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A Critical Review on Polymer Composites Reinforced with Artificial Fibers Using Fused Deposition Modelling

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ABSTRACT

The practical application of Additive Manufacturing (AM) technology expands constantly in the automotive, aerospace, and biomedical sectors, among others. Additive manufacturing technology has been categorized by ASTM into seven groups according to the type of material and process used to fabricate the parts. Intellectual property rights of manufacturer restrict the users to process few materials in a machine. Nevertheless, compared to extrusion or injection molding, the mechanical strength and robustness of three dimensional (3D) printed items are significantly lower. First, some researchers have looked into optimizing process factors such build orientation, layer height, infill density, and air gap with the purpose of enhancing the mechanical properties. Secondly, altering the material with reinforcement improves mechanical properties compared with un-reinforced material. Fusion Deposition Modelling (FDM) technology based on 3D printer retains a market share of 40% globally. This article reviews the mechanical performance of FDM feed stock filament of thermo-plastic polymers ABS/PLA/PP with a reinforcement of CF/CNF/CNT/JFRT/CPT. The researchers reported improvements in mechanical characteristics such as strength, strain failure rate, and Young's modulus.

Keywords: Additive manufacturing; Fused deposition modelling; 3D printing; Fiber reinforced polymer composite.

1. INTRODUCTION

In contrast to conventional manufacturing, additive manufacturing technology, sometimes referred to as three-dimensional printing or 3D printing, involves adding material layer by layer over one another to create an object based on created 3D models (CAD models). Over the course of 20 years, a number of additive manufacturing (AM) methods have been created with applications in a wide range of engineering professions and industries, including digital art, automotive, aerospace, architectural design, production, textiles, and biomedicine (Dinwiddie *et al.* 2014). Considering AM technology is adaptable and inexpensive for both industrial applications and prototyping, it has been steadily advancing in recent years. Customer-satisfied geometry is produced with less waste thanks to the AM technology (Sun *et al.* 2008). All these benefits support the AM technology geometries and customizability for developing complex structures with micron resolution and provide business to the industries (Shofner *et al.* 2003). The seven categories of additive manufacturing technology are shown in Fig. 1.

2. FUSION DEPOSITION MODELLING (FDM)

Additive manufacturing technology is generally applied for building prototypes from pure thermo-plastics. The FDM technology has a market share of about 40%. It is the most adopted tool to develop new prototypes with affordable cost, low operating temperature, acceptable accuracy, and flexibility (Ismail *et al.* 2022). In order to create final prototypes, a variety of thermoplastic materials, including Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), Polyamide (PA), and Polycarbonate (PC), are available for use as feed stock filament in FDM. Since manufacturing load-bearing components has certain limitations in mechanical properties and deficiencies in stiffness and strength, it is crucial to employ appropriate technology to produce functional parts. There are no advancements in the development of materials for pre-filler blended composites. Modification of FDM technology will subsequently improve the properties of the fabricated composite materials. Currently, FDM technology is employed to fabricate composite materials by adding reinforcement materials such as carbon fibers (Tekinalp *et al.* 2014), carbon nanofiber (CNF) (Matsuzaki *et al.* 2016), carbon nanotubes (Li *et al.* 2016), nano-clays (Tian *et al.* 2016), glass fibers (Nguyen *et al.* 2018) and graphene platelets (Lozano *et al.* 2001).

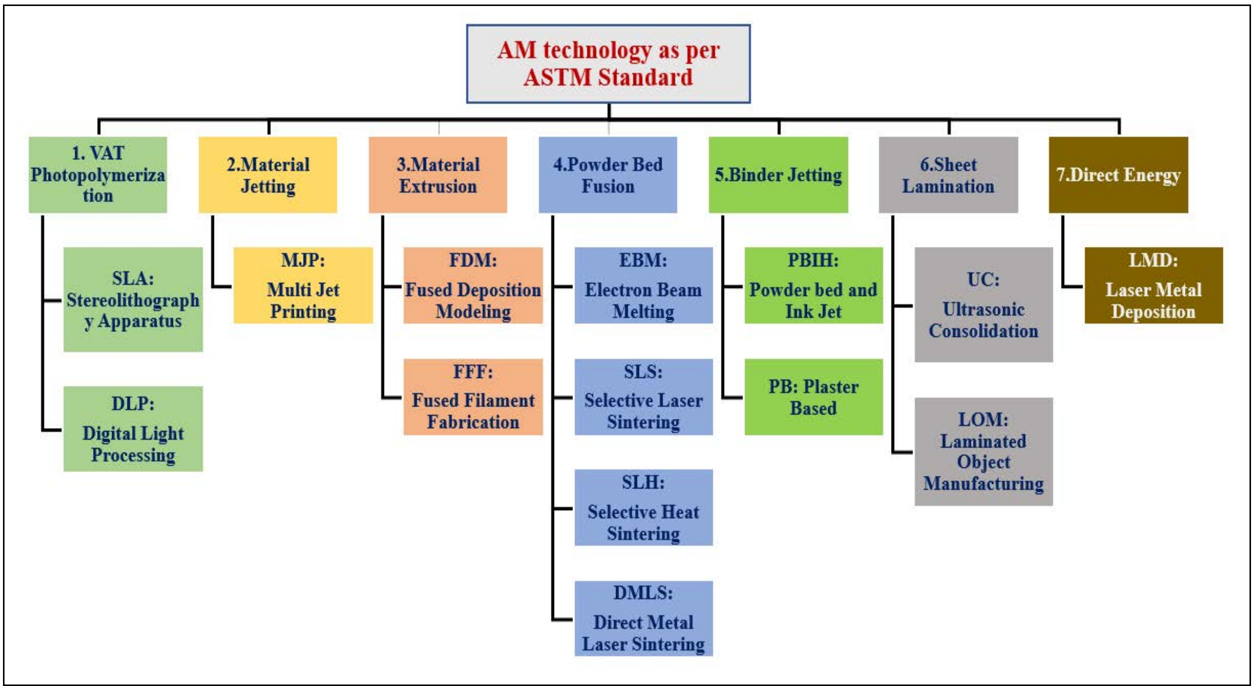


Fig. 1: Additive manufacturing technology classification

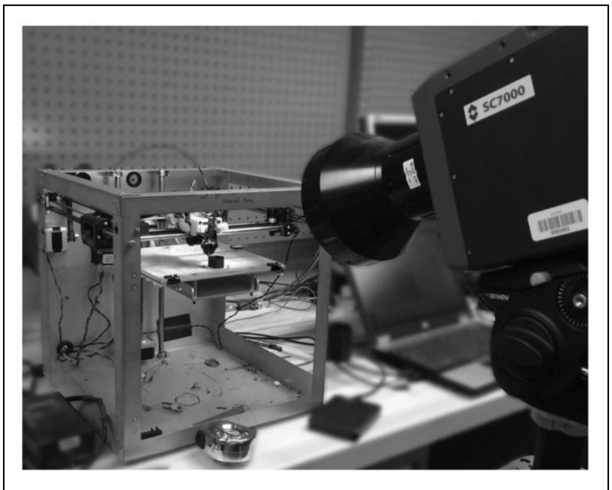


Fig. 2: Experimental arrangement (Dinwiddie *et al.* 2014)

Printer head, liquefaction and feed mechanism are the key elements of FDM (Li *et al.* 2016). Additive manufacturing has the advantages of wide customization and control factors (Matsuzaki *et al.* 2016). There are a number of important process parameters in FDM, such as, build temperature, infill density, air gap, raster orientation and bed temperature.

The consequence of raster angle orientation on properties such as compression and tensile strength has been investigated in detail (Nguyen *et al.* 2018) in which the infill density and layer orientation were considered most important factors for quality improvement (Tekinalp *et al.* 2014). The heat distribution of the 3D printed component was examined by an infrared camera (Fig. 2. IR camera) (Dinwiddie *et al.* 2014). The temperature also defines the quality of bonding between the adjacent layers of the 3D printed composite material (Ismail *et al.* 2022).

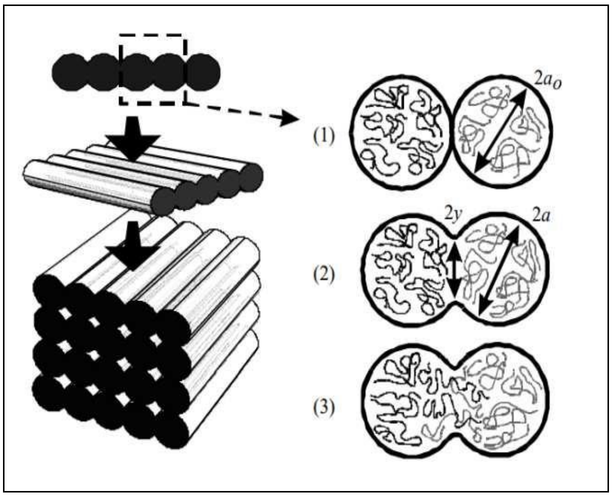
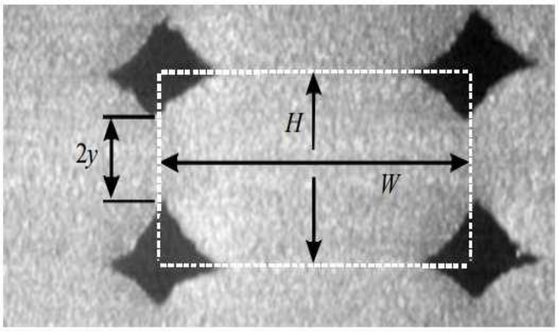


Fig. 3a: Formation of a bond between two filaments (Sun *et al.* 2008)

Fig. 3 (a and b) illustrates the FDM polymer composite bonding mechanism along the cross-section area of fabricated parts (Sun *et al.* 2008). A set of fabrication rules were recommended to enhance the accuracy. Besides strength of the layered manufactured components, the axis of printing direction ensures and improves the tensile strength. Negative air gaps increase the stiffness and strength. A low bead width increases the printing time and gives good surface quality.



W = Filament's Width, H = Filament's Height, and 2y = Collar distance between nearby filaments.

Fig. 3b: Microphotograph of FDM sample (Sun *et al.* 2008)

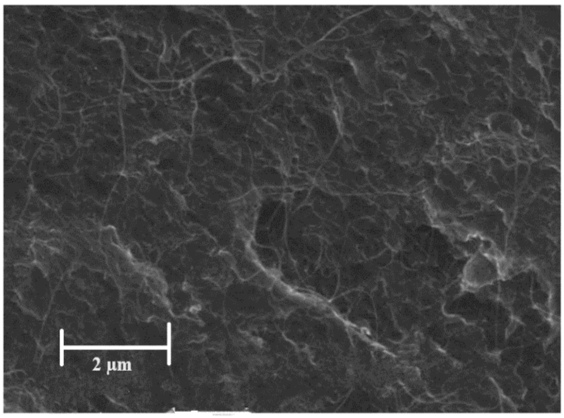


Fig. 4a: SEM micrograph of a 5 weight percentage component ABS/SWNT composite material after Banbury mixing (Shofner *et al.* 2003)

3. REINFORCEMENT OF FDM FEED STOCK FILAMENTS

Reinforcement of fiber into feed stock filament has witnessed a great importance among researchers to improve stiffness and decrease printing head tape swelling (Nguyen *et al.* 2018). Additionally, the tensile and storage moduli are improved by the glass bead fiber reinforcement (Gray *et al.* 1998). It has been studied that the glass fiber reinforcing content in polypropylene (PP) and found that, in comparison to pure PP, there was a 30% increase in Young's modulus and a 40% improvement in strength. Reinforcement with carbon and glass fibers is a typical methodology to enhance the structural characteristics of layered polymers. In a study, it was found that Acrylonitrile Butadiene Styrene (ABS) reinforced with single walled carbon nanotubes (SWNTS) and vapor grown carbon fibers (VGCF) aligned well throughout the extrusion process. The VGCF and SWNT oriented ABS shows the improvement of 93% in modulus. Fig. 4 (a) & (b) shows the SEM image of 5% SWNT/ABS dispersion and fiber orientation of VGCF/ABS (Shofner *et al.* 2003). The tensile strength showed an increase of 18% and 31% on using 5% of VGCS/ABS and 5% of SWNT/ABS, respectively. Nevertheless, strain to failure of reinforced build part was decreased dramatically with a combination of SWNT and VGCF (Carneiro *et al.* 2015).

In the matrix, the SWNTs were evenly and uniformly distributed. There was no porosity found in the sample (Shofner *et al.* 2003). Thermotropic polymeric liquid crystalline polymers (TLPCs) exhibit superior tensile strength, particularly in ABS and PP. Fiber reinforced components were employed to mitigate the limitations of low aspect ratio of short fiber filled FDM parts. Another important aspect that affects the mechanical behavior and surface morphology of TLCP is build temperature.

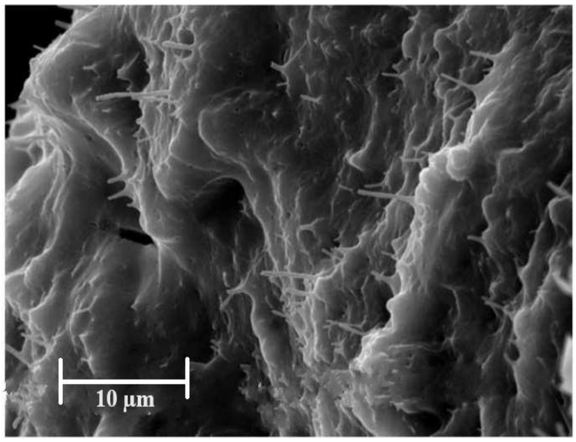


Fig. 4b: SEM micrograph of 5 weight percentage VGCF/ABS Composite (Shofner *et al.* 2003)

When 40% weight percentage of TCLP in ABS and PP was used, the tensile modulus was improved by 100% and 150%, respectively. The high ratio of carbon fiber requires maximum decomposition temperature and imparts high thermal stability (Yu *et al.* 2010). Investigated the Cu/ABS composites that improved the mechanical properties considerably (Rouf *et al.* 2022). The weight ratio, carbon fiber length, and physical characteristics of ABS/FDM samples were examined by (Kumar *et al.* 2021). Fig. 5 shows that the modulus and tensile strength improved significantly at 5 weight percent and 7.5 weight percent, respectively, of carbon fiber content. Long carbon fibers also have a higher modulus of elasticity and tensile strength, according to the investigator (Ismail *et al.* 2022).

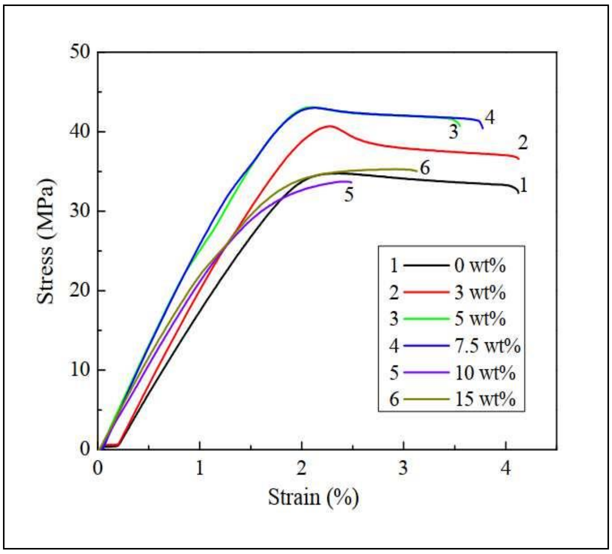


Fig. 5: Strain stress curve for different carbon fiber fillings (fiber length as 150 mm) (Ismail *et al.* 2022)

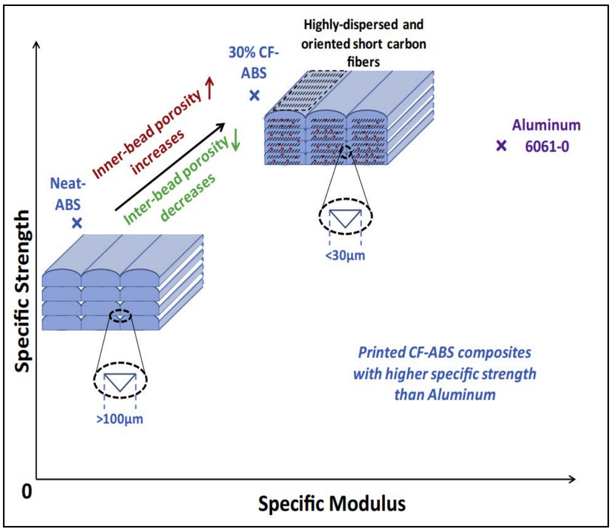


Fig. 6: Graphic representation of 3D-printed fiber embedded composite (Tekinalp *et al.* 2014)

As indicated in Fig. 6, aligned carbon fibers in the fusion deposition modelling process, the strength was improved 115% and Young's modulus with great improvement of 700% by reinforcement of ABS with 30 wt % of CF. Compared to aluminum, these manufactured CF-ABS parts have a higher specific strength. Because the die-swell temperature is lowered and thermal conductivity is improved, the triangle channels between beads are reduced when carbon fibers are added to the matrix. However, the internal spaces created by the carbon fibers in the filament lead to low stress failure of the manufactured pieces because of stress concentration. Fig. 7 shows the formation of porosity in the FDM printed parts, internal voids and void formation during deposition (Tekinalp *et al.* 2014). ABS-free extended fibers show weak fiber-matrix interfacial adhesion150.

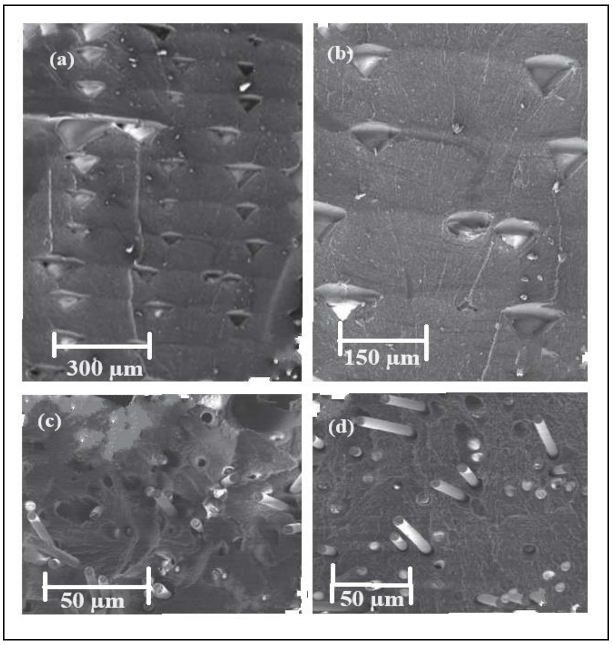


Fig. 7: SEM micrographs of (a) & (b) Pure ABS FDM printed parts, (c) Carbon fiber-filled FDM printed parts, and (d) 10 weight percent CF compression-moulded ABS/CF composites with reinforcement (Tekinalp *et al.* 2014)

4. REINFORCEMENT OF PLA WITH CARBON FIBRE (CF)/JUTE FIBRE REINFORCED THERMOPLASTIC (JFRTP)

The feeding of a continuous carbon fiber-polymer matrix composite is one of the main obstacles faced by researchers studying materials for 3D printing. Although it offers a significant improvement in mechanical qualities over discontinuous fiber, continuous fiber 3D printing lacks a reliable and standardized process. Recently, (Lakkala *et al.* 2023) devised an advanced technology for thermoplastic polymer (PLA) matrix and in-nozzle continuous carbon fiber impregnation (Fig. 8). Before being heated and mixed, the printer head receives separate supplies of fibers and resin filaments. Then, the mixture was deposited on the printing bed. Fig. 8 shows the schematic arrangement of integration of printing head and continuous carbon fiber (Matsuzaki *et al.* 2016). Natural fiber (twisted yarn) was used for reinforcement. Fig. 9 shows the continuous superiority on fiber composite Vs short fiber reinforcement and different 3D printing processes. It has been found that 36.68% increase in the average tensile strength of PLA/carbon when a single ring carbon fiber was used (Park *et al.* 2022).

Carbon fiber reinforced PLA based composite parts have been fabricated by (Cano-Vicent *et al.* 2021) FDM technique. The tensile strength of continuous carbon fibered PLA can reach up to 914 MPa, while with short carbon fiber reinforcement, it reached only 68 MPa. The different parallel layers can also be used as a reinforcement as shown in Fig. 10. When the sizing agent (deionized water) was added to the filament, the tensile strength increased (Matsuzaki *et al.* 2016). Electrical conductivity properties of graphene-based polybutylene terephthalate (PBT) has been investigated.

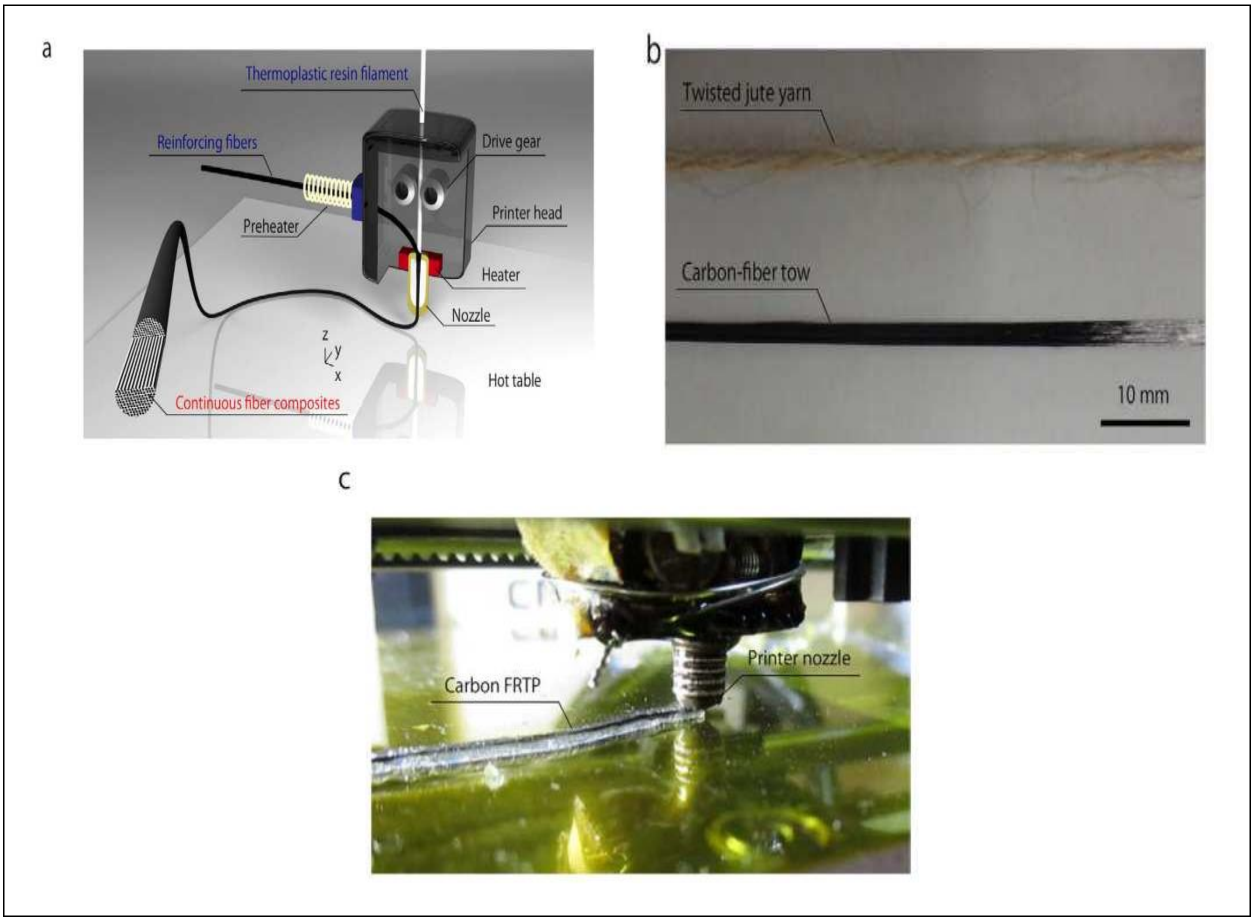


Fig. 8: (a) Thermoplastic in-nozzle impregnation based FDM utilizing continuous carbon fiber, (b) 3D Printing using Continuous Fiber Reinforced Filaments, (c) A picture showing the 3D printing procedure (Matsuzaki *et al.* 2016)

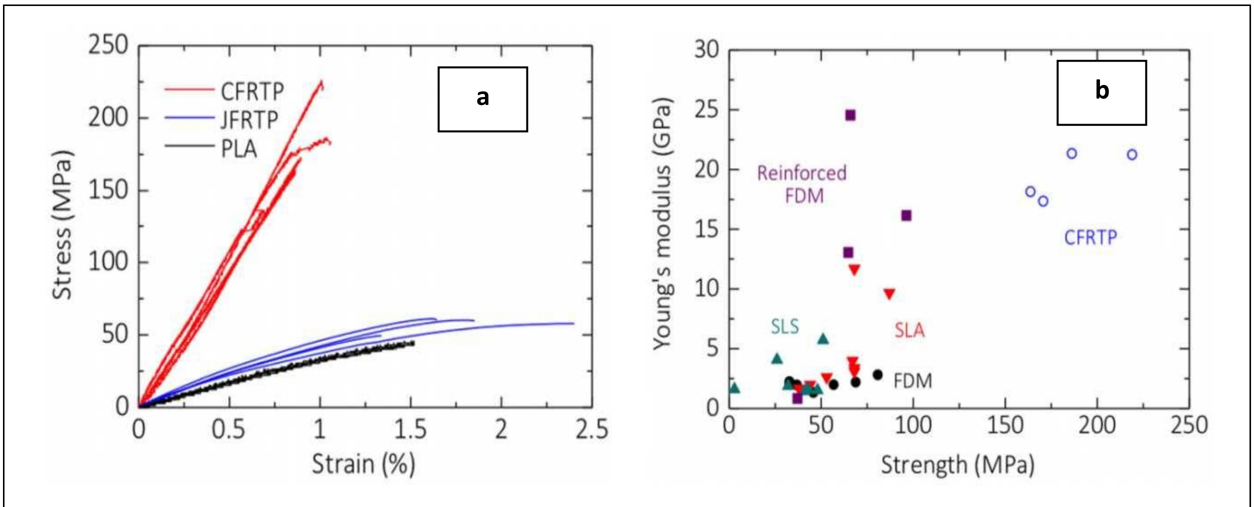


Fig. 9: (a) Relationship between stress and strain in unidirectional CFRTP, unidirectional JFRTP, and PLA, (b) Comparing Young Moduli of continuous carbon-fiber composites and strength of composites made with FDM, SLS, SLA, and FDM printers (Matsuzaki *et al.* 2016)

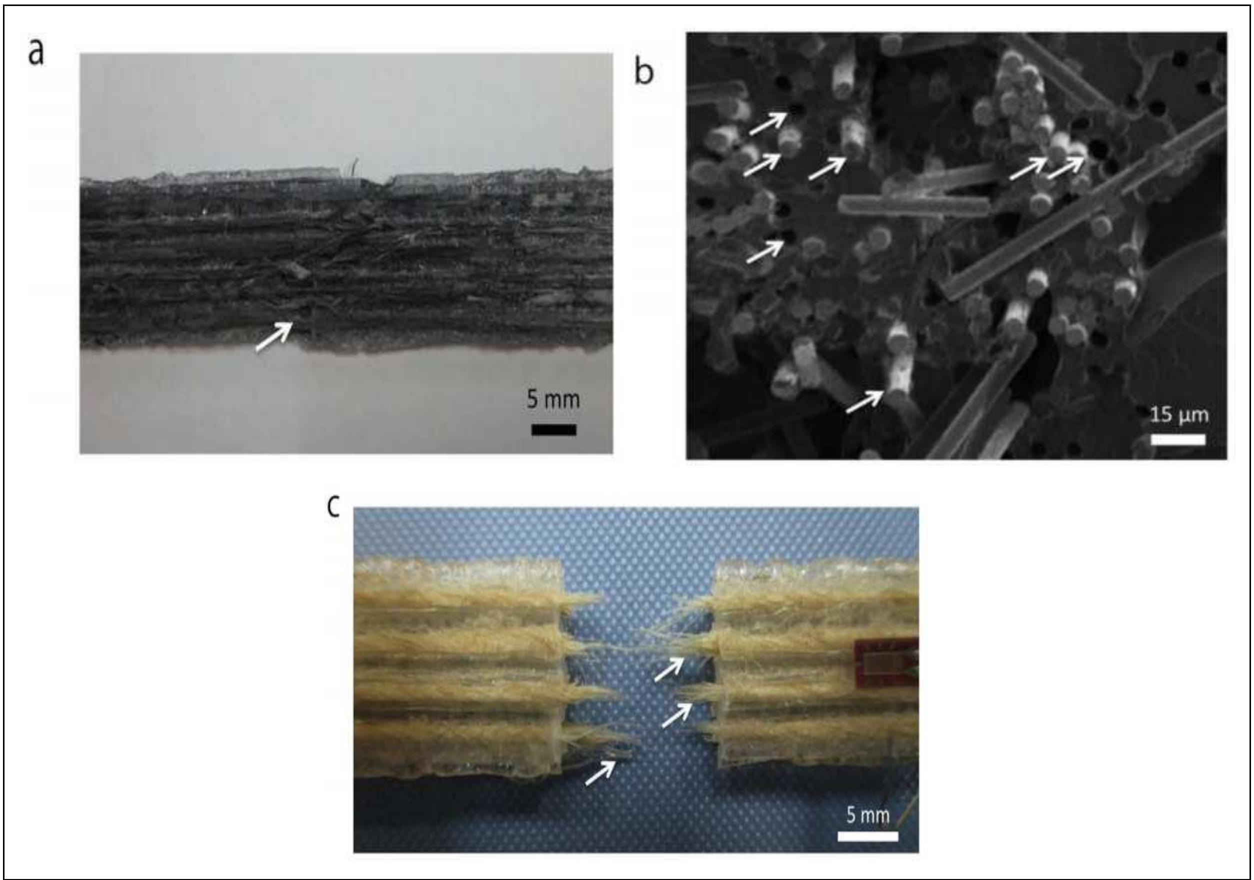


Fig. 10: A unidirectional FRTP breaking, (a) fiber removal-an overview of tensile fracture, (b) SEM micrograph of CFRTP specimen and (c) Pull-out of fiber in JFRTP sample (Matsuzaki *et al.* 2016)

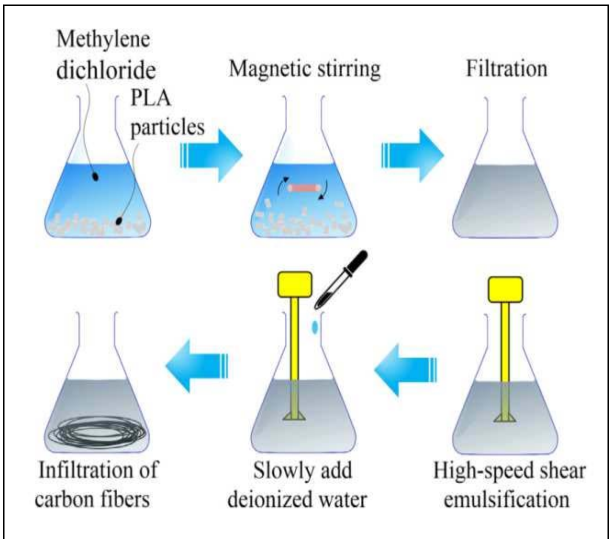


Fig. 11: Carbon fiber surface pre-processing modification (Li *et al.* 2016)

The mechanical property was found to be affected by the weak bonding existing between PLA and carbon fiber (Mahmoud Zaghloul *et al.* 2021). On the other hand, adhesion, tensile strength, and flexural strength increased after methylene dichloride surface modification of carbon fiber bundles (Li *et al.* 2022). The ultimate tensile and flexural strengths of Neat PLA, Carbon fiber/PLA, and Modified carbon fiber/PLA are shown in Fig. 11.

Fig. 12(a), shows green circles representing different process circumstances, such as material loading at the beginning of the test. After that a slight fall is observed due to the interfacial bonding of the fiber matrix. The transition of the load from resin to fiber at the beginning of the test is shown in Fig. 12(b). In the event that the carbon fiber breaks, the load is supported by the plastically expanded polymer chain (Li *et al.* 2016). The shrinkage and crystallization features of Polylactic acid (PLA)/Tricalcium phosphate (TCP) were investigated (Tian *et al.* 2016). The PLA/TCP combination showed semi-crystallization thermoplastic nature, while PLA without TCP showed amorphous structure. (Ning *et al.* 2015) conducted a systematic investigation on the carbon fiber orientation and performance of PLA/carbon fiber printing and influence of process parameters such as pressure and temperature. Fig. 13 shows the cross section of the specimens and the constant fibers on the breakage surface. This helps build the large curvature without losing continuous fiber reinforcement.

Table 1. Comparison of reinforcement improvement in polymer material

Author	Material	Reinforcement	%	Improvement of Tensile Strength (%)	Improvement of Modulus (%)	Strain to Failure
(Shofner *et al.* 2003)	ABS	SWNTs and VGCFs	5	31	93	-
(Shofner *et al.* 2003)	ABS	VGCFs	5	18	-	Decreased
(Lozano *et al.* 2001)	ABS	SWNTs	5	31	-	Decreased
(Nguyen *et al.* 2018)	ABS	NBR41 + CF	10&30	19.6	27.6	Decreased 53.6
(Gray *et al.* 1998)	ABS	TLCP	40	-	100	-
(Gray *et al.* 1998)	ABS	CF	30	115	700	-
(Gray *et al.* 1998)	PP	TLCP	40	-	150	-
(Carneiro *et al.* 2015)	PP	Glass fiber	-	40	30	-
(Matsuzaki *et al.* 2016)	PLA	Continuous carbon fiber	6.6	435	599	Decreased
(Matsuzaki *et al.* 2016)	PLA	Continuous jute fiber (JFRTP)	6.1	Not Improved	5.11	-
(Li *et al.* 2016)	PLA	Continuous carbon fiber with sizing agent	-	13.8	-	-
(Yu *et al.* 2010)	PLA	PLA / Remie	-	47.7	-	-

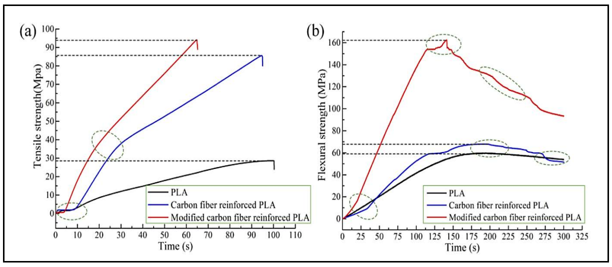


Fig. 12: Mechanical characteristics of modified carbon fiber and PLA: (a) PLA combination tensile strength; (b) PLA combination flexure strength (Li *et al.* 2016)

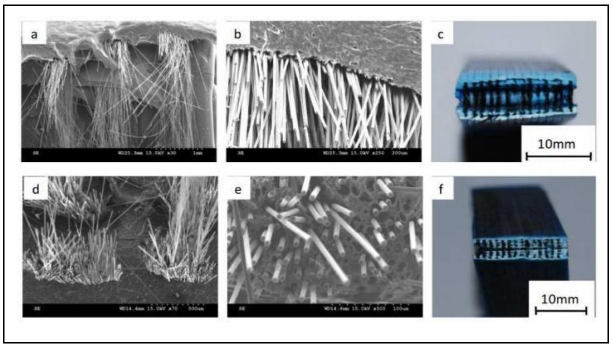


Fig. 13: The Microstructure Cross Section (a) and (d) Total Cross Section, (b) & (e) Interface, (c) and (f) Fracture Array (Tian *et al.* 2016)

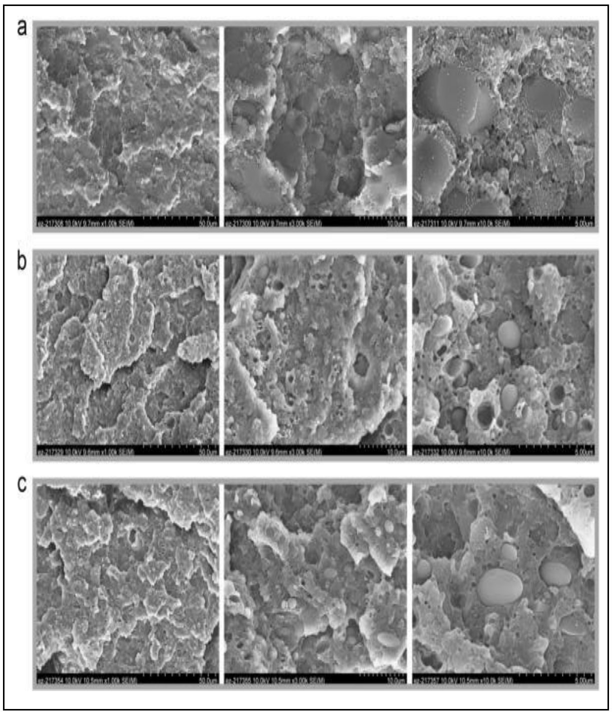


Fig. 14: SEM micrographs of the fractured surface of different samples after performing tensile tests: (a) ABS-Lignin-64. (b) ABS-NBR-Lignin-613. (c) ABS-NBR-Lignin-712 (Nguyen *et al.* 2018)

5. REINFORCEMENT OF ABS/RUBBER, NYLON/CNT, NYLON/KEVLAR COMPOSITE

The rubber composition in ABS/rubber composite increases the printability of the machine (Tian *et al.* 2016). The authors also investigated the mechanical properties of ABS/NBR41/CF composites. The average tensile strength of material and average Young's modulus increased by 19.6% and 27.6%, respectively, while strain at break reduced by 53.6%. Fig. 14 shows the SEM image of ABS and ABS/NBR41/CF (Nguyen *et al.* 2018).

The tensile strength of continuous kevlar fiber embedded nylon matrix has been studied. The rigidity and strength were enhanced considerably with high-level of reinforcement. (Penumakala *et al.* 2020), investigated the mechanical behaviour of Nylon- 6/CNT (less than 5%) matrix. This enhanced stiffness and strength of nylon-6 significantly. The carbon fibers were introduced between the layers of printed polymer for improvement of fatigue life and strength. Further, thermal treatment was performed to increase the mechanical characteristics (Mori *et al.* 2014). Recycled polymer with 30% harakeke showed a 77% improvement in tensile strength and a 275% in modulus of elasticity (Sidhu *et al.* 2023).

Nevertheless, (Wang *et al.* 2017) the increasing the amount of carbon fiber layer among the matrix provides large void areas causing a negative influence on tensile strength. Reinforcement of polymer with fibres can be attained by employing a temperature of 200 °C - 230 °C. Given that the size of layers around 0.4 mm to 0.6 mm with hatching space of 0.6 mm (Ngo *et al.* 2018), maximum flexural strength of 335 MPa could be achieved with a bonding strength of 30 GPa between the layers. Detailed review data are given in the Table1.

6. CONCLUSION

Fiber-reinforced AM polymer composites greatly increase the likelihood that the 3D printing prototype process will become a reliable manufacturing approach. This technology enables the fabrication of complex, functional 3D printed structures with precise control over material properties and a high degree of customization. The incorporation of fiber reinforcement is a distinctive feature of 3D printing, which has significantly increased interest in fiber/polymer composites within AM technology. This innovation has had a major impact on industries such as automotive, biomedical, robotics, and medical science. Introducing new types of composite materials can further enhance the application and effectiveness of this technology.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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