3D Printed Fiber Reinforced Composites Using Fused Deposition Modeling: A Survey

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Abstract

Using short and continuous fiber reinforcement to improve the mechanical properties of 3D printed parts has been an attractive remedy for the poor mechanical properties of 3D printed parts using pure thermoplastic materials. A brief description on the mechanical properties of the fiber reinforced composites are given. Further, the scanning electron microscope (SEM) were analyzed to understand the challenges that current research literature are facing. Furthermore, recent developments for improvements of the final properties are given. Plus, future research opportunities are mentioned as well.

Introduction

Additive manufacturing also referred as 3D printing has been popular since its very first prototypes that were created in mid 1980s [12]. It is a process of adding materials to build a three-dimensional model by depositing the raw material into successive layers. Numerous AM processes have been developed throughout the years with applications in aerospace, automotive, biomedical, digital art, architectural design, etc [19]. Fused deposition modeling (FDM), is one of most common additive manufacturing (AM) techniques, and has the most contribution in prototyping throughout the industry. Making complex parts almost directly from CAD models with little to no material waste and making small number of parts or even custom parts, while reducing manufacturing costs is advantageous for rapid prototyping [12]. To date, there has been various developments in the fused deposition modeling (FDM) additive manufacturing method to improve the mechanical properties of the 3D printed parts. Examples of these developments are choosing the right material for the desired mechanical properties and modified printing parameters such as; modifying print orientation with the print build [3], reducing layer thickness to achieve the desired strength and ductility [3].

Due to limited mechanical properties of pure thermoplastic materials used in FDM, it is needed to improve the mechanical properties of 3D printed parts. Adding fiber reinforced materials (such as carbon fibers) is an effective method to improve the mechanical properties [21]. The result of this process is a fiber reinforced composite, in which the thermoplastic acts as the matrix of the 3D

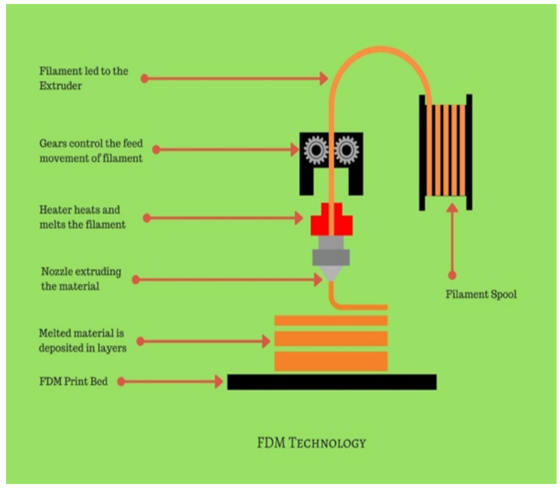

Figure 1: Schematic of fused deposition modeling (FDM) procedure [9]

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printed composite. The most commonly utilized fibers in 3D printed composites are short fibers [7,8,10,14,20,21,31], and continuous fibers [13,15,16,32]. Through the literature, there has been numerous reports showing significant improvements in mechanical properties of the 3D printed fiber reinforced composites as well as the constraints that needs to be addressed [2,7,8,10,13–16, 20,21,31,32].

This literature review helps the reader to understand the challenges and constraints associated with the FDM 3D printed fiber reinforced composites. Further, an overview of the fracture surface analysis of the 3D printed composite parts and the overall progress in the improvement of the mechanical properties of the 3D printed composite specimens is given. At the end, the future research opportunities in this area are mentioned.

Methodology

The general principal of fused deposition modeling (FDM) process is illustrated in Fig. 1. The part is built by selectively depositing melted material in a pre-specified path layer-by layer. The filament is pushed through a heated chamber to melt the filament material. The pushing force is provided by two rollers rotating in opposite directions.

Since the primary design of FDM 3D printing, is to use the raw materials as filaments, it is required to modify the system or filaments to be able to print 3D fiber reinforced parts. In the following, currently available methods of printing for short and continuous fiber reinforced composite parts are described.

Short fiber reinforced composites printing procedure

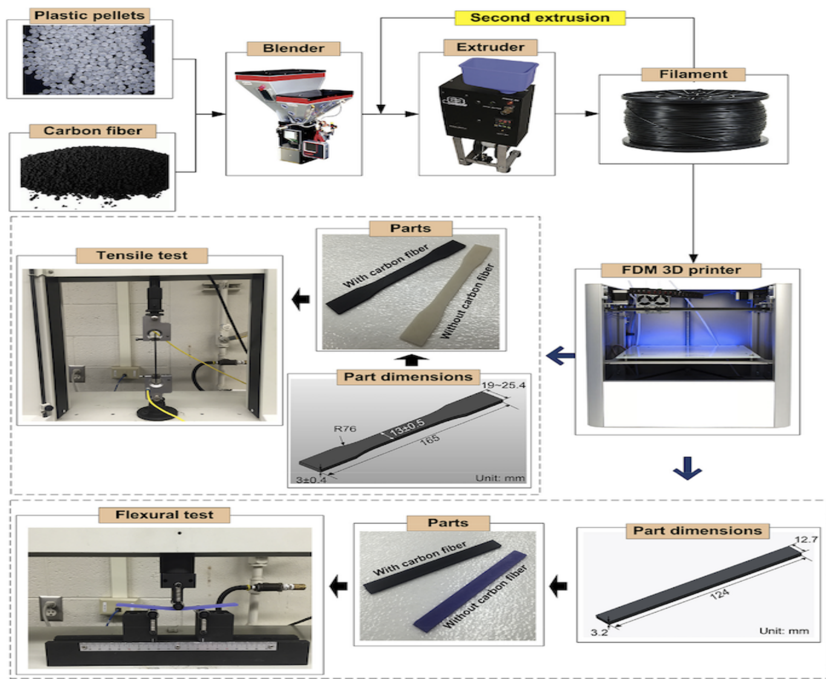


Figure 2: Procedure of Short fiber reinforced filament production by [21]

Fig. 2 is the summary of the fabrication process and testing of the short fiber reinforced composites demonstrated by Ning et al [21]. In the first step of this process, the thermoplastic and carbon fiber materials are mixed at a desired rate prior to blending. The percentage of the carbon fibers are measured carefully as the properties of the 3D printed material can be altered by this parameter. The materials are then mixed using a blender and then shaped into a filament by an extruder machine. The filaments are then used to print the designated part.

Continuous fiber reinforced composites printing procedure

FDM 3D printing of Continuous fiber reinforcement parts procedure follows the same principal of the original thermoplastic FDM 3D printing with minor alterations in print head. Two commercially available printers by Mark Forged are illustrated in Fig. 3. Fig. 3(a) demonstrates using two different nozzles, one for the plastic material to be placed as the matrix, and the other for fiber to be placed in the matrix [15]. Further, in Fig. 3(b), the fiber and matrix are formed in the print head and are deposited in the form of a fiber [13].

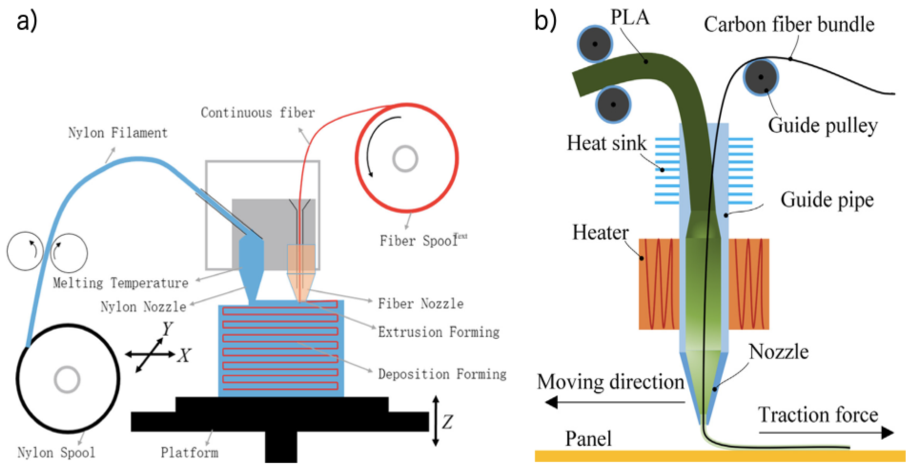


Figure 3: Continuous fiber reinforcement printing procedure Using two separate nozzles [15]. Continuons fibre reinforcement Printing procedure using one nozzle [13].

Mechanical properties

The ability to improve the mechanical properties of thermoplastics by fiber reinforcement has been proved through literature [2, 7, 8, 10, 13–16, 20, 21, 31, 32]. An experiment conducted by Tekinalp et al. [31] which was implemented on compression molded and FDM 3D printed specimens showed the dominant properties of compression molded samples. The dominancy of compression molded samples was reported to be due to existence of pores in 3D printed parts, which will be discussed in analysis section of this paper.

A study by Ferreira et al. [7] showed the addition of short carbon fibers to PLA specimens can increase the tensile modulus E1, E2 and the shear modulus up to 2.2, 1.25 and 1.16 times more than the pure PLA specimens respectively. Similar study on ABS thermoplastics by [8, 21] exhibited that adding short fibers can increase tensile strength and young modulus, but it will decrease toughness, yield strength and ductility. It was also found that the final properties of the composite depend on the length and the percentage of short fibers in the filaments as well [21].

The results of continuous carbon fiber reinforcement on nylon thermoplastic illustrated higher stiffness and ultimate strength in printed parts with a higher volume percentage of carbon fibers [15, 16]. Another experiment by Nanya et al. [13] showed additional improvement in the final properties of the continuous fiber reinforced composites. The author has achieved a better wetting and thus a higher tensile and flexural strength compared to the original carbon fiber reinforced samples up to 13.8% and 164% respectively. (The modification process is described briefly in analysis section.) Fig. 4(a, b) are comparing the

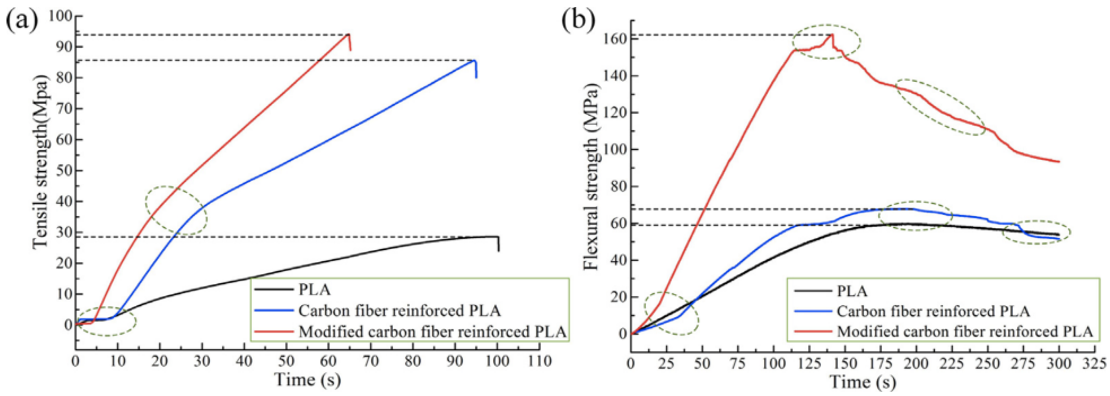


Figure 4: Mechanical properties of three different materials printed by the same process condition, (a) Tensile strength of PLA, carbon fiber reinforced PLA and modified carbonfiber reinforced PLA, (b) flexure strength of PLA, carbon fiber reinforced PLA and modified carbon fiber reinforced PLA [13]

stress-strain curve of the modified and original carbon fiber reinforced samples with pure PLA samples [13].

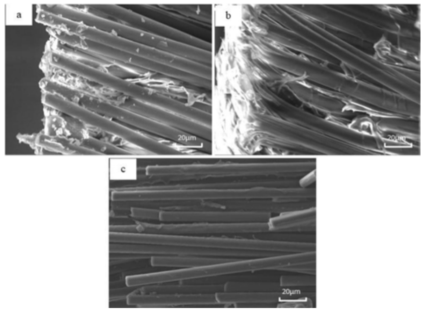
Generally, tensile and flexural test are carried out to determine the mechanical properties of the specimens. Specimen geometry and testing conditions are adjusted as per standard testing procedures such as ASTM D638-10 [28] and ASTM D790-10 [2].

Analysis

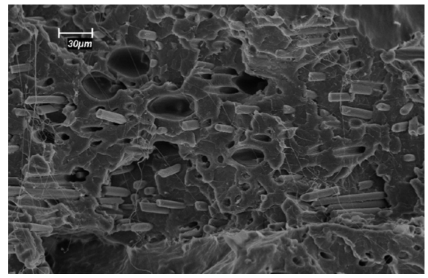
Fiber-Matrix Debonding

Fig. 5(a) [15] And Fig. 5(b) [7] are showing the scanning electron microscope (SEM) analysis of the fractured surface of both continuous and short fiber reinforced 3D printed composites respectively. Fiber matrix debonding was observed in both short and continuous fiber reinforced 3D printed composites as a common deficiency. This imperfection is easier to be identified in continuous fiber reinforced specimens. The fiber pull out of the continuous fiber reinforced composites is shown in Fig.5. The illustrated fiber pull outs of composite are almost free of any plastic matrix. In case of short fiber reinforced specimens, this deficiency is observed through the total mechanical behavior of the parts.

Fiber pre-processing was proposed by Nanya et al. [13] as a promising solution for fiber-matrix debonding in 3D printed continuous fiber reinforced composites. The surface modification of carbon fiber is conducted before the printing process to improve the interfacial strength, as shown in Fig. 7. The methylene dichloride solution is added and the PLA particles (8% mass fraction) partially dissolved after 30 min magnetic stirring. A high-speed dispersing and emulsification machine was used to shear and emulsify the filtrate of PLA resin in



(a)



(b)

Figure 5: (a) SEM micrographs of fiber pull out of Fiber for three different fiber reinforcement materials Glass fiber, Kevlar fiber, and Carbon fiber [15]. (b) SEM micro-graphs of Specimen of PLA+CF at ±45 [7]

methylene dichloride solution. The surface active, emulsifying and antifoaming agents are added in the deionized water with 1% mass fraction of total solution. Then slowly add the deionized water to process the aqueous PLA sizing agent and modify the surface condition of carbon fibers.

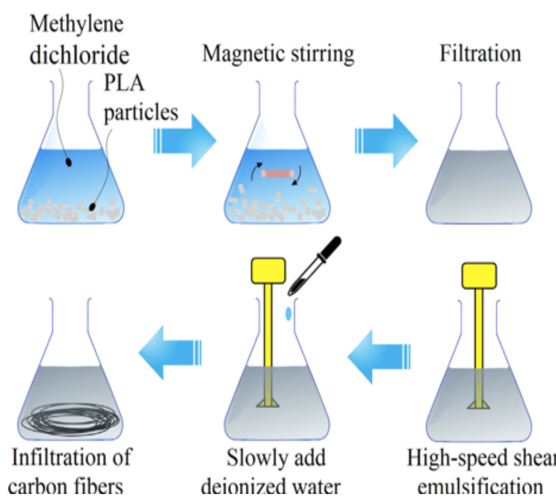


Figure 6: Preprocessing procedure for continuous Fibers [13]

The SEM micrographs in Fig. 7(a-f) demonstrate the fiber matrix interface before tensile test (a and d), the fiber matrix interface after tensile test (b and e) and the morphology of fiber pull out of the carbon fiber reinforced sample (c and f) respectively [13]. Comparing the micrographs between fiber matrix interface of the original and modified carbon fiber reinforced composites, homogeneous distribution of thermoplastic between fibers and nearly void free microstructure can be found in the modified carbon fiber reinforced samples.

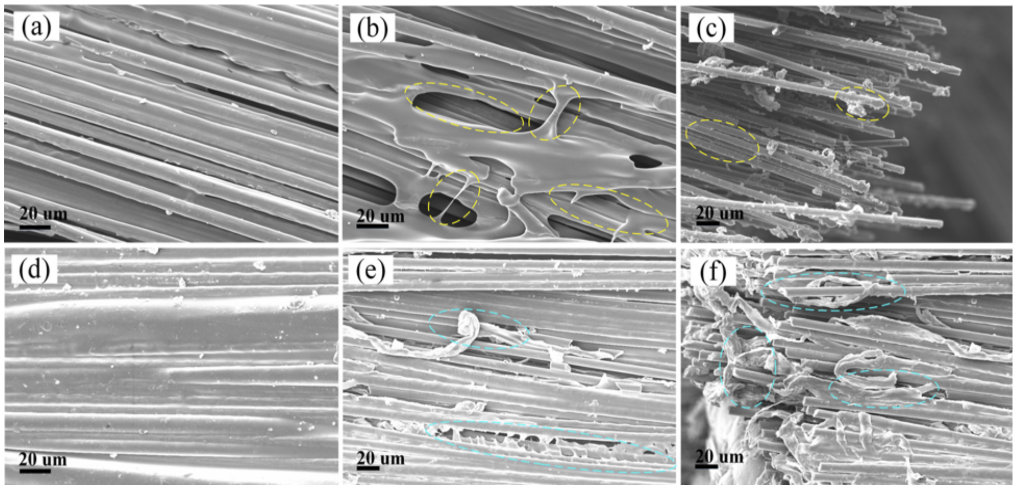


Figure 7: SEM micrographs of printed composites, (a) fiber-matrix interface of carbon fiber reinforced PLA specimen, (b) carbon fiber reinforced PLA specimen after tensile test, (c) fiber pull-out of specimen after tensile test, (d) fiber-matrix interface of modified carbon fiber reinforced PLA specimen, (e) modified carbon fiber reinforced PLA specimen after tensile test and (f) fiber pull-out of modified carbon fiber reinforced PLA specimen after tensile test [13]

Pores and voids

Pores and voids are described as unfilled spaces in the material. The presence of voids reduces the material integrity, thus resulting in poor mechanical properties. Ning et al. [21] reported three types of pores as are depicted in Fig. 8.

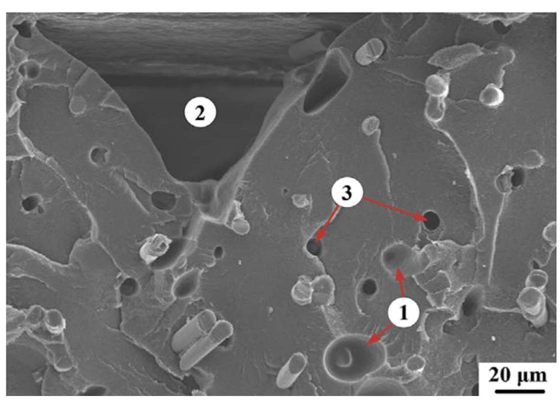


Figure 8: Illustration of different categories of the specimen porosity [21]

Pores can be categorized in three types [21]; Type 1 pores (inner-beads), are gas evaluated, and are generated during the fabrication of feedstock filaments [21], which can be related to the pores inside the raw as-received thermoplastic filaments as well. Type 2 pores (interbeads), are actually physical gaps between each layer, and are identified as the largest defects and highest stress concentrators. To minimize this deficiency, various systematic approaches has been taken that will be discussed. Type 3 pores are due to fiber pull out on the fracture surface, hence are not counted as imperfections. Tekinalp et al. [31] investigated the relationship between fiber content and void formation. The study illustrated a better packing of deposited beads as the result of increasing the fiber contents, and thus smaller inter bead voids. However, it resulted in a bigger inner bead void formation. Fig. 9 Illustrates an overall comparison of fiber content between compression molding and FDM process. Generally, there is no effect of fiber content on void formation in compression molding, and significant effects were only observed on 3D printed specimens. Fig. 9(e) shows the inter bead voids of pure plastic 3D printed parts. Fig. 9(f) shows the addition of 10% of short carbon fibers, which resulted in better packing of deposited beads, and thus smaller inter bead voids. The increase in short fiber content results in even smaller inter void beads as depicted in Fig. 9(g, h). despite the reduction in size of inter bead voids, the number of small inner voids is observed as the fiber content increased [31].

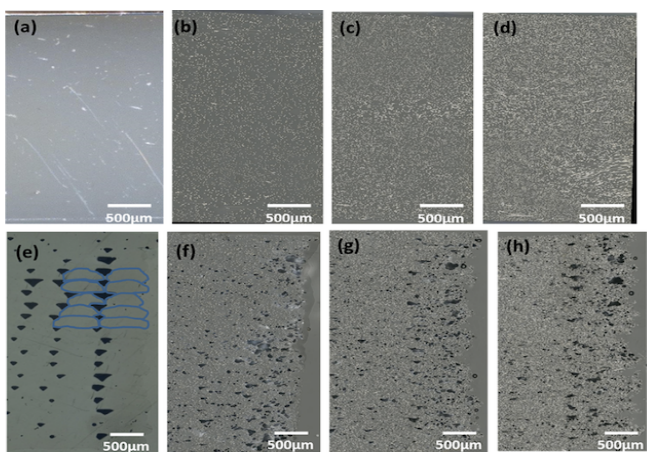


Figure 9: Micro-graphs of polished surfaces of dog-bone slices. (a) CM neat-ABS, (b) CM10% CF, (c) CM20%CF, (d) CM30%CF, (e) FDM neat-ABS, (f) FDM10%CF, (g) FDM20%CF, and (h) FDM30%CF [31]

Increasing the volume of fiber contents proved to be an effective way to reduce the voids in the 3D printed short fiber reinforced composites, but it did not show any effect on voids in 3D printed continuous fiber reinforced composite samples. However, increasing the volume of fiber content in the specimens resulted in a higher stiffness and ultimate strength [16].

Vibration Assisted FDM (VA-FDM) method was developed by Keles et al. [10] to minimize the inter bead voids. This method manipulates the printing procedure itself by connecting a vibrator to the print-head and transfer the straight printing path into a zigzag path. Fig. 10 Illustrates the difference between vibration assisted and vibration free inter bead voids.

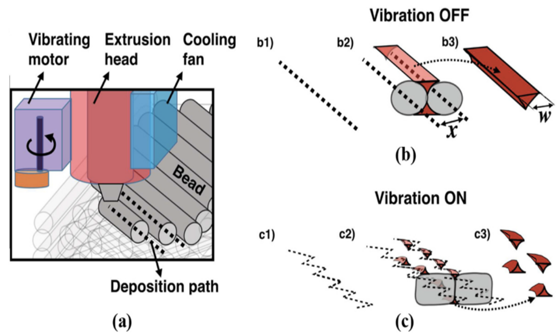


Figure 10: a) Schematic showing the FDM process and vibration motor at the extrusion head; b) and c) schematic showing the changes in deposition path, inter-bead porosity and deposition path, and isolated inter-bead pores when the vibrations are on and off [10]

The SEM analysis of fracture surface of the vibration assisted experiment is illustrated in the Fig. 11. Vibrations decreased inter-bead porosity and reduced pore size, which resulted in an increased fracture strength, tensile strength, nominal strain at break and elastic modulus of the printed parts [10].

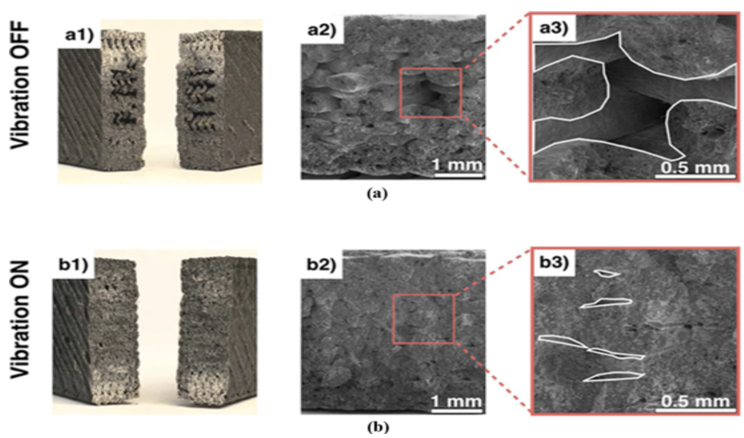


Figure 11: Digital images of the fracture surfaces of the composites produced a1) without and b1) with vibrations; a2-3) and b2-3) SEM micrographs showing the inter-bead porosity. White borders in a3) and b3) show the inter-bead pores [10]

Printing pattern and procedure

Printing pattern and procedure of continuous fiber reinforced composites is effective in governing the failure patterns. As reported by Melenka et al. [16], Kevlar fibers exhibited a nonlinear stress-strain curve as depicted in Fig. 12.

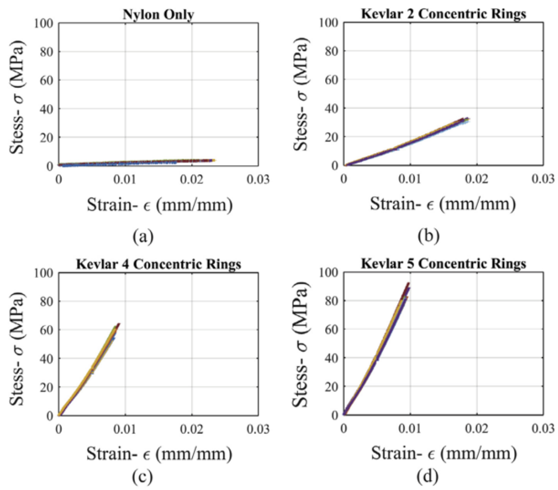


Figure 12: Stress-strain curves for the four Kevlar fiber reinforcement configurations (a) Nylon only sample configuration (b) Two-concentric Kevlar rings configuration (c) Four concentric Kevlar rings configuration (d) Five concentric Kevlar rings configuration [16]

These nonlinear curves are resulted from the Kevlar fiber waviness, which their presence is due to the lack of tension in the Kevlar fiber while being deposited [16].

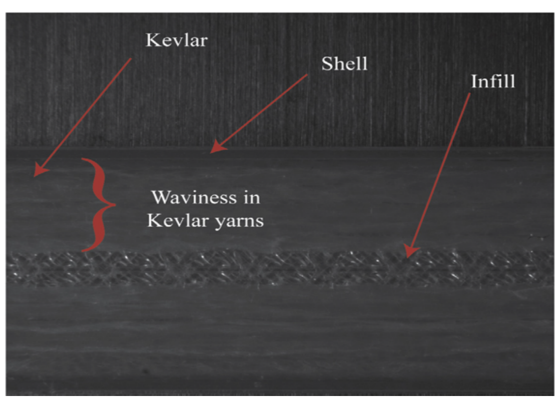


Figure 13: Cross-sectional image of a test specimen. The shell, infill and Kevlar regions of the test specimen are shown [16]

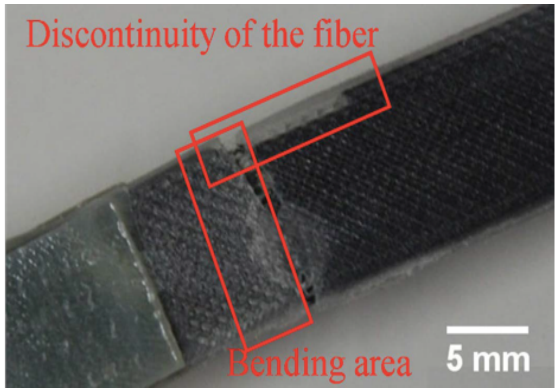


Figure 15: Sample failure location. Sample failure occurs at the fiber end location location of the carbon fiber reinforced specimen [32]

Another factor of printing pattern that governs the mechanical behavior of the 3D printed composites is the starting point as was reported by Keles et al. [16]. Fig. 14 Shows the failure location where the fiber path begins [16].

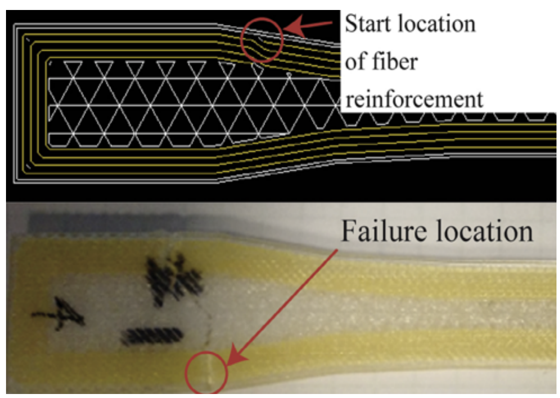


Figure 14: Sample failure location. Sample failure occurs at the starting location of the Kevlar fiber reinforcement [16]

Fig. 15. Illustrates the same effect on locations where the fiber ended which was reported by [32].

Also, it was seen that the fiber pattern and reinforced material governs the final properties of the composite [15]. As it is illustrated in Fig. 16 (1, b), the rectangular carbon fiber with 8 rings has the highest value of tensile strength and elastic modulus.

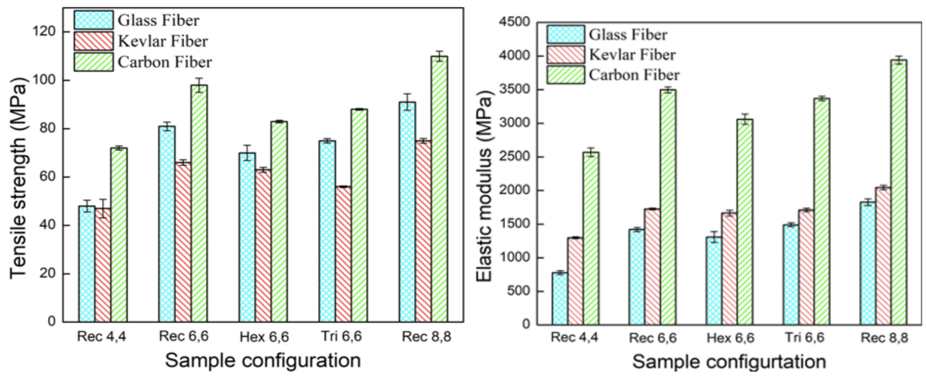


Figure 16: a) Comparison of the tensile strength of the three fiber reinforced 3D printed sample configurations b) Comparison of the elastic modulus of the three fiber reinforced 3D printed sample configurations [15]

The effect of raster angle orientation, infill speed and printing temperature was investigated by Ning et al. [20]. Raster angle of [0, 90] exhibited a larger tensile strength, compared to the Young's modulus, and yield strength of raster angle of [45, 45], since tensile load was more effectively transferred from outside to carbon fibers by matrix. Further, they proved that a certain infill density can lead to a better tensile properties, in which, infill speed of 25 mm/s led to the largest mean values of all the tensile properties. The authors also indicated a lower interbonding between the rasters at the lower nozzle temperatures where led to a decrease in tensile properties [20].

A comparison in material choice by Matsuzaki et al. [14] was carried out. The material choice is indeed a key parameter that governs the final properties of the composite parts. As illustrated in Fig. 17 the continuous carbon-fiber composites fabricated in this study showed superior Young's moduli and strengths compared with jute fiber reinforced samples.

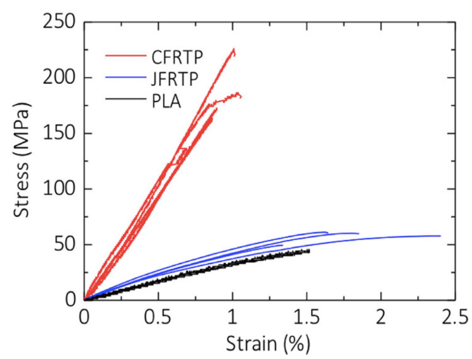


Figure 17: Stress-strain curves of PLA, unidirectional CFRTP, and unidirectional JFRTP specimens fabricated by 3D printing [14]

Conclusion

The present paper summarizes past published work on Fused Deposition Modeling (FDM) with fiber reinforced thermoplastic materials. Many reviewed papers focus on investigating mechanical properties of printed reinforced material systems as well as analyzing the fracture surface of the specimens to investigate failure behavior of the 3D printed fiber reinforced composites. Fiber matrix debonding and inter and inner bead voids are addressed as the primary imperfections. Various successful solutions were given to prevent the failures arising from these imperfections such as increasing the short fiber contents and pre-processing of the continuous fibers prior to printing. In recent years Machine Learning (ML) has also got attention in different fields for control and optimization of various range of problems in different disciplines [1,4–6,11,17,18,22,24,26,27,29,30,33–35] [25] [23]. These methods can be used to identify failure points at the initial stage of printing, and thus making sure to achieve optimum properties. Material choice is the key feature governing the final properties of the 3D printed part, however, it should be chosen according to the application of the printed part. Printing parameters such as start and end point of the printing, raster orientation, nozzle temperature and infill speed are also playing a role in the final properties of the part. The SEM analysis micro-graphs after the treatment were still showing a high amount of pores in the short fiber reinforced composites. Plus, the waviness was only seen in Kevlar fiber reinforced specimens, hence the main cause that why it was only seen in Kevlar fiber samples needs to be addressed systematically.

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