An Overview of Research on FFF Based Additive Manufacturing of Polymer Compositet

Jitendra Kumar, Vishal Mishra and Sushant Negi

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AN OVERVIEW OF RESEARCH ON FFF BASED ADDITIVE MANUFACTURING OF POLYMER COMPOSITE

Jitendra Kumar[1], *Vishal Mishra*[2], *Sushant Negi*[3]

[1] Department of Mechanical Engineering, NIT Silchar, Assam, India, Email:
jitendra_rs@mech.nits.ac.in, Contact no.7004090824.

[2] Department of Mechanical Engineering, NIT Silchar, Assam, India, Emal:
vishal_rs@mech.nits.ac.in, Contact no. 9151633165

[3] Department of Mechanical Engineering, NIT Silchar, Assam, India, Email:
sushant@mech.nits.ac.in, Contact no. 9816111560.

Abstract

The current article focuses on FFF technology for polymer-based additive manufacturing. Among the additive manufacturing process, Fused filament fabrication (FFF) is a more popular Additive Manufacturing process. It is regarded as the most accessible, versatile, and cost-effective prototyping procedure for polymer and composite materials. It is a layer-by-layer deposition of a thermoplastic melt filament that can rapidly construct complicated geometries, eliminating design constraints and reducing production costs associated with traditional manufacturing processes. Polymer filament is made by thermoplastically bonding nylon, ABS, PLA, PP, and other thermoplastics with various reinforcements. The inclusion of fiber reinforcement enhances the thermoplastic matrix, allowing FFF to be employed in more structurally complex-shape small tech applications. Single or twin-screw extruders with varying extrusion settings are employed (Temperature, speed) to make a filament. The physical qualities of the produced component are influenced by process parameters such as printing speed, layer height, orientation, raster angle, raster width, air gap, infill structure, fill density, and bed temperature. This review paper provides a brief insight about 3D printer's composite feedstock filament production using thermoplastic matrix and artificial fiber as reinforcement. The feedstock filaments were reportedly utilized for the fabrication of superior components using an FFF printer. Furthermore, the structural, thermal, and mechanical properties of the composite filament samples were studied.

Keywords: *Additive Manufacturing, Fused Deposition Modelling, 3D printing, Composite fused feedstock filament*

1. Introduction

Additive manufacturing (AM) or 3D printing is a manufacturing process that produces an object in an additive manner, layer by layer, directly from CAD model data. AM provides various advantages, including making lightweight items with less waste of materials, fewer assembly stages, shorter lead times, and no additional expenditures [1]. In 1986, Charles Hull pioneered stereolithography (SLA), which was followed by innovations like powder bed fusion, Fused filament fabrication (FFF), inkjet printing, and contour crafting (CC) [2]. Various methods were used depending on the machine technology, application, and materials used. Additive manufacturing is employed in various fields, including aerospace, defense, space, prototyping, construction, medical, biomechanical, automotive, energy, food processing, composite materials, and robots. Metals, thermoplastics, ceramics, food, and bio-materials have all been studied for use as additive manufacturing materials. Because of its low cost and lightweight, thermoplastic is commonly used in FFF, Multi-Jet Fusion (MJF), Selective Laser Sintering (SLS), and Stereo-Lithography (SLA) [3].

Fused filament fabrication (FFF) is an easily accessible, changeable, and cost-effective prototype approach for manufacturing and polymer and polymer composite materials among the additive manufacturing (AM) group[4]. The majority of AM processes deposit a single material in a single manufacturing process and depend entirely on geometry. Due to advancements in the FFF process, a single extruder FFF machine can print a multi-material (similar or dissimilar) structure in a single fabrication process. As a result, functionally graded materials (FGMs) might be deposited in a particular section with an upgraded interface zone to produce better thermos-mechanical properties. It is a high-tech engineering material that differs in composition and structure throughout volume [1].

The FFF technique employs fiber-reinforced thermoplastic. A heated chamber melts a continuous supply of thermoplastic filament and extrudes the melt material onto a preceding layer or platform through the nozzle. The flow behavior is influenced by the rheological qualities of the melt substance[3]. Polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS), poly-lactic acid (PLA), Polyamide (PA), PC-ABS blends, PC-ISO, and PC-ISO blends are common thermoplastic materials used in FFF. Because of their low mechanical properties and low melting point, these materials can be heated and molded quickly. Several experiments on printing process parameters and post-process treatment were carried out to improve AM products' mechanical qualities. But continuous fiber-reinforced thermoplastic polymer provides better mechanical strength [5].

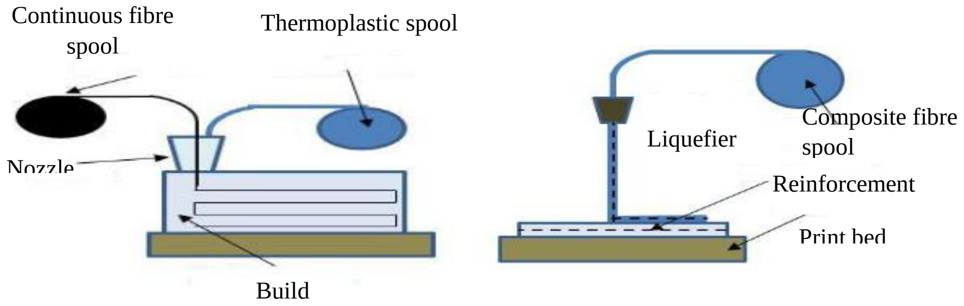

Figure 1. Classification of FFF based on (a) continuous fiber (b) short fiber

The purpose of a literature review is to provide background information on additive manufacturing to be considered in this research work and emphasize the present study's relevance. This section incorporates the review of relevant published papers/articles in the proposed research area of additive manufacturing of composite structures using FFF technology. Mainly the study dealing with different fillers /reinforcement to make 3D printed composites via FFF has been reviewed.

2. Composite filament fabrication

The substantial growth of thermoplastic-based composite has resulted in the advancement of the building and automotive industry. The popular thermoplastic-based composite includes polypropylene (PP), high-density polyethylene (HDPE), Nylon, PLA, ABS, and LDPE as a matrix material. The fundamental technology considered for processing thermoplastic-based hybrid fused feedstock filament for FFF printing is extrusion. The filaments can be extruded by using a single screw or twin-screw extruder. The schematic illustration of filament production and 3D printing is shown in figure 2. Barrel and screw are the two primary parts that are considered as the main constituent for extruder setup. The polymer granules/ flakes with the reinforcement are fed in the hopper and get traveled from the feed zone to the compression zone through a rotating screw where the mixture gets transformed into a solid block and reaches a plasticizing zone. In the plasticizing zone, the solid block gets converted in a molten state and gets ejected from the die, forming a filament of the desired dimension. During the overall extrusion process, certain process parameters like extrusion temperature, screw speed, roller puller speed, etc., need to be controlled efficiently to get a good quality product. Further, the processed fused filament will be ready to be used as feedstock for the FFF printer.

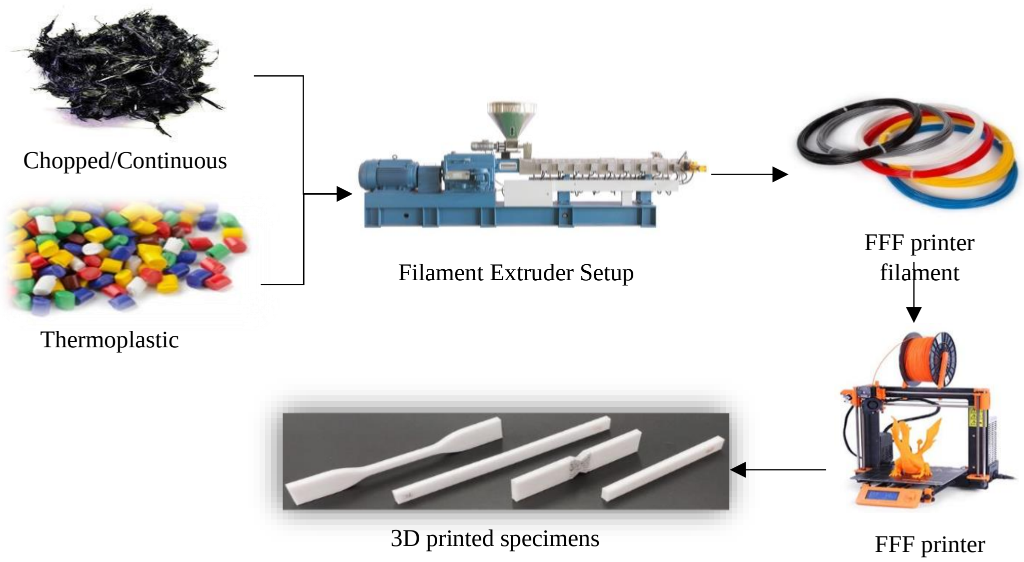

Figure 2. Schematic illustration of filament production and 3D sample fabrication

3. Literature review on FFF based composite fabrication

The increasing popularity of FFF-based 3D printed products among common public and large-scale industries has made researchers develop novel composite fused filament for the fabrication of superior products. Initially, it has been observed that neat thermoplastic polymer that was used as fused filament for 3D printers limits the application of product due to poor product quality and performance. In order to tackle the problems of glass, carbon, Kevlar, etc., fibers in the continuous or chopped state were reinforced with a thermoplastic polymer matrix to extrude hybrid fused filament for the FFF printer. Using the same filaments, the 3D printed samples were fabricated and subjected to thermal and mechanical testing. Table 1 illustrates the outcome of 3D printed samples that were fabricated using composite feedstock filament and an FFF printer.

Table 1. A brief insight into 3D printing using composite feedstock filaments

Sr. No	Matrix Material	Reinforcement (Fibre) material	Short / Continuous fiber	Process parameters	Major finding	Ref.
1.	Nylon	Glass, Carbon, and Kevlar	Continuous	Nylon layer thickness 0.1, 0.125 mm Carbon fiber layer thickness 0.125 mm Glass/Kevlar layer thickness 0.1 mm Width of fiber layer 11.1/2.4 mm Average fiber filament bundle contents 0.345 %	➢ The strength and rigidity of a continuous fiber-reinforced composite are greater than those of an unreinforced composite. ➢ Strength and stiffness improved as the volume content of the fiber increased. ➢ The inadequate interfacial adhesion between the nylon matrix and the fibre (Kevlar and glass).	[6]
2.	Nylon-6	Carbon	Short and continuous	Fiber Orientation 0 +-45 Build orientation Flat 8 No of layers 8 0.125 Layer thickness 0.125 mm 2 mm No of rings	➢ Interlaminar interactions are weaker than interfacial connections inside the substrate. ➢ Ductile adhesives and adhesive-modulus tailoring technologies may be utilized to lessen stress concentration at joint edges.	[7]
3.	ABS	carbon	Short	Print bed temperature 80 ℃ Number of contours 3 Infill pattern Rectilinear Infill density 100% Nozzle diameter 0.35mm	➢ Tensile strength and flexural strength increased by 70% and 18.7%, respectively. ➢ The amount of void space in printed pieces has risen.	[8]
4.	ABS	Carbon	Continuous	Nozzle diameter 0.8 mm Layer thickness 0.5 mm Extrusion temperature 230 ℃ Envelope temperature 90 ℃ Feeding speed 5 mm/s Printing speed 10 mm/s	➢ Tensile strength, Elongation at break, flexural strength, and flexural modulus improved by 5 times, 2 times, 2 times, and 3.9 times respectively. ➢ Very low interlaminar shear strength (2.81 MPa).	[9]
5.	PLA	Carbon	Short	Printing orientations 0°,90°,+-45°, Nozzle diameter 0.4 mm Nozzle extrusion temperature 190 ℃ Heat bed temperature 70 ℃ Printing speed 3000 mm/min	➢ Short carbon fibers increased tensile modulus by 2.2 times. ➢ Composite materials become brittle with short carbon fibers. ➢ Longer fiber lengths have poor adhesion.	[10]
6.	Polypropylene (PP)	carbon	Short	Nozzle diameter 0.6 mm Nozzle temperature 230 ℃ Printing bed temperature 70 ℃ Layer thickness 0.25	➢ Flexural and modulus strength was increased by 150% and 400%. ➢ Thermal conductivity increased by 200%.	[11]
7.	PA, PC, PETG, PLA, and SCF/PA	Carbon fiber reinforced plastic (CFRP)	Continuous	Nozzle diameter 1 mm Layer thickness 0.3 mm Raster width 1 mm Printing speed 270 mm/min	➢ C-CFRP with SCF/PA and PLA matrix exhibited maximum tensile strength (288.65 GPa) and the highest elastic modulus (29.12 GPa). ➢ Better impregnation degree (V_{f1} and V_{f2}) of fiber-matrix exhibited larger UTS and elastic modulus.	[12]
8.	Polyamide	Carbon	Continuous	Filament feed rate 1.5 cm/s Heated temperature 254 ℃	➢ 33% strength of carbon fiber is reduced.	[13]

				Nozzle Diameter 2 mm Filament diameter 0.38 mm The gap between nozzle and platform 0.15 mm	➢ The 3D printed filament material's compression kinking stress and tensile strength are reduced by 25% and 60%, respectively.	
9.	Onyx	Glass	Continuous	Onyx filament diameter 1.75 mm HSHT fiberglass diameter 0.4 mm Fiber volume fraction 0.3 No of layers 25 Raster Rectilinear, ±45°, crisscross	➢ The incorporation of glass fiber reinforcement into the Onyx polymer matrix boosts tensile strength by 250 percent while increasing specimen weight (11.43 %) and printing time (70 %). ➢ Parts made of composite materials can be employed in aeronautical and automotive applications.	[14]
10.	PETG	Carbon fiber, OMMT Nanoclay	Short	Process zone Compounding Extrusion Feed zone 270-280℃ 175-180℃ Compression zone 275-290℃ 185-200℃ Mixing zone 285-295℃ 205-215℃ Die head 280-300℃ 200-220℃	➢ The thermal stability enhanced as the SCFs concentration increased. OMMT act as a thermal barrier. ➢ At 15% wt, hydrogen bonds developed between fibers and PETG molecules, resulting in a lower glass transition temperature and exothermic heat exchange.	[15]
11.	PETG	Carbon fiber, OMMT Nanoclay	Short	Print-bed temperature 75 Infill percentage 100 % Raster angle 0° Infill shape Linear Layer height 0.2 mm Material flow rate 110 (%)	➢ The combination of carbon fibers and PETG improves the natural frequency while substantially lowering the damping ratio. ➢ An optimal combination of 10% short carbon fibers and 5% Nanoclay results in maximum dampening and improved natural frequencies.	[16]
12.	PEEK	Short carbon fiber and Glass fiber	Short	Nozzle diameter 0.4 mm Nozzle temperature 440℃ Platform temperature 260 ℃ Layer thickness 0.2 mm Printing speed 15 mm/s Infill density 100 % Wall thickness 0.8 mm Raster angle [-45°, +45°]	➢ Fiber-reinforced PEEK composite has higher thermal stability. ➢ Glass and PEEK have superior interfacial bonding. ➢ Tensile strength, flexural strength, impact strength, and ductility all decrease as fiber weight increases from 5% to 15%.	[17]

4. Limitation of FFF process

Fused filament fabrication is the most popular Additive manufacturing process. Most graphic object design files are printed using thermoplastic polymer in the FFF printer. But FFF process has certain limitations. These limitations are the range of materials, process parameters, finish product quality (mechanical properties). One of the most significant challenges is the limited number of materials (polymer) that can be printed with FFF. Some binder melts in the print head, and fiber will attach to the previous layer. The print head velocity and temperature are set in stone and cannot be changed. During filament deposition, air inclusions (porosity) occur [6]. The presence of gaps appears to decrease interlayer bonding [7]. Compared to traditional processes (vacuum bag resin infusion and autoclave curing of prepreg lamination), 3D printed composites have poor mechanical characteristics. FDM filament is abraded due to the gear's gripping action, the formation of abrasion grooves, contact with the nozzle, the formation of abrasion grooves, and the bending effect of the filament [13].

5. Application

FFF technology offers enormous potential for usage in material processing, the food industry, medicinal applications, tissue engineering, aerospace, construction, and other fields. The FFF technique is used to create functionally graded materials (FGMs) [1], metal fused filament fabrication [18], highly dense alumina parts (bars, cylinders, and pillars) [4], the high mechanical performance of Continuous Fibre Reinforced Thermoplastic Composites (CFRTPCs) [6] and Aligned discontinuous fiber composites (ADFRC) [5]. FFF has a high potential in biomedical and tissue engineering (TE) because of its multiple advantages, particularly for fabricating complex tailored parts and scaffolds for TE [19]. Excellent tensile properties high thermal and chemical resistance of the polymers are employed in aerospace and automotive components [20].

6. Future scope

Recent advances in FFF 3D printing of polymer-based composites are discussed in this paper. This FFF manufacturing process had been rapidly developing for several years and would open up a range of new possibilities in practical applications. The design and production of polymer composites for FFF 3D printing and the qualities of the FFF 3D printed parts are given special attention. Certain obstacles must be handled, from rapid prototyping to large-scale manufacturing. We need to close the gap between our current capabilities and what people expect in future work. Some of the limitations of FFF based additive manufacturing which needs to be addressed in the future to make this technology more efficient are highlighted herender:

- The strength and surface finsish of part is still lower than it convenetional counterpart.
- Printing speed is slow which needs a lot of improvement in future.
- Limited range of materials and lack of shared data of printing materials and their characteristics.

In addition, future research into the design of novel organic materials with ideal properties, suitable reinforcement, and reusable raw materials is required. Using the filament prepared from waste, superior quality products can be fabricated using FFF technology, and by this footstep can save the environment from plastic pollution. Apart from that, during 3D printing, there were some prominent FFF defects like void formation, layer shifting, improper layer adhesion, and lack of bonding between reinforcement and matrix, with affected the product quality and its performance. So, future research can be done to avoid/minimize those defects and to enhance the performance of 3D printed products.

7. Conclusion

The fundamental materials for the FFF manufacturing process are polymers. Polymers as FFF printing materials are a rapidly expanding topic in terms of technological advancement and research. Our objective is to compile a collection of recent articles that review of the relevant polymer FFF processes in terms of a matrix, reinforcements, process parameter, finding, and limitation, as well as highlight the application, address existing issues, and chart a course for the future. FFF technology is growing rapidly due to the upbringing of inexpensive and efficient 3D printer's in-home consumer market, and now the demand for a low cost. In the review, specimens fabricated using novel composite feedstock filaments were highlighted. It was concluded the addition of artificial fibers like kevlar, carbon fiber, etc., either in a chopped or continuous state as a reinforcement in a thermoplastic matrix, helps the 3D printed specimen to withstand high loads and impacts. Moreover, the fabricated parts possess good surface roughness and are lightweight. Although there were some FFF defects like porosity, improper layer adhesion has been observed, which are due to inappropriate FFF process parameter selection.

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