Advances in hybrid fibers reinforced polymer-based composites prepared by FDM: A review on mechanical properties and prospects

Shixian Li [a,b], Ping Cheng [a,b], Said Ahzi [b], Yong Peng [a], Kui Wang [a,*], Francisco Chinesta [c], J.P.M. Correia [b]

[a] *Key Laboratory of Traffic Safety on Track of Ministry of Education, School of Traffic & Transportation Engineering, Central South University, Changsha, 410075, China*
[b] *ICUBE Laboratory – CNRS, University of Strasbourg, Strasbourg, 67000, France*
[c] *ESI Chair, PIMM, Arts et Métiers Institute of Technology, Paris, 75013, France*

A R T I C L E I N F O

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A B S T R A C T

Recently published research indicated that, in additive manufacturing fields, single fiber reinforcements often increased some mechanical properties of composites, but at the same time decreased other mechanical behaviors, leading to a limited application of single fiber filled composites in the industry. Therefore, 3D printed hybrid composites made from a combination of short/short fibers, short/continuous fibers, or continuous/continuous fibers have received significant attention from researchers, owing to the comprehensive performance improvements and tailored mechanical behaviors. This paper reviewed the state-of-the-art 3D printed hybrid composites and elaborated on their mechanical behaviors, application limitations, potential improvements and future perspectives. The review started with a detailed discussion of different existing hybrid composite printing methods. Then, the mechanical performance, deformation and failure behaviors of hybrid composites were discussed. Finally, this review explored the limitations of printed hybrid composites and looked forward to printing hybrid composite with improved performance.

1. Introduction

Fiber-reinforced polymer (FRP) composites have received much attention from research and industry alike, such as automobile, civil engineering, aircraft and space, due to their lightweight, high specific stiffness and strength in comparison with metal as well as alloys [1,2]. However, forming fiber composites by traditional methods, such as injection molding, compression molding, filament winding, vacuum bagging and resin transfer molding, etc., was still a mold-dependent process, requiring specific tools, which were costly, inflexible, and unsuitable for small batch production. These drawbacks and limitations hindered the further opportunities of fiber reinforced composites for innovative structural applications.

The appearance of 3D printing, also known as additive manufacturing (AM), brings new hope for engineering fiber composites to obtain components with complex geometries and high performance [3,4]. It can produce intricate parts with less cost and without using special tools [5]. 3D printing of FRP was mainly conducted by stereolithography (SL), laminated object manufacturing (LOM), fused deposition modeling (FDM) and selective laser sintering (SLS), etc. Among these, FDM, a technique for fabricating objects by layering extruded molten material using a computer-machine interface, is one of the most versatile and common AM approaches applied in commercial 3D printers due to its flexibility, low cost, simple operation, low material waste and environmental friendliness [6–8]. However, FDM printed parts with pristine polymers, or short fiber reinforced polymer composites, present limitations to being used for structural applications due to their relatively poor mechanical properties [9,10]. In order to improve the mechanical properties of FFF printed components and to meet load-bearing requirements, the lightweight structure was increasingly being introduced into FDM processing [11–16], which drew much attention in industry areas. For example, the printed composites were widely used in sports products such as the bike rocker, in industries such as the mold for turbine blade production, the drone frame and vehicle frame as well as in aerospace engineering such as the suspension parts for a lunar rover (see Fig. 1).

To further enhance the limited mechanical performance of thermoplastic matrix, short fibers or continuous fibers as the reinforcements

* Corresponding author.
E-mail address: kui.wang@csu.edu.cn (K. Wang).

were used to add in raw materials for FDM processes [19]. One of the earliest research about the design of 3D printed short fiber filled composites was published by Zhong et al. [20] in 2001. For continuous fiber reinforcements, two patents on 3D printing of CFRC began to be published in 2014 [21]. Subsequently, the increasing number of papers about the mechanical and thermal behaviors of printed short fibers or continuous fibers filled composites were investigated [7,8,22–26]. Although short fiber reinforced polymer (SFRP) composites offered good mechanical behaviors compared to unreinforced materials, continuous fibers still have become the better replacement for short fibers due to their higher stiffness and strength over short fiber [27–29]. One primary problem of 3D printed continuous fiber reinforced polymer (CFRP) composites was the relatively poor interfacial adhesion between adjacent continuous fiber layers, which led to a low interlaminar strength that affected the final mechanical properties [21,30,31]. For this problem, Yang et al. [32] found that the CNT could be effectively employed as reinforcers in polymer composites based on well-distributed nanoparticles, which can provide good dispersion of CNT in the polylactic acid (PLA) matrix and improve interface strengthening. Besides, the introduction of the short fiber might bridge the printed layers and reinforce the weld areas, which could enhance the interfacial bonding between layers [33]. On the other hands, researchers found that the addition of a single type of short fibers or continuous fibers often increased some mechanical properties of composites, but at the same time decreased other mechanical behaviors [34–36]. For example, the addition of carbon fiber in printed composites enhanced the strength and stiffness but reduced the toughness, while Kevlar fiber showed the opposite properties. Thus, the balance of materials properties, required from composite structure applications, could not be achieved by only using one type of fibers.

To overcome the drawbacks and limitations induced by single reinforcement, a hybrid concept, by adding more than one type of fiber in the matrix, therefore, has started to receive attention from researchers for FDM process. Hybridization could reduce the weak aspects of both short and continuous fibers to have comprehensive performance improvements and designable mechanical properties [37,38]. In literature, the designs and investigations of hybrid FRP composites in the context of 3D printing spanned two levels: materials and structures, as shown in Fig. 2.

Here, this review aimed to focus on the current studies of 3D printed hybrid fibers reinforced polymer composites prepared via the FDM technique. The mechanical performance, including tensile, flexural, interlaminar shear strength (ILSS) and quasi-static indentation (QSI) behaviors of printed hybrid composites would be discussed. In addition, the deformation and failure behaviors were investigated by microstructural behaviors. Ultimately, this review fully explored the limitations of printed hybrid fibers reinforced composites and looked forward to printing hybrid composites with improved performance.

2. FDM processes

In the literature, different studies were carried out using three different hybrid kinds, including short/short fiber, short/continuous fiber and continuous/continuous fiber, for the manufacturing of hybrid FRP composites, summarized in Table 1. Unlike the raw materials for the printing of pure polymer plastics, the reinforced short fiber or/and continuous fiber filaments were composed of fiber clusters/bundles infused with a large amount of thermoplastic sizing agent. To effectively print the composites reinforced by short fiber or/and continuous fibers, various techniques were established, as illustrated in Fig. 3. These

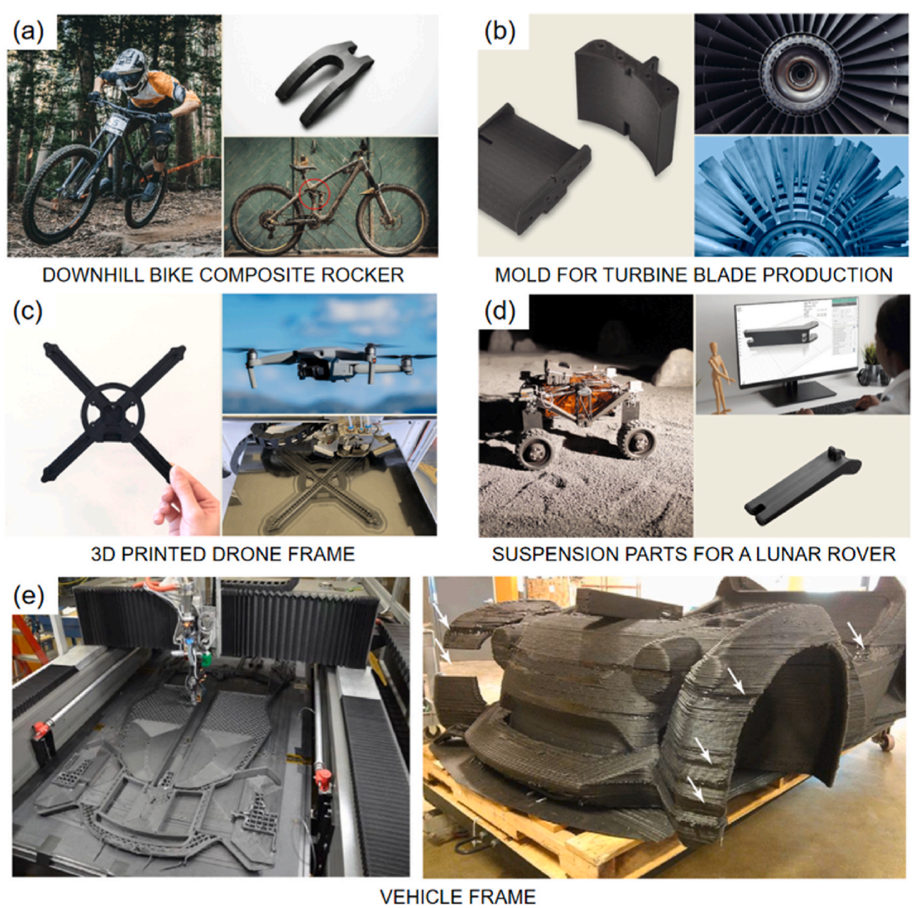

Fig. 1. Applications of the FDM-printed composites [17,18].

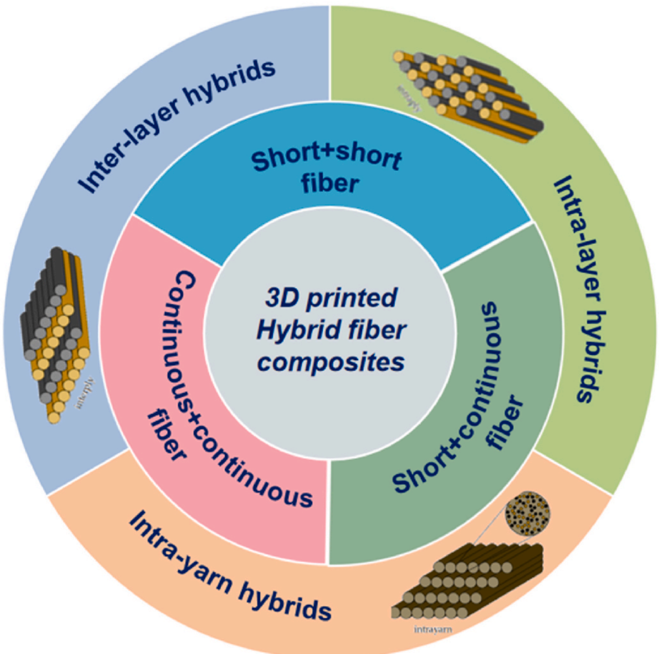

Fig. 2. Design of 3D printed hybrid fibers reinforced composites under materials and structural levels.

methods could be generally divided into two main categories. One category was based on a way of using pre-impregnated (prepreg) filament materials, and the second category was based on an in-situ or inline impregnation method using dry fiber bundles.

The schematics of printing prepreg single/hybrid fibers filaments materials were shown in Fig. 3 (a) and (b). Noted that the most popular printer for printing prepreg thermoplastic filament materials was the commercial Markforged® (Markforged® Mark X7, Watertown, Massachusetts, USA) 3D printer. The prepreg materials supplied by the Markforged® also could be used in other commercial 3D printers. For short/short hybrid fiber reinforced composites, the prepreg filaments were extruded when the extrusion head was heated to the preset melting temperature of the materials. Then, the composites were built by the extruded deposition lines arranged on the printing platform layer by layer (see Fig. 3 (a)). For short/continuous hybrid fiber reinforced composites, the printer used two independent nozzle designs (see Fig. 3 (b)). First, the left nozzle extruded the thermoplastic matrix with short fibers to form the layers of the printed parts; then the right nozzle conveyed the continuous fiber prepreg tow, and the fiber tow was heated and melted near the [37], nozzle opening, and was squeezed through the nozzle. Through the alternate operation of the left and right nozzles, the manufacture of the hybrid fibers reinforced parts with layers by layers was realized. The printed continuous/continuous hybrid fiber filled composites could be manufactured by pausing the machine and changing the types of fiber in the selected layer [38].

Another flexible and simple way of impregnating single/hybrid fibers for use in FDM was through an extrusion process to impregnate dry

Table 1
Hybrid types and materials used for FDM 3D printed hybrid composites.

Hybrid types	Reinforcing fiber		Types of fiber	Matrix	References
	Short	Continuous			
Short/short fiber	Carbon/Kevlar	–	Prepreg tow	ABS	[42]
Continuous/short fiber	Carbon	Carbon	Prepreg tow	PA	[43–50]
	Carbon	Carbon	In-situ impregnation	PLA	[40,41]
Continuous/Continuous fiber	-	Carbon/Glass	Prepreg tow	PA	[51]
	-	Carbon/Kevlar	Prepreg tow	PA	[37,52,53]
	Carbon	Carbon/Kevlar	Prepreg tow	PA	[38]
	–	Carbon/Glass	In-situ impregnation	PLA	[54]
	–	Carbon/Kevlar	In-situ impregnation	PLA	[55]

*ABS - acrylonitrile butadiene styrene; PA - polyamide; PLA - polylactic acid.

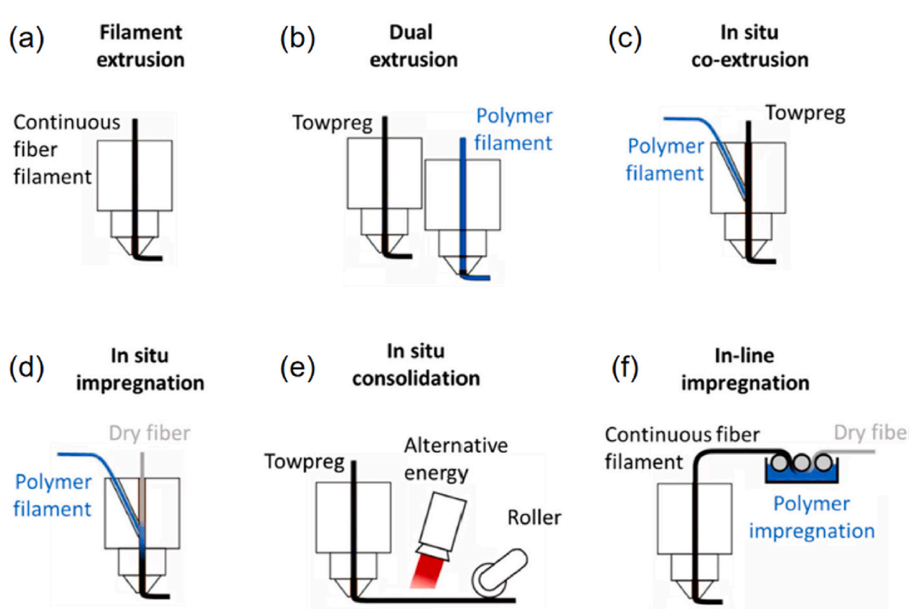

Fig. 3. Schematic representation of main FDM process for 3D printing of fiber reinforced composites [39].

fibers with thermoplastic polymer. As shown in Fig. 3. (c) and (d), the thermoplastic polymer resin with/without short fiber was heated above its melting point in the nozzle, while the dry continuous single/hybrid fibers were pre-heated before entering the nozzle and then extruded from the print head to form a mixed melting of hybrid fibers filled composites. The impregnated fibers tow and the plastic were extruded from the nozzle together and deposited directly for the manufacturing process. The ribbon was finally laid on the printing platform layer by layer until a complete component was formed. However, due to the short impregnation time between dry fiber and matrix, the fiber impregnation for printed hybrid composites manufactured by the in-situ impregnation method was poorer than that of the composites prepared by prepreg extrusion [40,41].

3. Mechanical behaviors

Several factors affected the mechanical performance of hybrid FRP composites. One of the factors was the influence of fiber nature (type and properties) on composite materials. Specifically, the type of 3D printed hybrid composites could be classified to 3 parts under materials level: including short/short, short/continuous and continuous/continuous hybrid fibers reinforced composites. In addition, volume fraction, fiber arrangement and stacking sequence, etc. Were other factors affecting composites' final performance. Therefore, this section would detailedly discuss the mechanical performances of different types of hybrids FRP composites with different types of hybridization and different printing parameters.

3.1. Short/short fibers reinforced composites

Wang et al. [42] first designed 3D printed ABS-based hybrid short carbon and Kevlar fibers filled composites with different raster orientations (0°/90° and ±45°) as well as with different building directions (horizontal and side) (see Fig. 4). They further analyzed the flexural mechanical properties and morphological structures of the printed hybrid composites by using 3 points bending test, digital camera and scanning electron microscopy (SEM), respectively. Experimental results demonstrated that the reinforcement of the ABS by the short carbon and Kevlar fibers under optimized 3D printing conditions led to balanced flexural strength and ductility. In this study, they also found that the hybrid composites with a raster orientation of ±45° and side-build direction showed the highest energy absorption capacity (see Fig. 4 (a)), due to the printed contour layers and the irregular zigzag paths, which could delay the initiation and propagation of microcracks (see Fig. 4 (c) and (d)).

3.2. Short/continuous fibers reinforced composites

Although short hybrid fibers reinforced composites offered better mechanical behaviors compared to their unreinforced and single-reinforced counter materials, short fiber still showed limited stiffness and strength in engineering structural applications. Therefore, the combination of continuous fibers with short fibers as the hybrid reinforcements in fiber composites became a better choice to synthetically enhance mechanical properties. Here, the majority of short carbon fiber filaments (named "onyx", chopped carbon fiber in nylon plastic) were supplied by Markforged [56].

3.2.1. Elastic properties

Maqsood et al. [40] reported a respective increase of 82.85% and 7.12% in the tensile modulus of the hybrid PLA–SCF–CCF printed with short carbon fiber (SCF) and continuous carbon fiber (CCF)), compared to PLA-SCF and PLA-CCF, respectively. Similarly, Wang et al. [43] also mentioned the use of both short and continuous carbon fiber as reinforcements could increase the mechanical behaviors of PA-based composites. They found that the introduction of hybrid CCF and SCF fibers increased both the tensile modulus and strength of composites more than those of single CCF and SCF fiber reinforcements.

To investigate the damage modes of hybrid short/continuous fibers filled composites under tensile loads, researchers analyzed the failure mechanisms of materials by combining experimental and theoretical methods. Fernandes et al. [47] reported that in the printed hybrid composites manufactured by prepreg extrusion filament materials, the stresses were carried mostly by the continuous fibers, i.e., the stress in

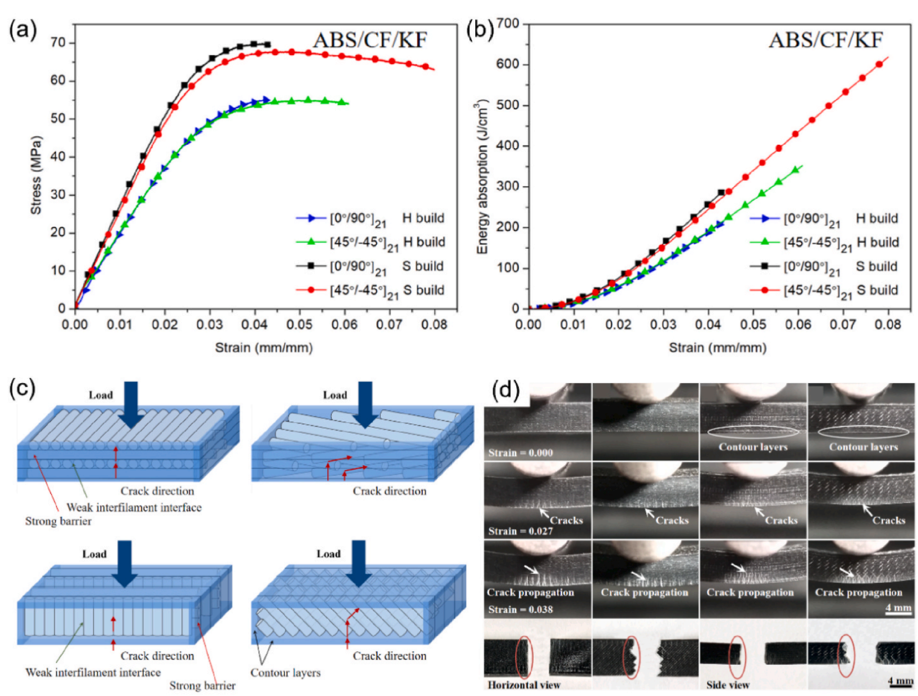

Fig. 4. (a) Stress-strain curves, (b) energy absorption-strain curves, (c) schematic representation of crack propagation and (d) cross-sectional graphs of printed ABS-based hybrid short carbon and Kevlar fibers filled composites with raster orientations and different building directions [42].

the continuous fiber raster orientations was the most determinant in the failure analysis (see Fig. 5 (a)). In addition, the presence of voids or defects, common in additively manufactured composites could initiate failure [57]. Analogously, Peng et al. [48] found that the laminated hybrid composites had different kinds and numbers of interfaces between different printed material layers depending on the designed stacking sequence, which also was a key indicator of fracture behaviors. Specifically, as shown in Fig. 5 (b), the materials with separated continuous carbon fiber reinforced layers (CCFRLs) owned more S–S and C–S interfaces with better interfacial strength, therefore resulting in higher tensile properties ("C" means continuous carbon fiber and "S" presents short carbon fiber). Besides, Wang et al. [43] reported that the unimpregnated fibers were pulled out of the matrix with remarkable void formation, due to the limited fiber-matrix impregnation behavior of hybrid composites manufactured by using the in-situ impregnation method (see Fig. 5 (c)).

Various researchers also investigated the flexural behaviors of printed hybrid composites by using the three-point bending test. Parmiggiani et al. [45] reported that the flexural strength and stiffness of the materials were significantly dependent on the stacking sequences of CCF. As shown in Fig. 6 (a), the composites with [0°/90°/+45°/-45°] orientation reflected advantages in the flexural properties, owing to better collaboration between the differently oriented layers built to observe. They, therefore, adopted that the mixed orientations of the hybrid fibers reinforcements were recognized as a promising solution for the realization of balanced laminates able to be subjected to multiaxial stress states, thanks to compromised properties of strength and stiffness from hybrid composites.

To investigate the fracture interface of the 3D printed hybrid composites under flexural loads, researchers analyzed the fractured modes of materials by using fractography. Peng et al. [50] found that the flexural behaviors of hybrid composites manufactured by the prepreg extrusion method were highly dependent on the stacking sequence of continuous carbon fiber reinforced layers (CCFRLs). Specifically, as shown in Fig. 6 (a), hybrid samples with separated CCFRLs (SD) demonstrated the capability to delay the cracks' propagation, resulting in higher flexural strength and ductility compared to the specimens with concentrated CCFRLs sequence (CD). On the other hand, Maqsood et al. [40] observed the fracture interface of specimens prepared by the in-situ impregnation method with an optical microscope. Optical micrographs after performing a flexural test presented a clear fractured region in pure PLA (Fig. 6 (b)-a)) and PLA-SCF (Fig. 6 (b)-c)). A fractured region in PLA–SCF–CCF (Fig. 6 (b)-(d)) and PLA-CCF (Fig. 6 (b)-b)) still hold the fibers together within the PLA matrix, resulting in hybrid composites with continuous fiber reinforcements could be used to support the loads during the bending. While for PLA–SCF–CCF specimen, when undergoes bending delamination occurs instead of rupture at the applied load, representing a poor interfacial bond between the matrix and fiber.

3.2.2. *Post-yield behaviors*

To sum up, many studies focused on the elastic properties of 3D printed hybrid short fiber and continuous fiber filled composites. However, the post-yield behaviors of composites, such as the energy absorption capability, were a key index for collision protection structures applications of materials. Peng et al. [50] studied the energy absorption capability of 3D printed PA-based composites containing both short carbon fibers and continuous carbon fibers under different printing parameters, such as raster orientations (0°, 90° and 45°), stacking sequences (SD and CD) and loading directions (loading direction parallel to the thickness (H) and width (W) direction of specimens). They found that the introduction of ±45° layers into laminated composites increased the energy absorption capability of composites due to the significant shearing effect on interfaces between ±45° layers. And there were no obvious cracks in the compressive region of specimens, resulting in high elongation at break and further ensuring high energy absorption. As shown in Fig. 7, the 45-H with high energy absorption capability has advantages to be applied in energy absorption components requiring high energy absorption capability. Besides, 0°-SD-H brought the benefits of a high energy absorption rate due to their high rigidity, which could be applied in energy absorption components where high energy absorption capability was needed within relatively small deformation.

3.2.3. *Interfacial behaviors*

As discussed above, for 3D printed hybrid fibers filled composites, both tensile and flexural properties would not only depend on the properties of each reinforcement fiber materials but also the interactions between the different printed filaments and layers induced by the printing parameters. The relatively weak interfacial bonding of hybrid composites was due to the less printing pressure during the FDM process,

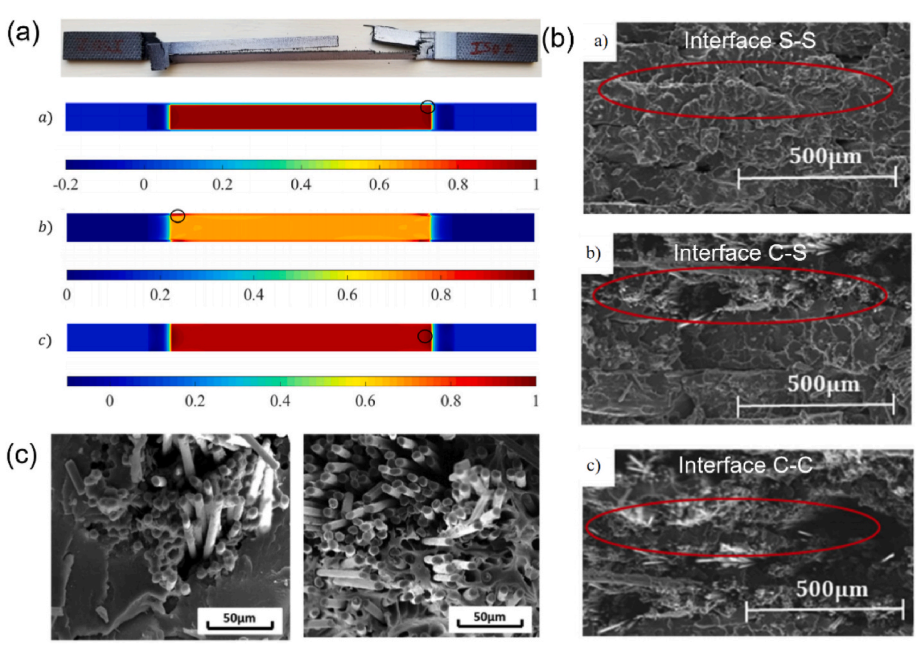

Fig. 5. Failure mechanisms of specimens (a–b) manufactured by prepreg extrusion method [47,48]; and (c) by in-situ impregnation method [43].

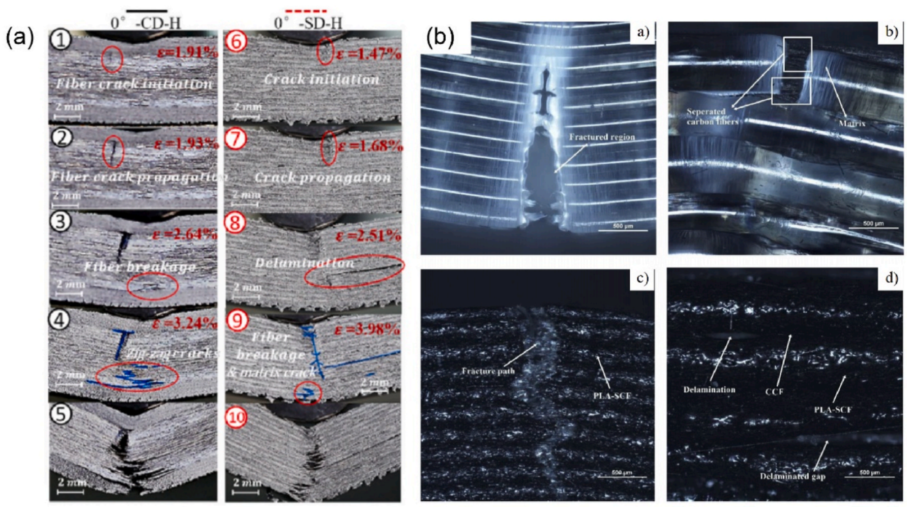

Fig. 6. Fractured modes of specimens (a) manufactured by prepreg extrusion method [50]; and (b) by in-situ impregnation method [40].

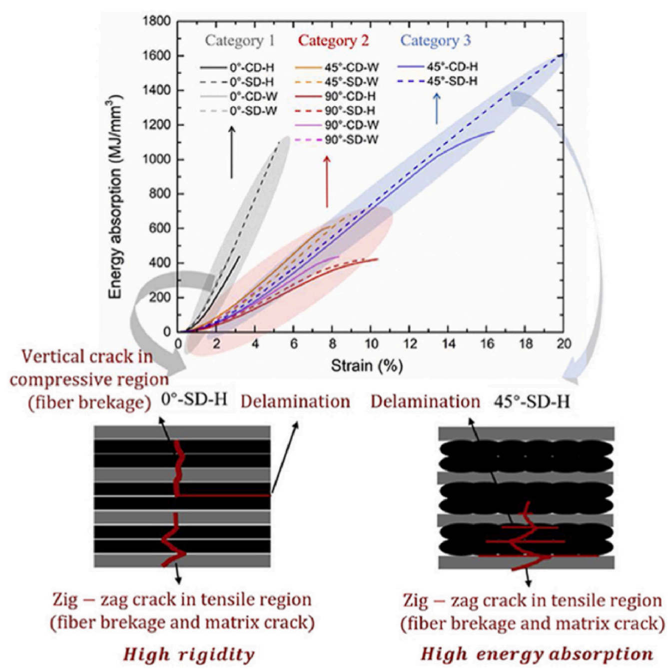

Fig. 7. Energy absorption-strain curves and schematic presentation of the relationship between microstructure design and properties including failure modes for the printed specimens (grey layers are SCFRLs and black layers are CCFRLs) [50].

which led to significant delaminations and de-bonding between deposition lines and layers after fracturing [29]. As a result, researchers investigated the contributions of interface properties of hybrid composites by using the interlaminar shear test.

In Fig. 8 (a) and (b), Fernandes et al. [47] reported that the hybrid short carbon and continuous fibers filled composites tripled the ILSS of single short carbon fiber filled composites. For damage modes, shown in Fig. 8 (b) -a) and -b), the cracks propagated transverse to the bending direction and the predominant mode of failure of the composites samples was interlaminar shear (delamination) which emphasizes the poor adhesion between fiber and matrix layers. On the other hand, the SCF + PA samples displayed a crack propagating at the midspan of the sample from the bottom upwards (Fig. 8 (b) -c)). Similarly, Yavas et al. [46] quantitatively investigated (ILSS) of composites with two different combinations of continuous and short carbon fiber reinforcements by using short beam shear (SBS) tests. They also validated the results of the experiment by using numerical simulations which incorporated the extended finite element method (XFEM) and cohesive zone model (CZM). As shown in Fig. 8 (c), the ILSS exhibited a significant sensitivity to the stacking sequences and showed an increasing tendency with the number of consecutive short CFRP layers. The combined experimental and simulated results showed that the enhancement of fracture strength and toughness of the introduction of thicker short CFRP layers, which prevented the short CFRP layers from brittle matrix cracking at a lower ILSS level and leads to the enhanced plastic deformation of the short CFRP layers.

3.2.4. Post-treatment method to improve interlaminar adhesive properties

To solve the problems of relatively weak interfacial bonding between adjacent layers in hybrid composites, researchers used the post-treatment method for printed composites to improve interlaminar adhesive properties. Wang et al. [49] found that the enhancement of the mechanical properties of hybrid CFRP was mainly due to the decrease of the porosity by heat treatment, which enhanced the interface bonding. In Fig. 9 (a) and (b), it seemed that the adhesion between fiber bundles and impregnated matrix was improved due to less fiber debonding. And the crack initiation of hybrid CFRP during bending tests could be delayed after 100 °C heat treatment.

3.3. Continuous/continuous hybrid fibers composites

To further enhance the compromised mechanical behaviors of printed composites, hybrid continuous fibers as the reinforcements attracted more attention. Researchers investigated the hybridization of continuous Kevlar, carbon and glass fibers filled composites by both experimental and simulated methods [58,59]. There are different approaches for hybridization in continuous fibers filled composites. According to the literature [37,51,60], a distinction was made between the following approaches in this review (see Fig. 10): Inter-layer hybrids, alternating layers of different fiber materials; Intra-layer hybrids, the regular or irregular mixture of fiber materials on a laminate level; Intra-yarn hybrids, mixed fiber materials on filaments/roving level.

3.3.1. Inter-layer hybrids

Wang et al. [38] raised an idea for the first time to design a novel 3D printed continuous hybrid carbon and Kevlar fibers filled laminated composites with Inter-layer hybridization (layer-by-layer). Meanwhile, they analyzed the hybrid effect on the energy absorption capabilities of

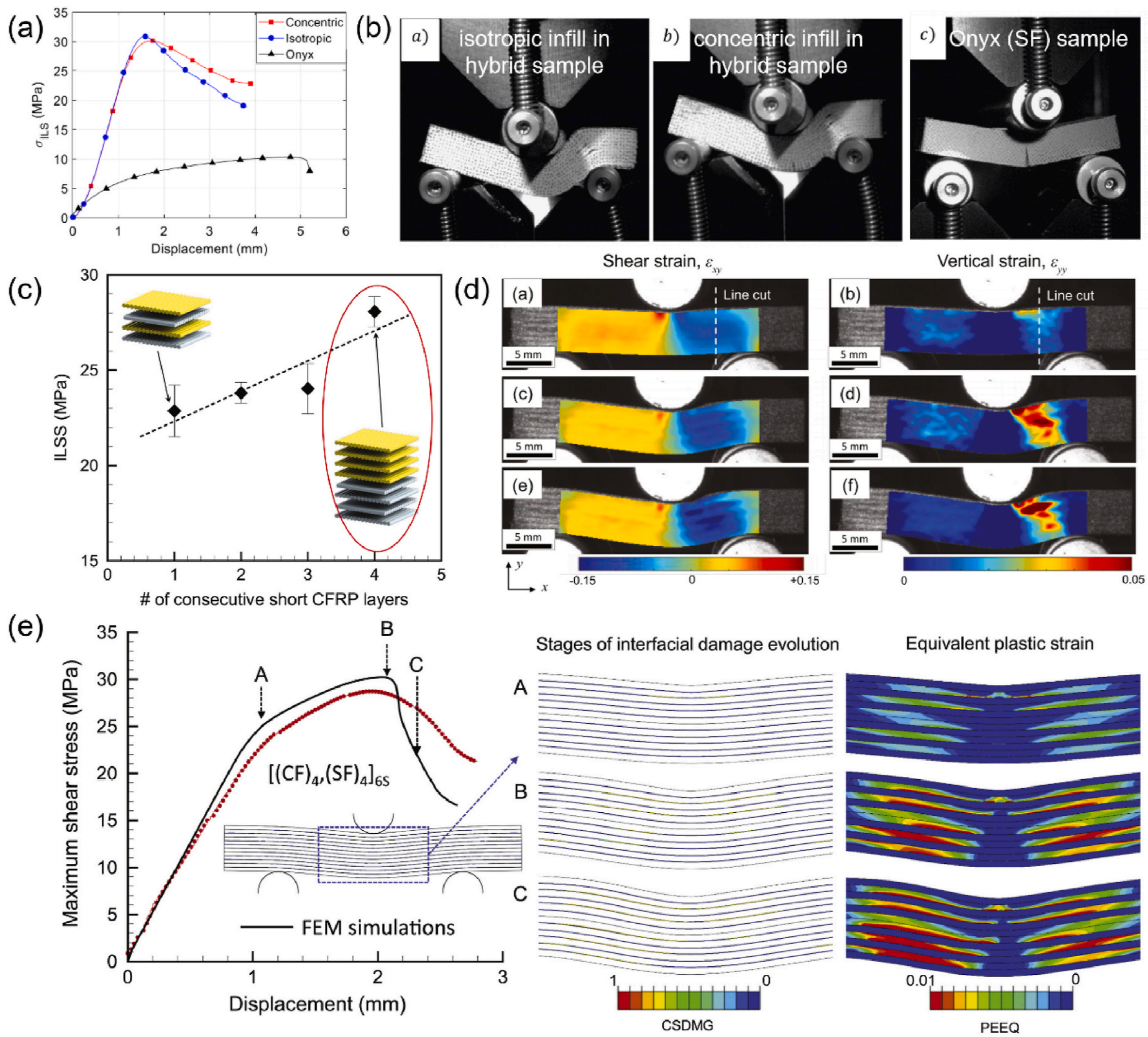

Fig. 8. (a) Average interlaminar shear strength (ILSS)-displacement curves and (b) failed interlaminar shear test samples for hybrid and non-hybrid composites [47]; (c–e) the comparations of experimental and simulated results for the composites with stacking sequence of $[(CF)4, (SF)4]_{6S}$ [46].

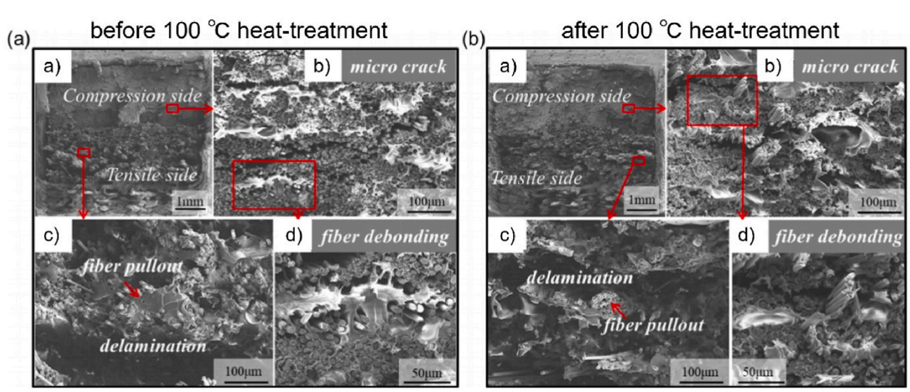

Fig. 9. SEM images of fracture surfaces for printed hybrid CFRP composites (a) before and (b) after 100 °C heat-treatment [49].

the printed hybrid composites by using a hybrid effect model [61,62]. They reported that the printed composites containing both continuous carbon and Kevlar fibers simultaneously tailored rigidity and ductility, showing a positive hybrid effect at a relatively large deformation displacement (see Fig. 11 (a)). As shown in Fig. 11 (b), the deformation and failure mechanisms of hybrid continuous fiber reinforced composites highly depended on the designed position of fibers. Specifically, the highest indentation force could be achieved when continuous Kevlar fiber layers were placed at the rear side. While the highest energy absorption capability of the printed composites was captured when continuous carbon fiber layers were positioned at the rear side.

Based on this conclusion, Wang et al. [52] further investigated the

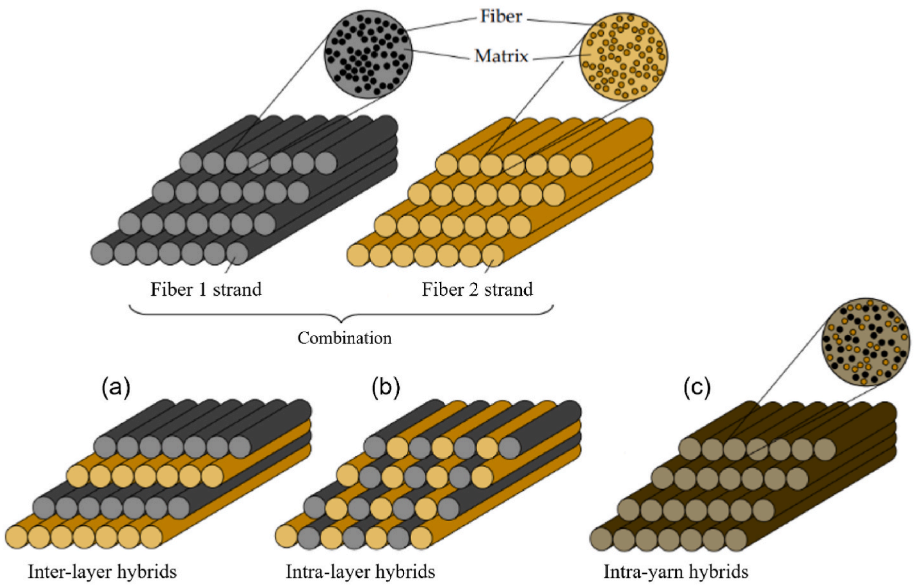

Fig. 10. Schematic of three types of hybrid composite structures. (a) Inter-layer hybrids, (b) Intra-layer hybrids, (c) Intra-yarn hybrids [37].

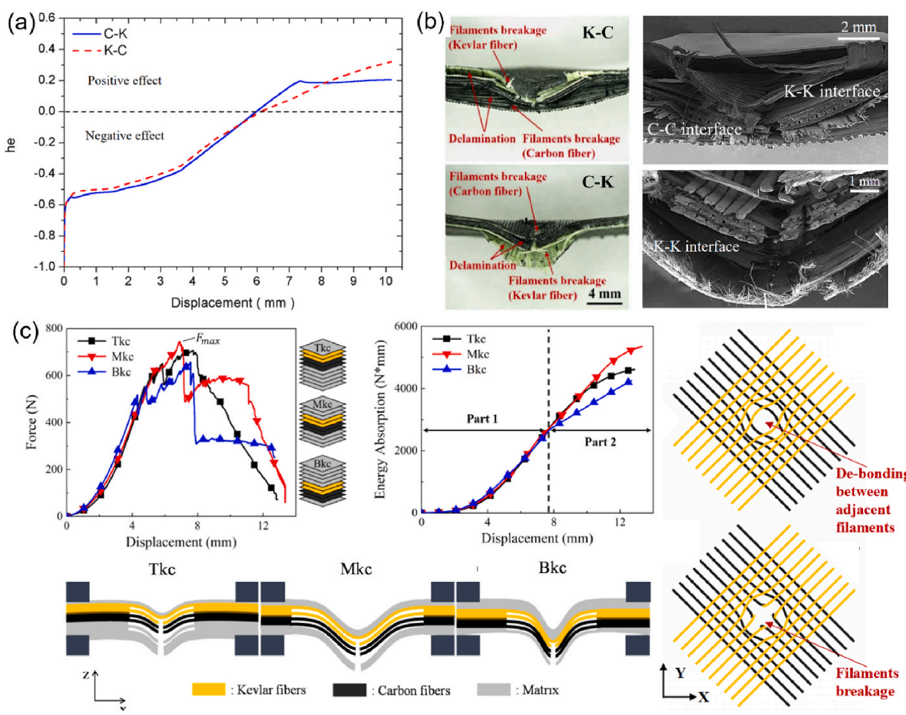

Fig. 11. (a) Hybrid effect and (b–c) deformation and failure mechanisms of hybrid composites [38,52].

effect of fiber layer locations and stacking sequences on printed hybrid composites by using the quasi-static indentation (QSI) tests, as shown in Fig. 11 (c). Results demonstrated that the printed composites with the middle fiber layer locations showed the highest force value (Fmax) and higher energy absorption capabilities than the printed composites with the fiber layers placed in other locations, which was attributed to the delayed cracking propagation and large delamination, respectively.

Similar to printed hybrid short fiber and continuous fiber reinforced composites, the interfacial bonding between different materials layers were relatively poor, which led to distinct delamination, further weakening the mechanical properties. Based on this, Li et al. [53] evaluated the adhesion properties of different interfaces in printed hybrid composites by using a peeling test (see Fig. 12 (b)). Then they considered the interfacial contributions into a Volume Average Stiffness (VAS) model [10,23] to predict the mechanical behaviors of hybrid composites under various printing parameters, such as printing orientations and stacking sequences. The combined experimental and predicted results showed that the hybrid composite specimens with separated distribution sequences showed a higher tensile modulus compared to concentrated distribution hybrid composites (see Fig. 12 (a) and Fig. 12 (d)), which were attributed to the strong interfacial bonding which delayed the crack's initiation and propagation.

To evaluate the damage behavior of 3D printed continuous hybrid fibers reinforced thermoplastic composites. Huang et al. [51] used a well-established analytical model developed by Jalavand et al. [63] to predict the stress-strain response and damage modes of several laminate

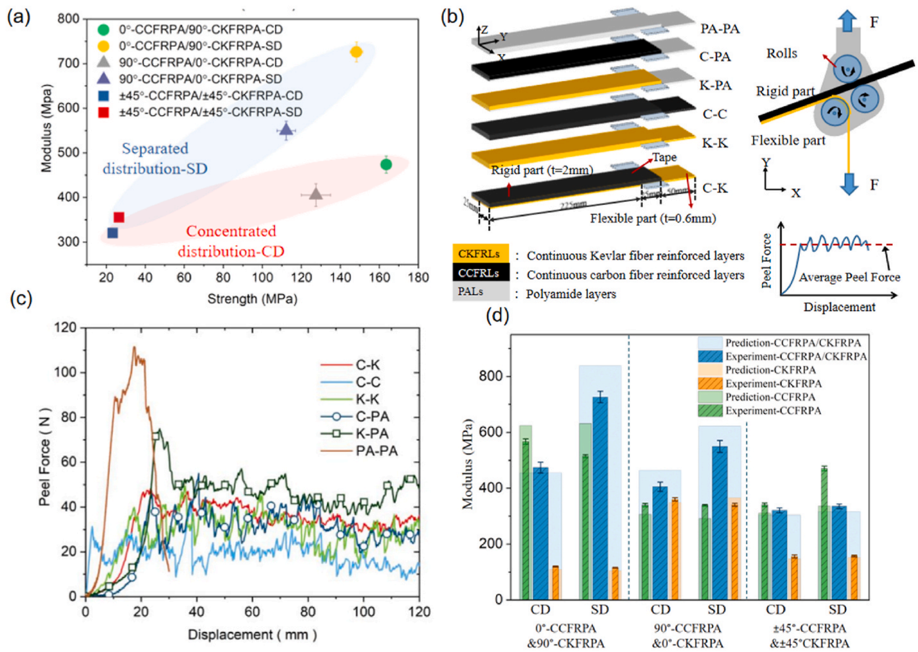

Fig. 12. (a) Tensile modulus and strength, (b) schematic diagram of peeling test setup, (c) peeling force-displacement curves and (d) predicted results of 3D printed continuous hybrid FRP composites [53].

configurations and validated them against a series of experimental measurements. They divided four types of damage modes for hybrid composites under different ply thicknesses and different relative hybrid ratios, as shown in Fig. 13 (The numerals refer to the damage modes: (1) High strain material (HSM) failure, (2) Catastrophic delamination & HSM failure, (3) Low strain material (LSM) fragmentation & HSM failure, and (4) LSM fragmentation, diffuse delamination & HSM.).

3.3.2. Intra-layer hybrids

Compared to the Inter-layer hybrid approach, the intra-layer hybrid approach led to improve dispersion of fibers, and better adjustability of mixing ratio-especially for thin, plat parts, which could increase the interfacial behaviors between adjacent layers. Heitkamp et al. [37] manufactured printed continuous hybrid fibers filled composites with the Intra-layer hybrids type, as shown in Fig. 14 (a) and (b). Besides, Luan et al. [54] fabricated a hybrid continuous carbon/glass fiber

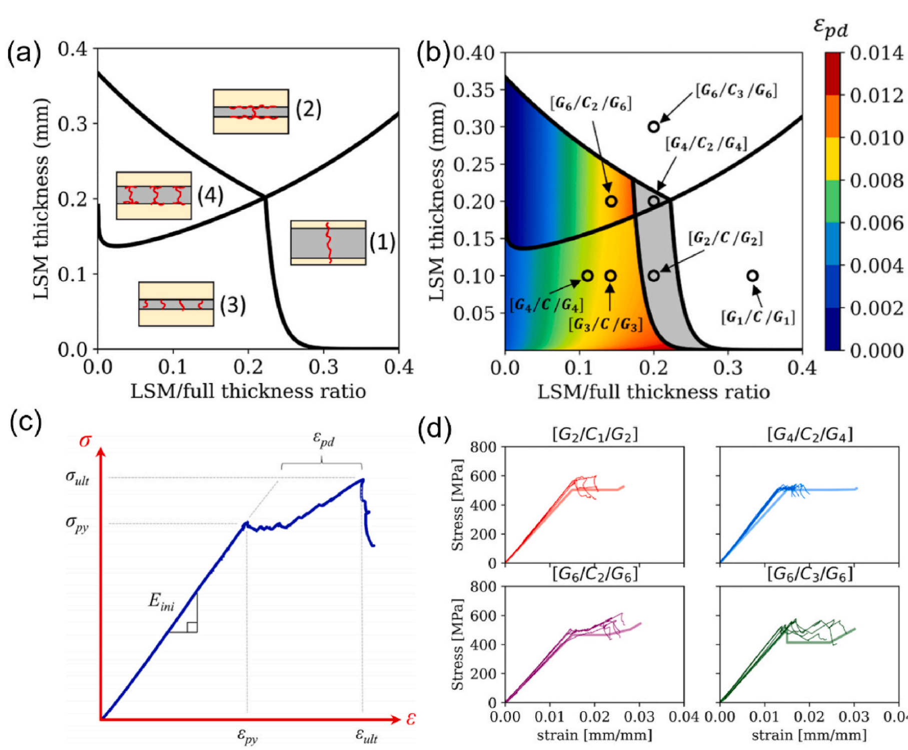

Fig. 13. (a) Schematic diagram and (b) experimental results of damage mode map and (c–d) tensile results of the stress-strain curve for 3D printed hybrid carbon-glass composite [51].

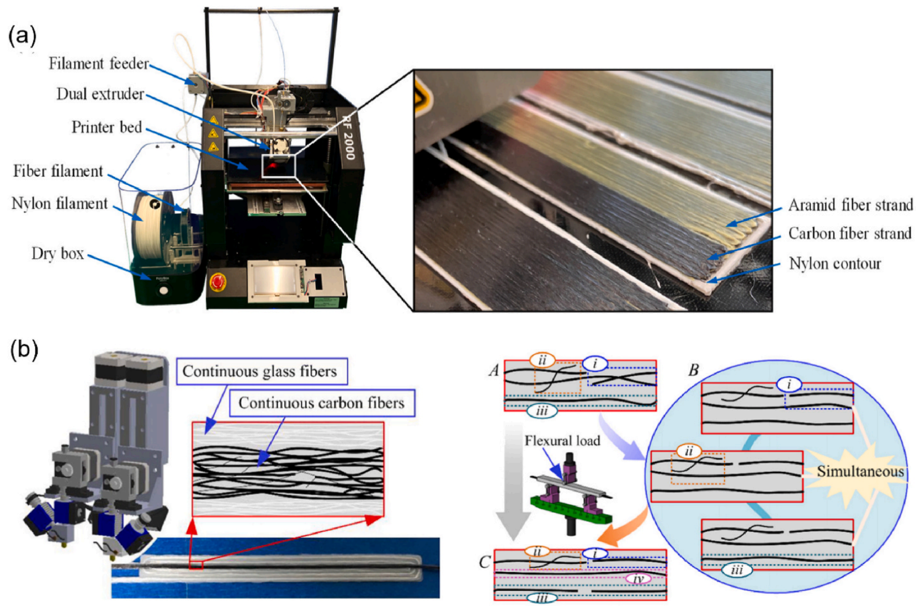

Fig. 14. (a–b) Schematic representation and picture of the continuous hybrid composites during the printing processes by using intra-layer hybrids methods [37,54].

reinforced thermoplastic composite that possesses self-sensing capabilities, and in which continuous carbon fibers were employed as sensory elements (see Fig. 14 (b)). They found an irreversible dramatic change in electrical resistance when structural damage occurred, which was a prospective indicator of both strain/stress self-sensing and damage detection. However, the number of fiber cuts required per layer and the duration for a fiber or tool change thus increased production time and increased effort for path planning. It was therefore not yet widely used in printed continuous hybrid fibers composite manufacturing.

3.3.3. Intra-yarn hybrids

An intra-yarn hybrid approach requires the use of different fiber materials in one roving or fiber filament. Accordingly, this approach does not require tool changes or additional fiber cuts but is associated with a loss of flexibility. Consequently, the mixing ratio for machine code generation cannot be set in a defined way but depends on the ratio of the semi-finished dry fibers used. Zia et al. [55] manufactured a novel printed continuous hybrid carbon and Kevlar fiber filled composites with intra-yarn hybrid approach. They further investigated the fracture pattern of hybrid composites after the drop hammer impact testing. The proposed hybrids have greater impact force and energy absorption ability than standard single-type fiber composites (see Fig. 15(a and b)). For non-hybrid specimens, there were nearly fractures at the end of the impact test, whereas hybrid specimens almost no fracture propagation was seen by the naked eye, and with unbroken fibers on the back sides (see Fig. 15 (c)).

4. Conclusion, limitation and prospective

The hybridization of the different types of fibers in the FDM 3D printing process could be described as one of the great achievements in the evolution of composites science and smart manufacturing technology. As such, the printed hybrid fibers composites with superior comprehensive properties had rendered a huge potential to be used in the future structural and functional applications of polymer composites. Recently, many studies conducted by the research community to reveal and to exploit different types of hybrid fibers to be used in polymer composites. Although researchers have been dedicated to the development of hybrid fibers reinforced printed polymer composites for various purposes, it was still in its infant stage of being realized on real products.

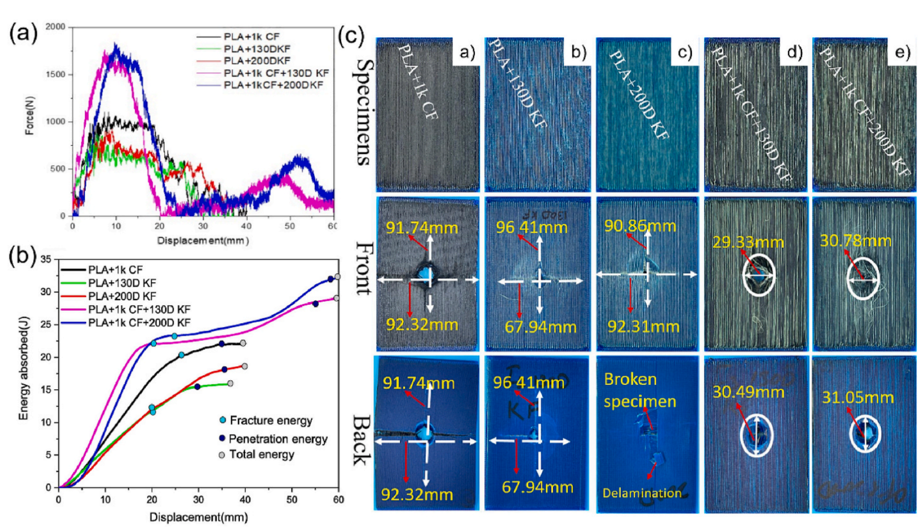

Fig. 15. (a) Force-displacement curves, (b) energy absorption-displacement curves and (c) fracture picture of composites by using low-velocity impact test [55].

As such, the selection of the best fabrication parameters for producing the printed hybrid fibers composites was found to be crucial before the implementation and introduction of the real applications. This paper therefore reviewed the research focusing on the mechanical properties of hybrid fibers (short/short, short/continuous and continuous/continuous fibers) reinforced composite materials based on FDM fabricating method, under different printing parameters.

Up to now, there were two kinds of 3D printing techniques to manufacture the hybrid FRP composites. However, both hybrid FRP composites prepared by the prepreg extrusion method and in-situ impregnation method showed limitations as discussed following. For the in-situ 3D printing approach, the incomplete impregnations of fibers made the poor bonding behaviors between hybrid fibers and matrix. The bad impregnating properties were due to the (1) high viscosity of the molten thermoplastics, the extremely short impregnation times and a lack of compressive force during the printing process; (2) uneven distribution of the matrix and poor impregnation could lead to the rich regions of hybrid fibers and polymers during layer-by-layer formation printing processes, which caused by the difficulty in impregnating the hybrid dry fiber tows. For the prepreg extrusion method, several fiber cuts were required per layer and the duration for fiber changing, which led to low-efficiency manufacturing.

The hybrid materials selection for 3D printed FRP composites was few in current studies, which were mainly composed of short fiber and continuous fiber, including carbon fiber, Kevlar fiber and glass fiber. Though these hybrid fibers showed a synergistic enhancement effect compared to those raw or single fiber filled materials, it was still a limited application in the industry. Besides, most current studies focused on the mechanical behaviors of 3D printed hybrid FRP laminated composites, also resulting in a limited application in practical engineering situations.

The major articles denoted that a significant issue concerning the printed hybrid FRP composites was the weak mechanical properties obtained at the interface bonding. Nevertheless, although there were combinations of printing parameters and post-treatment methods which could increase it, the final value of the bond strength was lower than that of the base material [49]. By using solid and immiscible materials, the intermolecular diffusion was reduced and the interfaces obtained were usually abrupt, causing physical discontinuities and reducing the mechanical properties especially the interface was generated between different materials. The relatively weak interfacial bonding of printed hybrid FRP composites was also due to the less printing pressure during the FDM process, which led to certain voids of manufactured composites, resulting in significant delaminations and de-bonding of materials after fracturing.

Before the newly developed 3D printed hybrid fiber filled composites could be applied in industry, improvement needed to be achieved in the process, materials, properties and structures. The future challenges for printed hybrid FRP composites in our minds were as followed.

- The mechanical performances of 3D printed FRP composites could be enhanced by increasing the impregnation degree through the multiple in-situ impregnations process and the pressure devices designs at the extrusion nozzle. The concentration of solution has a high influence on the quality of impregnation fiber tows. Increasing the concentration of the plastic solution allowed decreasing the number of air voids in impregnated fiber tows, resulting in a better interface between fibers and matrix. Besides, for prepreg extrusion method, an approach involving the combination of more than two prepreg fiber extrusion heads could save production time and cost. In addition, the composites could be manufactured by hybrid fibers with multi-matrix resin, to enhance the interface between fibers and matrix. Because the different properties owned by the different matrix resins may improve the diffusion and contact between materials.
- The materials selection for 3D printed FRP composites were not only aimed to enhance the mechanical behaviors, but also needed to focus on the functional properties, such as conductivity for self-detecting, hydrophobicity for fireproofing, porosity for cushioning and degradability for environment-friendly, etc. Specifically, the addition of more optical fibers to printed composite structures to monitor health status or to realize health self-monitoring.
- Another future challenge for expanding the application of printed hybrid FRP composites in our minds was manufacturing products with modularization, function and load-bearing. One of the greatest advantages of printed hybrid materials was that versatile materials could be simultaneously used for building a single object, which was ideal for the fabrication of control components consisting of different parts. In addition, lightweight structures could be also applied in the printed hybrid fiber filled composites, to meet more load-bearing requirements.
- Surface modification for the prepreg fiber and matrix filaments could probably enhance layer-to-layer adhesion as well as further increase interfacial strength between the fibers and matrix. Meanwhile, mechanical interlocking characteristics were useful to strengthen the bonds between adjacent layers. The use of interlocks adjustments between dissimilar materials increased the resistance of the interface. As a consequence, the correct design of interface geometry that allowed mechanical interlocking, so that chemical forces were not the only ones that work, maybe became a key factor in hybrid FRP composites.
- Parts manufactured with a continuous gradient between dissimilar materials, rather than abrupt interfaces, tended to have better mechanical performance and improved bond strength than parts manufactured with discrete gradients.

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Author contributions

All authors contributed to the study's conception and design. Shixian Li: writing—original draft, data curation and methodology, Kui Wang: Conceptualization, resources and writing—review and editing, Ping Cheng: software, writing—review and editing Said Ahzi: Conceptualization, Supervision, Yong peng: data curation and Validation, Francisco Chinesta: Validation, writing—review and editing, J.P.M.Correia: software, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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