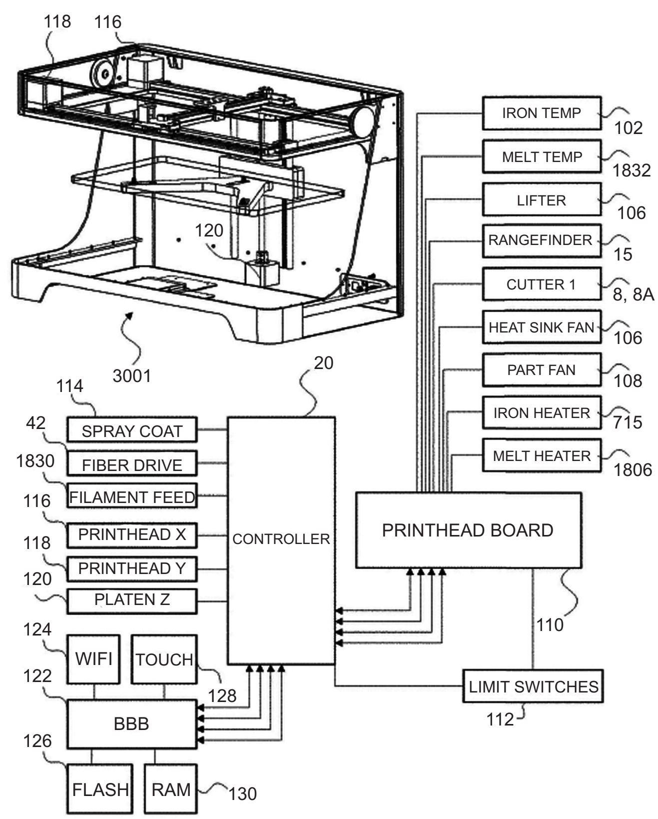

Fig. (6). A plane design for continuous and random reinforcement in a 3D printed part [60].

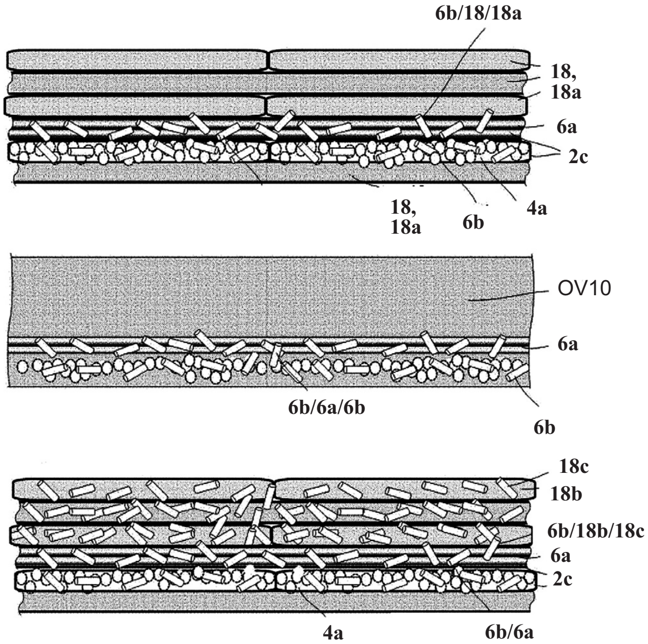

Fig. (7). A real photo for continuous and random reinforcement in a 3D printed part [60].

Another mechanical structural innovation patent by Markforged Company involves forming a reinforced mold piece, within which the preform continuous internal fiber piece is embedded. The designed structure is shown in Fig. (**8**) [63]. The reinforced continuous fiber deposits within the reinforced bulk so as to form the prefab reinforced continuous fiber piece. Then the preformprepreg reinforced piece is placed in the mold of the molding equipment [64]. The mold is equipped with mobile and basically isotropous molding material, such as infusing heated and/or pressurized resin [65]. Hardening is conducted on the molding material (via solidification or cooling) so that it covers the preform reinforced continuous fiber piece. The hardened and basically isotropous molding material is employed to enclose the prefab reinforced continuous internal fiber piece of the obtained reinforced mold product [66, 67].

3. XI'AN JIAOTONG UNIVERSITY

Xi'an Jiaotong University also has a number of patents in terms of printing technique and a few patents in terms of structural innovation of the printer.

3.1. Patents Related to Novel Technique Methods

A 3D printer fabricating continuous long fiber reinforced composite material and its printing method is one of the patented printing techniques invented by Xi'an Jiaotong University, which can be viewed in Figs. (**9** & **10**) [68]. It utilizes the 3D printing technique and combines with the composite material fiber placement technology, achieving the fabrication of reinforced continuous long fiber resin matrix composites. This process does not require prefab mold or pre-processed fiber prepreg, which greatly reduces the cost. At the same time, adopting 3D printing method can better

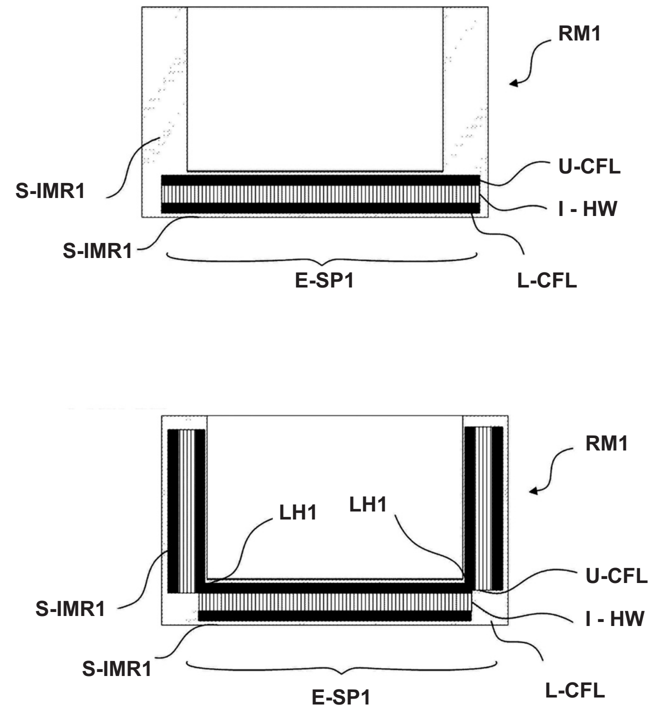

Fig. (8). A design paper for embedding 3D printed fiber reinforcement in molded articles [63].

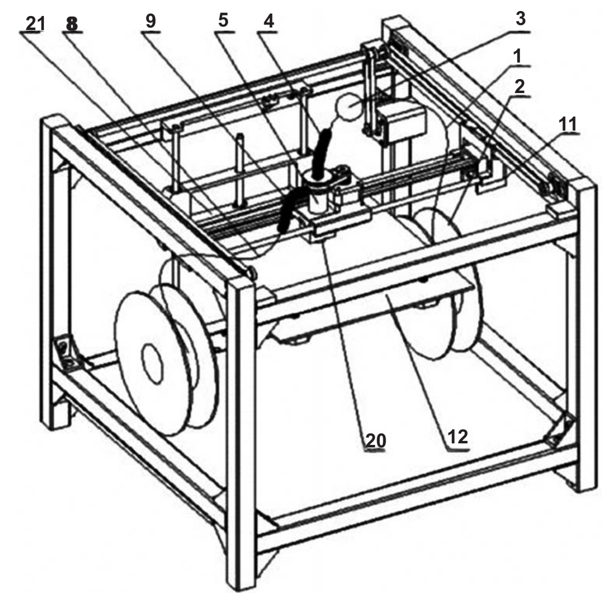

Fig. (9). A 3D printer made of continuous long fiber reinforced composites [68].

and more conveniently control the direction of reinforced fiber in the manufactured component, and obtain composite material component with customized mechanical properties more easily [69, 70]. It can achieve speedy manufacturing of composite material component with complex structure [71]. Compared to the existing composite material fiber placement technology, this invention has a wider range of application and higher production efficiency.

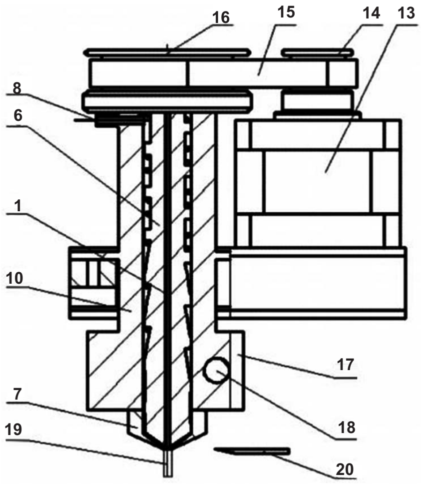

Fig. (10). A 3D printing head capable of continuous long fiber reinforced composites [68].

Another printing technique invention is also about the AM of continuous fiber reinforced thermosetting resin matrix composite. First, thermosetting resin prepolymer, high-temperature curing agent, photo-curing resin prepolymer and photoinitiator as prepreg materials are optioned [72]. After heating and even mixing, the resin prepolymer system is pre-impregnated with continuous dry fiber tow, and then cooled to obtain a continuous fiber reinforced thermosetting resin-based composite wire; the composite wire is conveyed to a 3D printing head, heated again, and the molten wire is pulled out from the printing nozzle [73]. The tow is immediately ventilated and cooled after being pulled out and is pre-cured by irradiation with a follow-up ultraviolet light source. Here, the layer-by-layer printing is performed to obtain a pre-formed component. In the end, the preformed piece is placed under a temperature that is able to trigger a thermosetting reaction to form a solid shape, thus creating the 3D printed parts [74]. This invention realizes rapid forming of a continuous fiber reinforced thermosetting resin-based composite component by 3D printing.

In another printing technique innovation patent, various surface modified metal-based continuous fiber reinforced composites are fabricated via 3D printing. Continuous fiber is first coated by metals, which is pulled out from the coated filament disk [72]. The soldering flux adheres on the container and is processed into mold, providing the continuous fiber with uniform and adhesive flux. The wire is pulled out, in which the continuous fiber uniformly adheres the flux from the continuous fiber reinforced composite material, and is put in through the line tray printer. The printer flux in the 3D melting chamber is melted, removing the oxide layer on the surface of continuous fiber of the metal coating. The continuous fiber of the coating penetrates with the liquid metal matrix. Starting from the nozzle, under the action of the wetting force, the liquid metal matrix uniformly adheres to the continuous fiber of the coating and continuously flows out, and then forms a part through the superposition layer [74]. This invention improves the feasibility of 3D printing and printing resolution of continuous fiber reinforced metal matrix composites, so as to improve the mechanical properties of the components.

Another patented printing technique innovation involves the fabrication of an electromagnetic shielding structure of continuous fiber reinforced composite material via AM method [75]. A rough layout for this design is shown in Fig. (**11**). Firstly establish a three-dimensional model of shielding structure, then design a conductive fiber path, correct a 3D conductive fiber path, then generate a shielding structure printing path, and finally perform a 3D printing to produce a shielding structure. The shielding structure manufactured by this invention not only has high shielding performance, but also has low density, and design capability of electromagnetic shielding performance and mechanical property [76]. It can adjust the electromagnetic shielding performance of the shielding structure according to the needs of the application situation [77]. At the same time, the continuous fiber composite used has good mechanical properties.

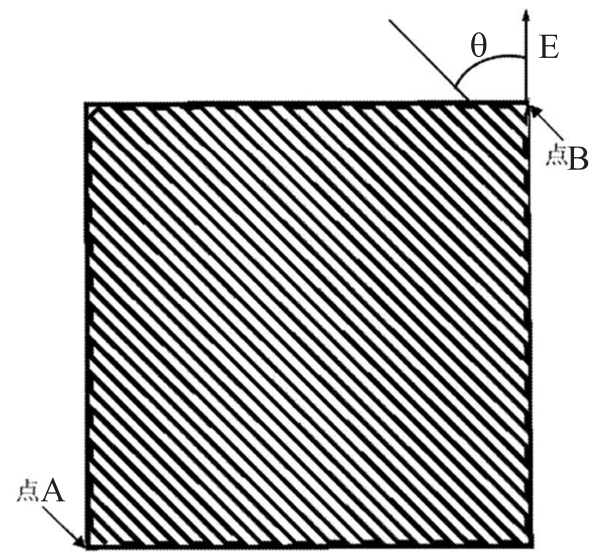

Fig. (11). A rough layout for 3D printing manufacturing via an electromagnetic shielding structure of continuous fiber reinforced composite material [75].

This method uses computer-aided design software to establish a 3D model of the workpiece according to the shape characteristics of the function control structural material and then introduces computer-aided engineering software to perform corresponding performance analysis on the workpiece. It also conducts function adjustment design for key feature areas, and draws the curve of fiber trajectory; then conducts algorithm optimization for the fiber trajectory, and considers the technique in 3D printing, and re-adjusts the fiber trajectory to obtain the final fiber trajectory curve [78]. The 3D printing path instruction file of the product is generated according to the track curve; finally, the instruction file is imported into the continuous fiber reinforced composite material 3D printer to complete the preparation of the function control structure material. This invention can realize dynamic control of the fiber path and content in the composite material, enabling designable manufacture of function control materials such as variable stiffness fiber composite materials, heat conduction regulatable materials and electromagnetically tunable materials [79]. Both design layout and real photo can be seen in Figs. (**12** & **13**).

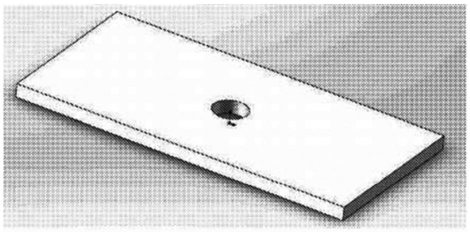

Fig. (12). A real photo for function regulation and control structure production method [78].

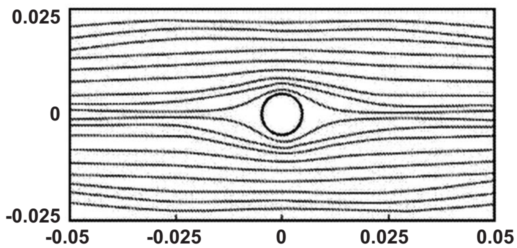

Fig. (13). A design layout for function regulation and control structure production method [78].

A method for manufacturing a lightweight structure of continuous fiber reinforced composite material is another patented printing technique innovation owned by Xi'an Jiaotong University [80]. A rough design layout in 2D and 3D drawings can be seen in Figs. (**14** & **15**). It utilizes the lightweight structure of a continuous fiber reinforced composite material, namely inner core material jointing method and inner core material complex shape jointing method, to obtain an integrated lightweight structure made of continuous fiber-reinforced composite material; it utilizes the 3D printing technique by continuous fiber enhanced composite, and uses continuous path strategy, in order to achieve speedy and low-cost integrated manufacturing of high-performance continuous fiber reinforced composite lightweight structures.

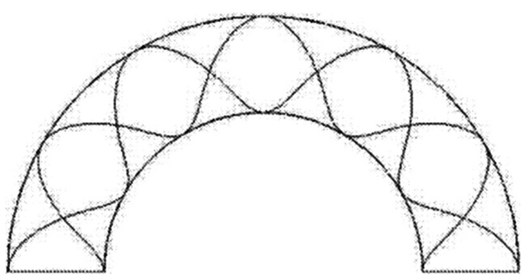

Fig. (14). A method for manufacturing lightweight structure of continuous fiber-reinforced composite material (2D drawing layout) [80].

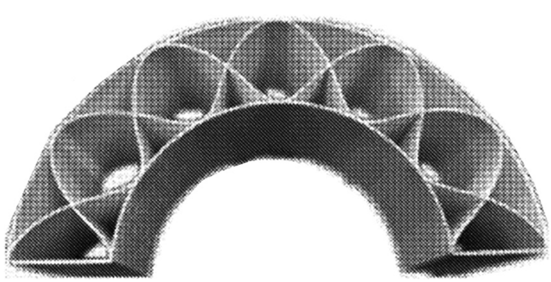

Fig. (15). A method for manufacturing lightweight structure of continuous fiber-reinforced composite material (3D drawing layout) [80].

A fiber reinforced thermosetting resin-based composite material 3D printing device is one more printing technique patent held by Xi'an Jiaotong University. Dry fiber filament material is rolled and placed on an unwinding device, and the dry fiber tow is conveyed into a hot-melt pre-dip mixing chamber by a conveying device and a tension control device [81]. The dry fiber wire is pre-impregnated by the thermosetting resin and then outputted by the printing nozzle, laid on the printing platform or the printed fiber layer, and then cured by the follow-up low-energy electron beam emitter to complete the printing. This new utility model directly adopts dry fiber wire for heat-melt prepreg, 3D printing and low energy electron strand radiation curing [82]. During the heat-melt prepreg process, temperature control and prepreg path control are achieved through the tension control, making the fiber tow and the resin matrixuniformly mixed, and then output completed composites through the printing nozzle [83]. Finally, it conducts irradiation and curing by the follow-up low-energy electron strand emitter. The chemical bonding of curing is fast and efficient, and the component performance is excellent. A design layout is shown in Fig. (**16**).

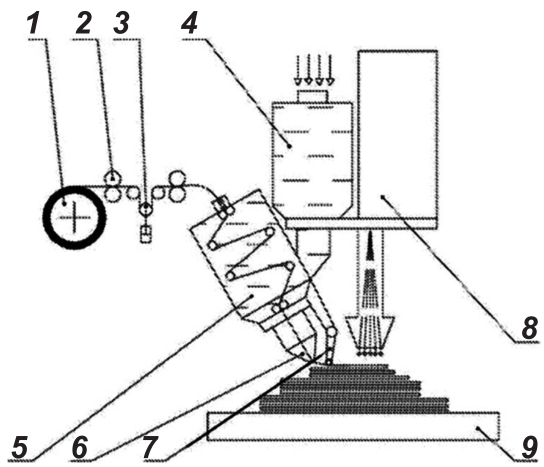

Fig. (16). A design layout for a fiber reinforced thermosetting resin-based composite material 3D printing device [81].

3.2. Patents Related to Novel Structures

A fiber reinforced composite material multi-freedom-degree 3D printer is one of the patented printing innovations made by Xi'an Jiaotong University in terms of structural innovation, as is shown in Fig. (**17**). It utilizes the flexibility of a robot so that 3D printing can be performed at any angle and any motion tracking. The 3D printing head mounted thereon can perform 3D printing of high strength and short fiber reinforced composite materials [84]. It can also be used for slicing and weaving continuous resin-based long fibers in order to produce a continuous fiber reinforced resin-based composite material [85]. This invention can accurately control the orientation of reinforced fibers in composite material during 3D printing, enabling rapid manufacturing of composite material with complex structures that have specific mechanical, electrical and thermal properties; at the same time, no pre-customized molds and pre-treated fiber prepreg tapes are required in the process. It is not only suitable for manufacturing large components, but is also suitable for high-volume manufacturing of small components, which greatly

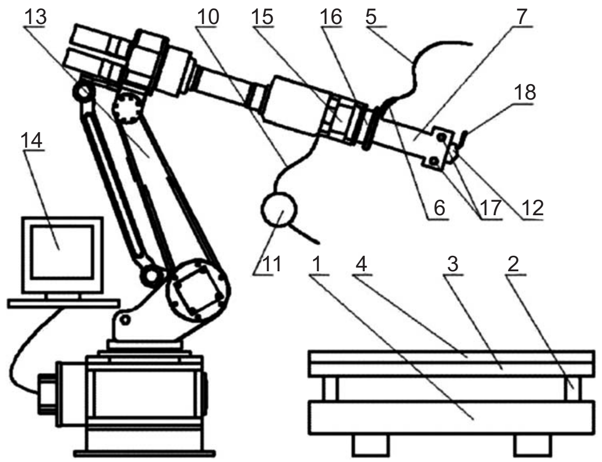

Fig. (17). A design layout illustrating a fiber reinforced composite material multi-freedom-degree 3D printer [85].

reduces manufacturing costs and production cycles, and further promotes the wide application of composite material [86].

Continuous fiber reinforced intelligent composite material 3D printing head includes a 3D printing head support, as it can be seen in Fig. (**18**) [87]. The 3D printing head support is connected with a 3D printing head truss. A throat is connected between the 3D printing head truss, and the two ends of the throat are respectively connected with the heat dissipation frame and the heating block. The heat dissipation frame is connected with a thermoplastic base material, which forms the first inner hole with the throat tube via the heat dissipation frame. The heating block is connected with a needle tube, a copper nozzle, a heating tube, a thermal sensor. The continuous fiber bundle passes through a second inner channel formed by a copper nozzle via the needle tube [88]. The continuous fiber bundle and the thermoplastic base material which is under the molten state are compounded at the front end of the copper nozzle, and extruded from the copper nozzle outlet, thereby realizing rapid manufacturing of the composite material component with complicated structures [89].

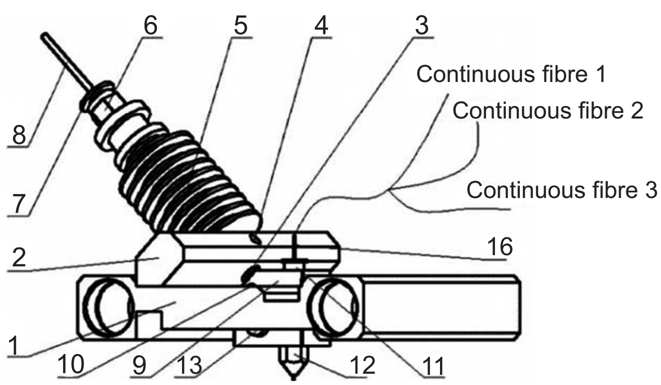

Fig. (18). The schematic of a continuous fiber reinforced intelligent composite material 3D print head [87].

A multi-stage wire feeding printing head for continuous fiber reinforced composite material 3D printing is another patented structural innovation in printing made by Xi'an Jiaotong University. It includes a fiber conduit fixed on the upper surface of the first-level heating block [90]. The inner channel of the fiber conduit forms a fiber passage, and the first-level throat pipe is fixed on one side of the first-level heating block. The inner hole of the first-level throat forms a first-level inner channel, and the polymer material passes through the first-level inner channel and enters the melting chamber of the first-level heating block; the first-level heating block is fixed above the second-level heating block, and the second-level throat pipe is fixed on one side of the second-level heating block. The inner hole of the secondary throat pipe forms a secondary inner channel, and the high-performance thermoplastic material passes through the secondary inner channel into the melting chamber of the secondary heating block; by the same structure, all the heating blocks are fixed above the end heating block eventually. The nozzle is fixed on the lower surface of the final heating block. This invention adopts a multi-stage wire feeding print head, which enables great coating of the continuous fiber in a multi-level manner with the base material, providing a continuous fiber reinforced composite material components with good comprehensive properties. Some design layouts are presented in Figs. (**19**-**21**) [90].

4. PRESIDENT AND FELLOWS OF HARVARD COLLEGE

The president and fellows of Harvard College have also come up with a printing patent in terms of technological innovation.

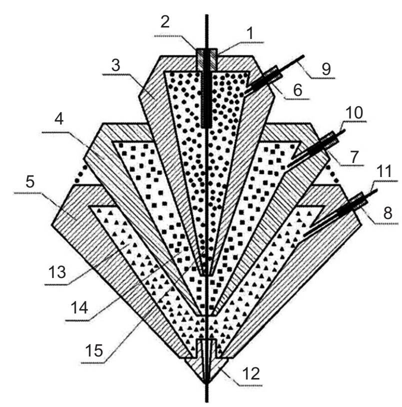

Fig. (19). Design layout 1 for a multi-stage wire feeding print head [90].

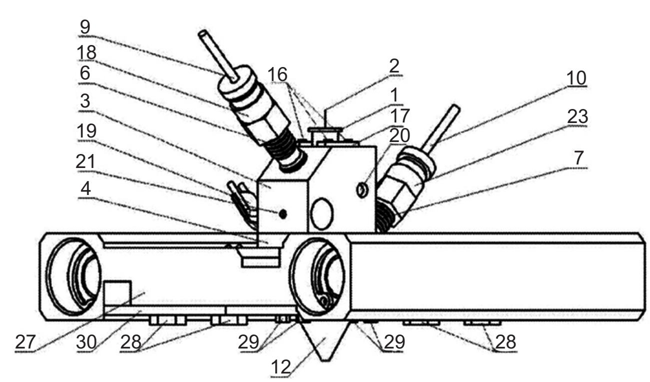

Fig. (20). Design layout 2 for a multi-stage wire feeding print head [90].

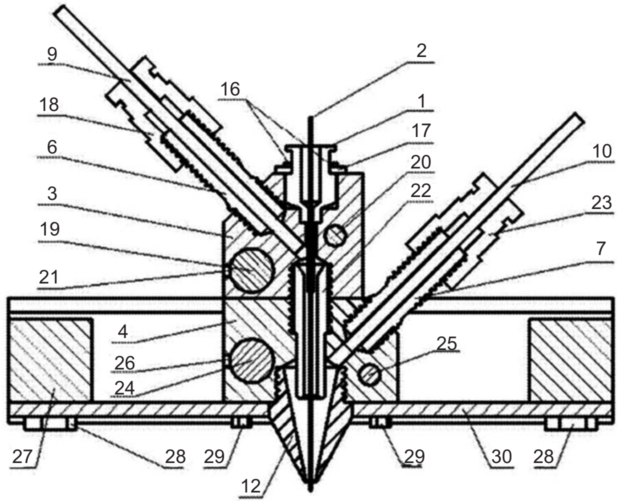

Fig. (21). Design layout 3 for a multi-stage wire feeding print head [90].

4.1. Patents Related to Novel Technique Methods

The filamentary structure squeezes out from the nozzle during 3D printing to shape continuous long filaments. This long filament comprises filling particles dispersed within it. At least part of the filling particles in the continuous long filaments comprise high aspect ratio particles with a predetermined orientation relative to the longitudinal axis of the continuous filaments [91]. Three real photos can be seen in Figs. (**22**-**24**) respectively for this technique patent [91]. The high aspect ratio particles can, at least partially, align along the longitudinal axis of the continuous filaments. In some implementation plans, the high aspect ratio particles can be aligned along the height of the longitudinal axis. Additionally or alternatively, at least part of the high aspect ratio particles is able to form a screwing orientation including a tangential component and a longitudinal component, within which the tangential component is attached through rotation of the deposition nozzle while the longitudinal component is attached through the translational component.

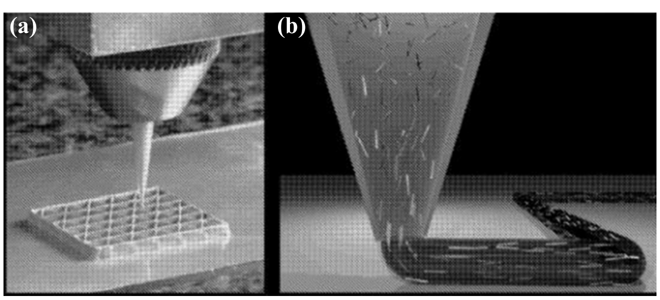

Fig. (22). Images for the patented 3D printing process [91].

CONCLUSION

3D printing of continuous fiber reinforced composites will be the turning point for both AM technology and conventional composite industry. Based on the superior mechanical properties of CFRC, the huge possibility of fabricating these materials by properly modifying existing commercial 3D printers has aroused great interest in the development and research of this area. However, until now, Markforged is the only company commercializing the 3D printing of this kind of composites. There are numerous challenges and obstacles to be solved in this new field before it becomes a mainstream manufacturing method.

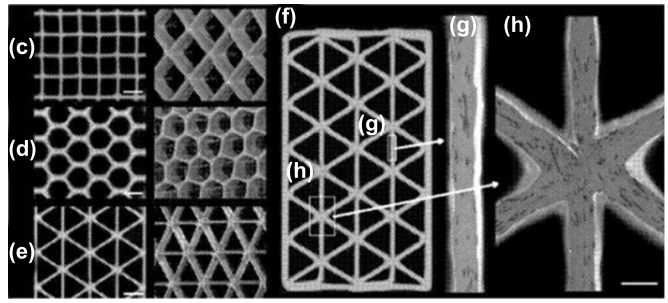

Fig. (23). Images for various 3D printed parts [91].

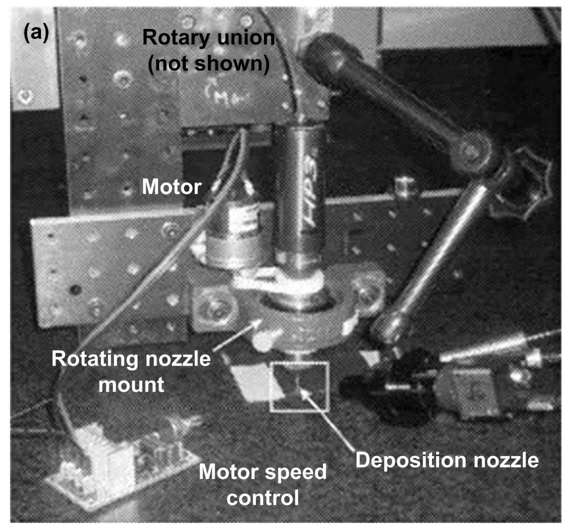

Fig. (24). The image of patented 3D printer structures [91].

CURRENT & FUTURE DEVELOPMENTS

Although 3D printed CFRC has already improved the mechanical performance compared to the short fiber reinforced counterparts, the overall strength and stiffness are still inferior to the polymer composites fabricated by conventional manufacturing methods. This limits the application of 3D printed CERC in high-end industries with strict mechanical requirements. Additional post-treatments such as infiltration, coating or consolidation can be employed to further improve the performance of 3D printed parts while the cost and time are correspondingly increased. One reason for the low mechanical strength is the void formation during 3D printing. With the introduction of fiber reinforcement, the porosity will be largely increased, leading to the poor interfacial bonding between fibers and matrix. How to reduce the void formation and increase the adhesion strength onto fibers becomes a big issue since it offsets the improvement from fiber reinforcement. For FDM method, how to enhance the bonding strength between neighbouring layers also requires significant research.

The printing process for most 3D printers are normally time-consuming and the volume can be printed is also restricted to small parts. These, to a certain extent, hinder the application of this technique into the industry. In addition, how to ensure the consistency of printed parts needs to be further investigated since the repeatability of 3D printing is usually difficult to be guaranteed. A feedback system should be introduced into 3D printer to timely monitor the printing process so that errors can be immediately detected following the proper correction. Since most of the current commercial printers are designed for pure polymers, the addition of continuous fibers will also cause the nozzle clogging, wear, curving and poor adhesion. In addition, how to design the composite structure with optimal orientation of fibers plays a crucial role in improving the overall mechanical properties. As a new technique, there is no related theoretical models and design optimization software for the 3D printing of CRFC. How to build new models or modify existing models for conventionally manufactured composites will be extremely important to take full advantage of this advanced manufacturing technology.

The fabrication of CFRC via AM method gives us a future vision for the industrialized manufacturing of composites with continuous fibers. The unique traits of this technology, such as high customization, full automation and minimal waste, combined with remarkable strength of continuous fibers, also enable the production of intricate 3D composites with multifunctional properties. Although many challenges and restricts still exist, the fast development in this field has been witnessed by the above-mentioned publications. With the progress and expansion of AM-based CFRC, it will undoubtedly promote the revolution of other industries, whether they are high-tech fields or consumer low-performance business markets.

LIST OF ABBREVIATIONS

AM	=	Additive Manufacturing
CAD	=	Computer-Aided Design
CFRC	=	Continuous Fiber Reinforced Composites
3D	=	Three-Dimensional
MTL	=	Material Template Library
PA	=	Polyamide
PLA	=	Polylactic Acid
PP	=	Polypropylene
RP	=	Rapid Prototyping
SFF	=	Solid-Freeform
STL	=	Surface Tessellation Language

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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REFERENCES

[1] Wang X, Jiang M, Zhou Z, Gou J, Hui D. 3D printing of polymer matrix composites: A review and prospective. Compos Part B-Eng 2017; 110: 442-58.

[2] Huang SH, Liu P, Mokasdar A, Hou L. Additive manufacturing and its societal impact: A literature review. Int J Adv Manuf Tech 2013; 67(5-8): 1191-203.

[3] Lee JY, An J, Chua CK. Fundamentals and applications of 3D printing for novel materials. Appl Mater Today 2017; 7: 120-33.

[4] Postiglione G, Natale G, Griffini G, Levi M, Turri S. Conductive 3D microstructures by direct 3D printing of polymer/carbon nanotube nanocomposites via liquid deposition modeling. Compos Part A Appl Sci Manuf 2015; 76: 110-4.

[5] Levy GN, Schindel R, Kruth JP. Rapid manufacturing and rapid tooling with Layer Manufacturing (LM) technologies, state of the art and future perspectives. CIRP Ann Manuf Technol 2003; 52(2): 589-609.

[6] Dikshit V, Nagalingam AP, Yap YL, Sing SL, Yeong WY, Wei J. Investigation of quasi-static indentation response of inkjet printed sandwich structures under various indenter geometries. Materials 2017; 10(3): 290.

[7] Saxena KK, Das R, Calius EP. Three decades of auxetics research materials with negative Poisson's ratio: A review. Adv Eng Mater 2016; 18(11): 1847-70.

[8] Chu C, Graf G, Rosen DW. Design for additive manufacturing of cellular structures. Comput Aided Des Appl 2008; 5(5): 686-96.

[9] Caulfield B, McHugh P, Lohfeld S. Dependence of mechanical properties of polyamide components on build parameters in the SLS process. J Mater Process Tech 2007; 182(1-3): 477-88.

[10] Serra T, Planell JA, Navarro M. High-resolution PLA-based composite scaffolds via 3-D printing technology. Acta Biomater 2013; 9(3): 5521-30.

[11] Carneiro OS, Silva A, Gomes R. Fused deposition modeling with polypropylene. Mater Des 2015; 83: 768-76.

[12] Gu H, Ma C, Gu J, Guo J, Yan X, Huang J, *et al*. An overview of multifunctional epoxy nanocomposites. J Mater Chem C Mater 2016; 4(25): 5890-906.

[13] Scheithauer U, Schwarzer E, Richter HJ, Moritz T. Thermoplastic 3D printing-an additive manufacturing method for producing dense ceramics. Int J Appl Ceram Tec 2015; 12(1): 26-31.

[14] Kroll E, Artzi D. Enhancing aerospace engineering students' learning with 3D printing wind-tunnel models. Rapid Prototyping J 2011; 17(5): 393-402.

[15] Chia HN, Wu BM. Recent advances in 3D printing of biomaterials. J Biol Eng 2015; 9(1): 4.

[16] Rayna T, Striukova L. From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. Technol Forecast Soc Change 2016; 102: 214-24.

[17] Perrot A, Rangeard D, Pierre A. Structural built-up of cement-based materials used for 3D-printing extrusion techniques. Mater Struct 2016; 49(4): 1213-20.

[18] Kalsoom U, Nesterenko PN, Paull B. Recent developments in 3D printable composite materials. RSC Adv 2016; 6(65): 60355-71.

[19] Gibson RF. A review of recent research on mechanics of multifunctional composite materials and structures. Compos Struct 2010; 92(12): 2793-810.

[20] Cen H, Kang Y, Lei ZK, Qin QH, Qiu W. Micromechanics analysis of Kevlar-29 aramid fiber and epoxy resin microdroplet composite by Micro-Raman spectroscopy. Compos Struct 2006; 75(1): 532-8.

[21] Feng XQ, Mai YW, Qin QH. A micromechanical model for interpenetrating multiphase composites. Comput Mater Sci 2003; 28(3): 486-93.

[22] Lei YP, Wang H, Qin QH. Micromechanical properties of unidirectional composites filled with single and clustered shaped fibers. Sci Eng Compos Mater 2018; 25(1): 143-52.

[23] Qin QH. Material properties of piezoelectric composites by BEM and homogenization method. Compos Struct 2004; 66(1): 295-9.

[24] Qin QH, Wang H. Special elements for composites containing hexagonal and circular fibers. Int J Comput Methods 2015; 12(4): 1540012.

[25] Qin QH, Yang QS. Macro-Micro Theory on Multifield Coupling Behavior of Hetereogenous Materials. Higher Education Press and Springer: Berlin, 2008.

[26] Qin QH, Yu SW. An arbitrarily-oriented plane crack terminating at the interface between dissimilar piezoelectric materials. Int J Solids Struct 1997; 34: 581-90.

[27] Parandoush P, Lin D. A review on additive manufacturing of polymer-fiber composites. Compos Struct 2017; 182: 36-53.

[28] Tekinalp HL, Kunc V, Velez-Garcia GM, Duty CE, Love LJ, Naskar AK, *et al*. Highly oriented carbon fiber-polymer composites via additive manufacturing. Compos Sci Technol 2014; 105: 144-50.

[29] Quan Z, Larimore Z, Wu A, Yu J, Qin X, Mirotznik M, *et al*. Microstructural design and additive manufacturing and characterization of 3D orthogonal short carbon fiber/acrylonitrile-butadiene-styrene preform and composite. Compos Sci Technol 2016; 126: 139-48.

[30] Ning F, Cong W, Qiu J, Wei J, Wang S. Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling. Compos Part B-Eng 2015; 80: 369-78.

[31] Goh G, Dikshit V, Nagalingam A, Goh G, Agarwala S, Sing S, *et al*. Characterization of mechanical properties and fracture mode of additively manufactured carbon fiber and glass fiber reinforced thermoplastics. Mater Des 2018; 137: 79-89.

[32] Love LJ, Kunc V, Rios O, Duty CE, Elliott AM, Post BK, *et al*. The importance of carbon fiber to polymer additive manufacturing. J Mater Res 2014; 29(17): 1893-8.

[33] Wang Y. Mechanical properties of stitched multiaxial fabric reinforced composites from mannual layup process. Appl Compos Mater 2002; 9(2): 81-97.

[34] Tian X, Liu T, Yang C, Wang Q, Li D. Interface and performance of 3D printed continuous carbon fiber reinforced PLA composites. Compos Part A Appl Sci Manuf 2016; 88: 198-205.

[35] Yang C, Tian X, Liu T, Cao Y, Li D. 3D printing for continuous fiber reinforced thermoplastic composites: Mechanism and performance. Rapid Prototyping J 2017; 23(1): 209-15.

[36] Melenka GW, Cheung BK, Schofield JS, Dawson MR, Carey JP. Evaluation and prediction of the tensile properties of continuous fiber-reinforced 3D printed structures. Compos Struct 2016; 153: 866-75.

[37] Gupta A, Ogale A. Dual curing of carbon fiber reinforced photoresins for rapid prototyping. Polym Composite 2002; 23(6): 1162-70.

[38] Mori K-i, Maeno T, Nakagawa Y. Dieless forming of carbon fibre reinforced plastic parts using 3D printer. Proc Eng 2014; 81: 1595-600.

[39] Nakagawa Y, Mori K-I, Maeno T. 3D printing of carbon fibre-reinforced plastic parts. Int J Adv Manuf Technol 2017; 91(5-8): 2811-7.

[40] Van Der Klift F, Koga Y, Todoroki A, Ueda M, Hirano Y, Matsuzaki R. 3D printing of continuous Carbon Fibre Reinforced Thermo-Plastic (CFRTP) tensile test specimens. OJCM 2015; 6(01): 18.

[41] Gardner JM, Sauti G, Kim JW, Cano RJ, Wincheski RA, Stelter CJ, *et al*. 3-D printing of multifunctional carbon nanotube yarn reinforced components. Addit Manuf 2016; 12: 38-44.

[42] Soutis C. Carbon fiber reinforced plastics in aircraft construction. Mater Sci Eng A 2005; 412(1-2): 171-6.

[43] Advani SG, Sozer EM. Process modeling in composites manufacturing: CRC Press: Boca Raton 2002.

[44] Mallick PK. Fiber-Reinforced Composites: Materials, Manufacturing, and Design. 3rd ed. CRC Press: Boca Raton, USA, 2007.

[45] Mark, G.T., Gozdz, A.S. Three dimensional printer for fiber reinforced composite filament fabrication. US9126367 (**2015**).

[46] Medney, J., Klimpl, F.E. Reinforced plastic laminates for use in the production of printed circuit boards and process for making such laminates and resulting products. US5037691 (**1991**).

[47] Crump, S.S. Modeling apparatus for three-dimensional objects. US5340433 (**1994**).

[48] Jang, B.Z., Liu, J.H., Chen, S., Li, Z.M., Mahfuz, H., Adnan, A. Nanotube fiber reinforced composite materials and method of producing fiber reinforced composites. US20030236588 (**2003**).

[49] Batchelder, J.S., Swanson, W.J., Crump, S.S. Method for building three-dimensional models in extrusion-based digital manufacturing systems using ribbon filaments. US8221669 (**2012**).

[50] Mark, G.T., Woodruff, R.B., Parangi, A.L., Benhaim, D.S., Sklaroff, B.T. Multiaxis fiber reinforcement for 3D printing. US20160311165 (**2017**).

[51] Ooba, Y., Katou, Y., Suzuki, K., Daicho, Y., Miyano, H., Okane, T., Imamura, S., Kajino, S. Three-dimensional molding device. US20170021564 (**2017**).

[52] Page, J.S. Systems and methods for improved 3D printing. US20150266244 (**2015**).

[53] Bui, M.-A.T., Fithian, T.R., Madeley, D. Apparatus and method for additive manufacturing. US20160263832 (**2016**).

[54] Hsiao, H.-M., Lee, S.M., Buyny, R.A., Martin, C.J. Core-crush resistant fabric and prepreg for fiber reinforced composite sandwich structures. US6261675 (**2003**).

[55] Nelson, P.E., Kramp Jr, R.A., Lum, M.K. Composite lamination using array of parallel material dispensing heads. US20060162143 (**2006**).

[56] Mark, G.T., Woodruff, R.B., Benhaim, D.S., Parangi, A.L., Sklaroff, B.T. Composite filament 3D printing using complementary reinforcement formations. US20160107379 (**2016**).

[57] Payne, L.R. Laminate forming and applying apparatus and method and product therefrom. US4955760 (**1990**).

[58] Mark, G.T. Methods for fiber reinforced additive manufacturing. US20140361460 (**2014**).

[59] Tayebi, A. Colored laminate and a method for coloring the surface of a membrane. US20030094728 (**2003**).

[60] Mark, G.T. Continuous and random reinforcement in a 3D printed part. US20170173868 (**2017**).

[61] Mayes, Jr, J.T., Rosene, W.A. Ribbed composite structure and process and apparatus for producing the same. US4137354 (**1979**).

[62] Cramer, D.R., Beidleman, N.J., Chapman, C.R., Evans, D.O., Passmore, M.K., Skinner, M.L. System and method for the rapid, automated creation of advanced composite tailored blanks. WO2009042225 (**2009**).

[63] Mark, G.T. Embedding 3D printed fiber reinforcement in molded articles. US20170120519 (**2017**).

[64] Jang, B.Z., Ma, E. Layer-additive method and apparatus for free-form fabrication of 3-D objects. US6471800 (**2002**).

[65] Tow, A.P. Multi-axis, multi-purpose robotics automation and quality adaptive additive manufacturing. US20130209600 (**2013**).

[66] Dunlap, E.N., Turner, D.M., Lawson, J.L. Process for tempering rapid prototype parts. US20030186042 (**2003**).

[67] Hauber, D.E. Reinforced thermoplastic pipe manufacture. US6773773 (**2004**).

[68] Tian, X.Y., Yang, C.C., Cao, Y., Tong, Z.Q., Zhang, Y.Y., Li, D.C. Continuous long-fiber reinforced-type composite material 3D printer and printing method thereof. CN104149339 (**2014**).

[69] Xu, Y.L. Printing head device applied to large industrial FDM3D printer. CN105584044 (**2015**).

[70] Yao, X.Y., Luan, C.C., Fu, J.Z., Lan, L.J. Carbon fiber sensing element embedding device and method based on rapid prototyping manufacturing technology. CN105881902 (**2016**).

[71] Hao, W.F., Chen, H.S., Chen, M.J., Pei, Y.M., Fang, D.N., Zhang, X.J. Thermosetting fiber composite material 3D (Three Dimensional) printer and printing method thereof. CN106739006 (**2016**).

[72] Duan, Y.G., Ming, Y.K., Ding, Z.Q. Kinds of continuous fiber reinforced thermosetting resin matrix composites 3D printing process. CN108381908 (**2018**).

[73] Keuchel, K.H. Method of delivering a thermoplastic and/or crosslinking resin to a composite laminate structure. US20090309260 (**2009**).

[74] Beall, F.C., Koppernaes, J.D. Pultrusion method for condensation resin injection. US5176865 (**1993**).

[75] Tian, X.Y., Shang, Z.T., Yi, L.X. 3D printing manufacturing method for electromagnetic shielding structure made of continuous fiber reinforced composite. CN107471629 (**2017**).

[76] Micheli D, Pastore R, Apollo C, Marchetti M, Gradoni G, Primiani VM, *et al*. Broadband electromagnetic absorbers using carbon nanostructure-based composites. IEEE Trans Microwave Theory Tech 2011; 59(10): 2633-46.

[77] Wang Z, Guang-Lin Z. Microwave absorption properties of carbon nanotubes-epoxy composites in a frequency range of 2-20 GHz. OJCM 2013; 3(2): 17.

[78] Tian, X.Y., Zhang, J.K., Hou, Z.J., Li, D.C. Function regulation and control structure production method based on continuous fiber composite material 3D printing. CN107433713 (**2017**).

[79] Sahebrao Ingole D, Madhusudan Kuthe A, Thakare SB, Talankar AS. Rapid prototyping-a technology transfer approach for development of rapid tooling. Rapid Prototyping J 2009; 15(4): 280-90.

[80] Tian, X.Y., Hou, Z.H., Li, D.C. Manufacturing method for continuous fiber reinforced composite lightweight structure. CN106980737 (**2017**).

[81] Duan, Y.G., Ding, Z.Q., Ming, Y.K. Fiber reinforcement thermosetting resin base combined material 3D printing device. CN207240859 (**2017**).
[82] Gomez, J.S., Dominguez, R.A., Martinez, A.B. Tool and process for manufacturing pieces of composite materials outside an autoclave. US20080023130 (**2008**).
[83] Wang, R.X., Cui, C.R., Wu, Y.T., Li, Q. Multilayer compound eccentric-wear-preventing continuous sucker rod and manufacturing device and method thereof. CN104060944 (**2014**).
[84] Li, J., Xie, Y.H., Lin, J.X., Li, F.Y. 3D printing system based on multi-axis linkage control and machine vision measurement. CN106264796 (**2016**).
[85] Tian, X.Y., Yang, C.C., Cao, Y., Tong, Z.Q., Zhang, Y.Y., Li, D.C. Multi-degree-of-freedom 3D printer of fiber reinforced composite material and printing method thereof. CN104097326 (**2014**).
[86] Tian, X.Y., Yang, C.C., Liu, T.F., Li, D.C. Space complex environment oriented multi-degree of freedom 3D printer and printing method. CN104626581 (**2015**).
[87] Tian, X.Y., Yang, C.C., Li, D.C., Wang, J.S. 3D printing head for continuous-fiber-reinforced intelligent composite material and use method of 3D printing head. CN104441658 (**2014**).
[88] Dan, B.S.C., Chen, R., Hu, B., Chen, S., Gao, Y.L., Dong, D.C. Liftable and high-temperature-resistant 3D printing sprayer device. CN105751513 (**2016**).
[89] Li, L.Q., Shao, G.B., Xia, Z.F., Zhou, D.K., Song, W.P., Zhang, G.Y. Ultrasound-enhancement-based 3D printing spray nozzle for continuous-fiber-reinforced composite material. CN106553341 (**2016**).
[90] Tian, X.Y., Liu, T.F., Yang, C.C., Li, D.C. Multi-stage wire feeding printing head for 3D printing of continuous fiber reinforced composite materials. CN105172144 (**2015**).
[91] Lewis, J.A., Compton, B.G., Raney, J.R., Ober, T.J. Three-dimensional (3D) printed composite structure and 3D printable composite ink formulation. WO2015120429 (**2016**).