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Enhancing Mechanical Characteristics of PETG Carbon Fiber Composite through Various Shell Thickness in FDM Processing

Deivasikamani S M[1], Mathiyazhagan.K[2], Mugeshkannan.G[3], Sridhar.D[4], Pranesh.M[5]*

[1]Assistant Professor, Department of Mechanical Engineering, Sri Ranganathar Institute of Engineering and Technology, Coimbatore, India.

[2,3,4,5]UG Student, Department of Mechanical Engineering, Sri Ranganathar Institute of Engineering and Technology, Coimbatore, India.

Email: deivasikamani@sriet.ac.in

****Corresponding Author Orchid ID:*** *0000-0002-6751-4191*

Abstract

The utilization of PETG (Polyethylene Terephthalate Glycol) carbon fiber composites in Fused Deposition Modelling (FDM) processes has gained significant attention due to their enhanced mechanical properties compared to traditional PETG filaments. This study focuses on investigating the impact of varying shell thickness on the mechanical characteristics of PETG carbon fiber composites fabricated through FDM. The objective is to optimize the shell thickness to achieve superior mechanical performance while maintaining printing efficiency. A series of PETG carbon fiber composites with different shell thicknesses were manufactured using an FDM 3D printer. Mechanical tests, including tensile strength, flexural strength, and impact resistance, were conducted to evaluate the performance of the fabricated specimens. Additionally, micro-structural analysis was performed to understand the influence of shell thickness on the interfacial bonding between PETG matrix and carbon fibers. Preliminary results indicate that increasing shell thickness positively affects the mechanical properties of PETG carbon fiber composites. Tensile and flexural strength show a noticeable improvement with an increase in shell thickness, attributed to enhanced interlayer adhesion and improved load-bearing.

Keywords: *MPa - Mega Pascal, KN - Kilo Newton, J - Joule*

1. Introduction

1.1. General Introduction

Additive manufacturing also known as 3d printing is one of the latest technologies used in the manufacturing industry today. In this process of manufacturing the specimen the printing is done by addition of layer-by-layer process. This method of manufacturing is used for the production of very critical and complex structural parts or used for the production of prototypes of models in the starting stage of any project. Initially was used to create visualization models for the products that were being developed in the industry or manufacturing sector. Due to the advancements in the whole product or part by part is being developed and used as an end product the basic principle of this technology is to develop a 3D printed CAD model and then imply the process without any further planning required. The process contains major steps like 3D model creation, slicing, support generation, 3D printing and post-processing of printed parts. Polyethylene terephthalate glycol (PETG) is a widely used thermoplastic polymer known for its excellent mechanical properties, durability, and ease of 3D printing using Fused Deposition Modeling (FDM) technology. The incorporation of carbon fibers into PETG matrix creates a composite material that combines the benefits of PETG with enhanced mechanical strength and stiffness attributed to the reinforcing nature of carbon fibers. One crucial parameter in the FDM process that significantly influences the mechanical characteristics of the PETG carbon fiber composite is the shell thickness [1-4]. Polyethylene terephthalate glycol (PETG) reinforced with carbon fibers is a promising composite material known for its exceptional mechanical properties, including high strength, stiffness, and resistance to deformation. This composite has found extensive applications across industries ranging from aerospace to automotive due to its lightweight nature and durability. However, the fabrication process plays a crucial role in determining the final properties of the composite. Among the various manufacturing methods available, fused deposition modeling (FDM) stands out for its cost-effectiveness, versatility, and ability to produce complex geometries. In FDM, optimizing shell thickness is critical as it directly impacts the mechanical characteristics of the final product. This study investigates the effects of varying shell thickness on the mechanical properties of PETG carbon fiber composites, aiming to enhance their overall performance for specific applications. By systematically analyzing the relationship between shell thickness and mechanical behavior, valuable insights can be gained to advance the design and production of high-performance composite components using FDM technology. Polyethylene terephthalate glycol (PETG) carbon fiber composites have garnered significant attention in various engineering applications due to their favorable blend of mechanical properties, including high strength, stiffness, and dimensional stability. These materials, derived from the combination of PETG polymer matrix and carbon fibers, exhibit enhanced performance compared to traditional polymers, making them suitable for applications ranging from automotive components to aerospace structures. In the realm of additive manufacturing, fused deposition modeling (FDM) has emerged as a prominent technique for fabricating PETG carbon fiber composites with intricate geometries and customized designs. However, optimizing the mechanical characteristics of these composites through FDM processing remains a critical challenge. One of the key parameters influencing mechanical properties is the shell thickness, which directly affects the interlayer bonding and overall structural integrity of the printed parts. This study aims to investigate the impact of varying shell thickness on the mechanical properties of PETG carbon fiber composites manufactured via FDM. By systematically altering the shell thickness during printing, we seek to elucidate its influence on crucial mechanical attributes such as tensile strength, flexural modulus, and impact resistance. Understanding these relationships is essential for tailoring the manufacturing process to achieve desired performance characteristics, ultimately advancing the practical applicability of PETG carbon fiber composites in diverse engineering applications. Through comprehensive [5-7] analysis and experimentation, this research endeavors to contribute valuable insights towards optimizing the mechanical properties of FDM-printed PETG carbon fiber composites, thereby fostering their widespread adoption in industries demanding high-performance materials. The integration of carbon fibers into polymer matrices has garnered significant attention in recent years due to the resultant composite materials' enhanced mechanical properties. Among these, Polyethylene Terephthalate Glycol (PETG) stands out as a promising thermoplastic matrix due to its favorable balance of toughness, chemical resistance, and ease of processing Additive manufacturing, specifically Fused Deposition Modeling (FDM), offers a versatile approach for fabricating composite structures with controlled geometries and material compositions. In this study, we explore the influence of varying shell thicknesses on the mechanical characteristics of PETG carbon fiber composites manufactured through FDM processing. By systematically investigating the effects of shell thickness on the composite's mechanical properties, we aim to optimize the design and manufacturing parameters to enhance the overall performance of PETG carbon fiber composites for diverse engineering applications [8].

1.2. Shell Thickness

Shells are the number of layers on the outside of a print. For FDM shells are always the first areas to be printed per layer. Several shell related design considerations for FDM printing are: Strength can be added by increasing shell thickness shown in Figure 1. Shell thickness in FDM refers to the thickness of the outer layers of a printed object. It plays a crucial role in determining the mechanical properties, surface finish, and overall strength of the final product.

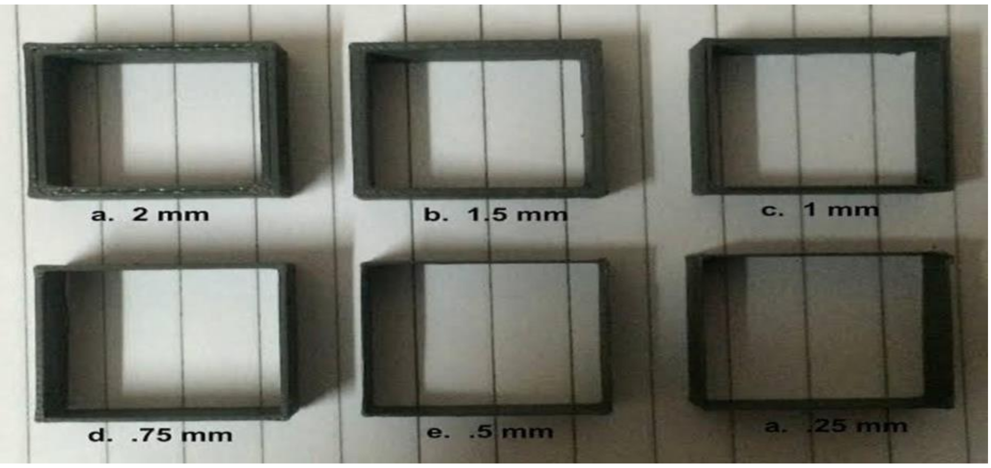

Figure 1 Shell Thickness

In the context of PETG carbon fiber composite, varying the shell thickness can lead to notable changes in the material's behavior. Thicker shells generally result in stronger parts but may affect other aspects such as print speed, material usage, and overall print time [9].

1.3. Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) is the AM technology where the filament or material is being melted, extruded by the nozzle and deposited on the film bed, layer over layer forming the required part. FDM started as a basic process, which was used for preparing prototypes buildings, which extended its base and now it is considered as a widely accepted manufacturing process in almost every possible industry. The main advantage of FDM is that the maintenance and fabrication cost is low and as well as environmental friendly. FDM started as a basic process, which was and also nowadays is used for preparing prototypes buildings, which extended its base and now it is considered as a widely accepted manufacturing process .Currently the traditional construction of buildings is slowly being replaced by FDM which is also a rapid prototype technique. FDM also finds several applications in the field of engineering, medical and almost everywhere. The main advantage of FDM over 3D printing is that it does not require any organic solvent, and there is no need to remove excessive polymer powder. But even FDM takes place at high temperature to melt the thermoplastic polymer, limiting the encapsulation of bimolecular or cells in the resulting scaffold. Fabrication of end-use parts. Without the expense and lead time of traditional tooling or machining, FDM produces end- use parts tough enough for integration into the final product. Ideal for building small quantities of parts while waiting for tooling, FDM Technology makes it possible to get the products to market faster. Fabrication of manufacturing tools. FDM reduces the time it takes to create manufacturing tools by up to 85%. It produces manufacturing tools such as jigs and fixtures, tooling masters and production tooling in hours without expensive machining or tooling. FDM is a widely used 3D printing process because of its versatility, accessibility, and relatively low cost [10].

1.4. 3D Printing

3D printing, also known as additive manufacturing, is a revolutionary manufacturing process that builds three-dimensional objects layer by layer from a digital model. The process typically begins by layer to construct the physical object. Various materials can be used in 3D printing, including plastics, metals, ceramics, and even biological materials. The printing process is highly customizable, allowing for intricate and complex designs that may be challenging or impossible to achieve with traditional manufacturing methods [11-13]. 3D printing has found applications in various industries, including aerospace, healthcare, automotive, and consumer goods, due to its ability to rapidly prototype, customize, and manufacture with increased efficiency and design flexibility. As technology advances, 3D printing continues to evolve, offering new possibilities and shaping the future of manufacturing. With the creation of a computer-aided design (CAD) file, which serves as a blueprint for the object to be produced. The 3D printer then reads this file and deposits material layer.

2. Selection of Material

2.1. PETG+CF (Polyethylene Terephthalate + Carbonfibre)

PETG Carbon Filament is a Polyethylene Terephthalate reinforced with carbon fibers. Due to the carbon fibers compounded in the PETG you can create 3D printed parts with exceptional stiffness, great dimensional stability and excellent surface quality. The specific properties of a PETG carbon fiber composite can vary based on the ratio of PETG to carbon fiber, the alignment of the fibers, and the manufacturing process used. Typically, carbon fiber composites are known for their high strength-to-weight ratio, making them suitable for applications where lightweight and strong materials are required.

Figure2 PETG+CF (Polyethylene Terephthalate + Carbonfibre)

The carbon fibers in the composite provide reinforcement and contribute to the overall mechanical properties of the material. The amount, orientation, and type of carbon fibers can influence the performance characteristics of the composite. Figure 2 shows PETG+CF (Polyethylene Terephthalate + Carbonfibre).

2.1.1. Print Setting

- Extruder: 230-260°C.
- Bed Temp: 70-90°C.
- Nozzle: We currently recommend a hardened steel nozzle with a minimum diameter of 0.4mm.
- Other: Ideal layer height is 60% of nozzle diameter.
- Bed Prep: Magigoo Bed Prep Adhesive gives us the best results.

2.1.2. PETG Carbon Filament Material Properties

- Density 1.317 g/cm³
- Charpy impact Strength 4.03 KJ/m2
- Tensile Strength 52.9 MPa
- Elongation at tensile strength 2.4%
- Tensile Modulus 4,015 MPa
- Deformation at Flexural Stress >4*%
- Flexural Modulus 2,987 MPa
- Shore D Hardness 76.4
- Glass temperature tg 76°C

2.1.3. Advantages

- High stiffness.
- High tensile strength.
- High heat tolerance.
- High chemical resistance.
- Low weight.

3. Methodology

The mechanical characteristics of PETG carbon fiber composites play a pivotal role in determining the structural integrity and performance of components manufactured through Fused Deposition Modeling (FDM) processing methodology. In the realm of additive manufacturing, FDM stands out as a versatile and widely adopted technique for producing polymer-based composites, offering enhanced mechanical properties through the incorporation of reinforcing elements like carbon fibers [14] Figure 3 shows PETG Methodology.

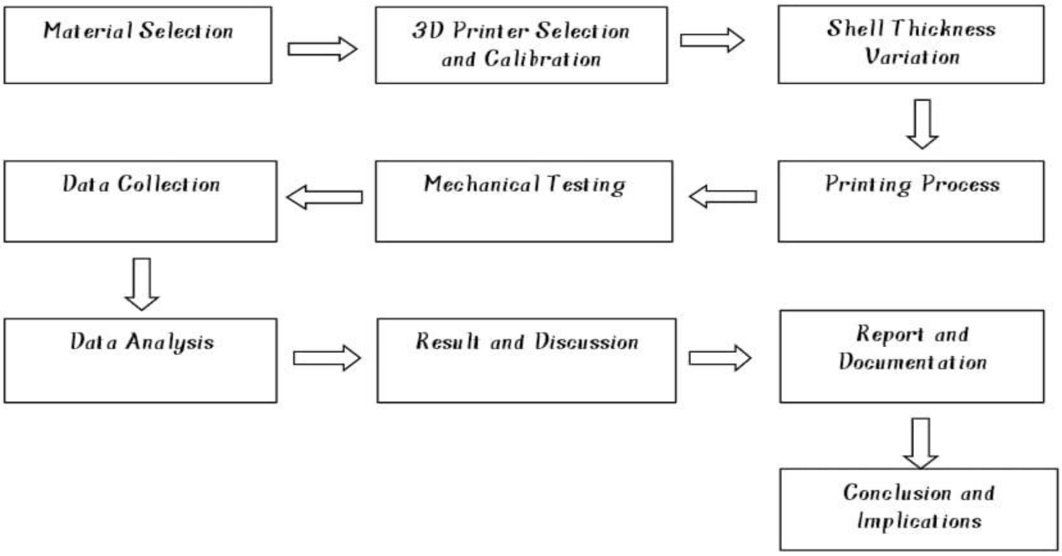

Figure 3 **PETG Methodology**

4. 3D Printing Process

3D printing, or additive manufacturing, is the construction of a three-dimensional object from a CAD model or a digital 3D model. The term "3D printing"can refer to a variety of processes in which material is deposited, joined or solidified under computer control to create a three-dimensional object, with material being added together (such as plastics, liquids or powder grains being fused together), typically layer by layer [15]. Figure 4 shows the 3D Printing.

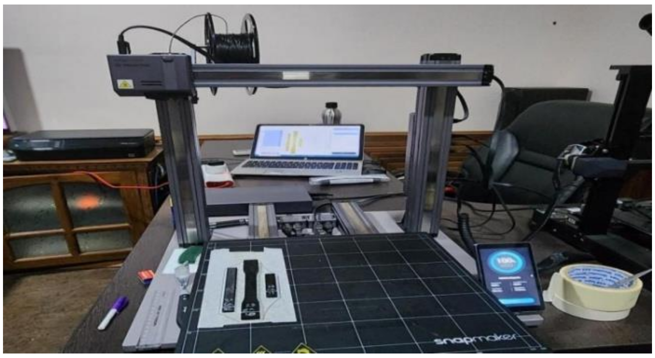

Figure 4 **3D Printing**

The touch screen device connected with the machine is the control unit of the 3D printing. Files uploaded from the software will be saved in the device. The device is connected with WIFI for the file uploading. The machine setup contains X, Y, Z coordinated tool head as displayed connected with nozzle head containing 0.4 mm diameter nozzle depicted. The top side of tool head is fed with the printing material from the material roll. The Power Module is connected at the back of the machine. The Power Module uses a fan whose speed can be adjusted automatically according to the real-time temperature with low noise [16].

4.1. 3D Printed Materials Specimens

There will be some extra material sticking in the specimen. The material will be removed by scissor. The printed materials are brittle so the specimens are handled with care. The chipping process is done with extra care so that the specimens are not broken. After printing all the materials under various in PETG+CF the materials are ready to test [17]. Figure 5 shows the Tensile, Flexural, and Impact Specimen.

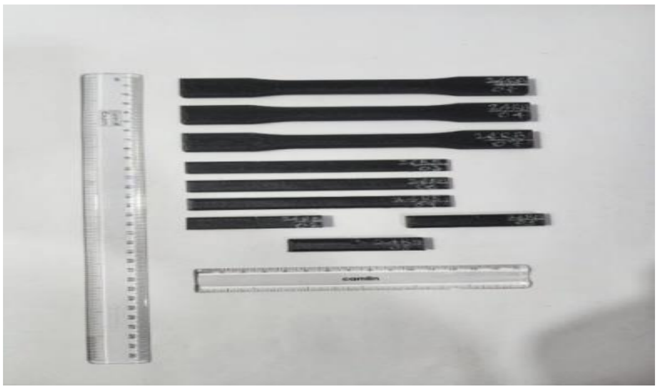

Figure 5 **Tensile, Flexural, and Impact Specimen**

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5. Mechanical Testing

5.1. Tensile Testing

Tensile Testing is a form of tension testing and is a destructive engineering and materials science test where by controlled tension is applied to a sample until it fully fails. This is one of the most common mechanical testing techniques [18].

5.2. Flexural Test

Flexural testing measures the force required to bend a beam of plastic material and determines the resistance to flexing or stiffness of a material. Flex modulus is indicative of how much the material can flex before permanent deformation.

5.3. Impact Test

Impact test, Test of the ability of a material to withstand impact, used by engineers to predict its behavior under actual conditions. Many materials fail suddenly under impact, at flaws, cracks, or notches.

6. Results

6.1. Tensile Test

Table 1 **Tensile Properties of PETG+CF**

Sl. No	Tensile Strength [MPa]	Modulus (Automatic Youngs) [MPa]	Maximum Force [KN]	Tensile Strain (Displacement) at Tensile Strength[%]	Tensile Stress Yield (offset 0.2%) [MPa]	Tensile Strain (Displacement) at Yield (offset 0.2 %)[%]
1	4.60	710.87	0.44	1.06	3.84	0.74
2	14.35	1496.91	1.38	1.65	10.73	0.91
3	21.11	2136.44	2.04	1.67	16.08	0

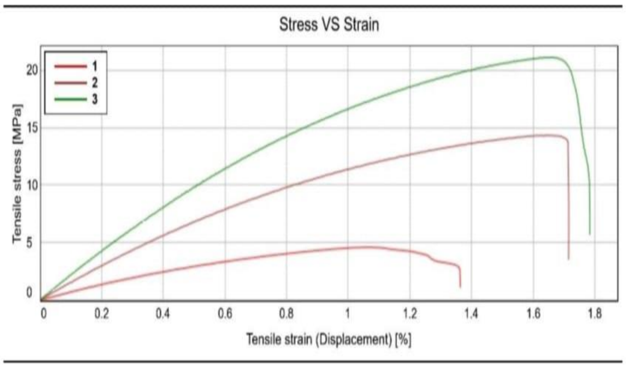

Figure 6 **Tensile Strain Vs Tensile Stress Graph**

The above graph (Figure 6) shows the test results for three Thickness .in such a diagram 1 is shell thickness 0.8mm, 2 is Shell thickness of 1.6mm, 3 is Shell thickness of 90mm. Table 1 shows the Tensile Properties of PETG+CF.

Figure 7 **Before Tensile Test of the Specimen**

Figure 8 **After Tensile Test of the Specimen**

In materials testing, particularly for metals, there are standardized procedures established by organizations such as ASTM (American Society for Testing and Materials) or ISO (International Organization for Standardization).

6.2. Flexural Test

Table 2 **Flexural Properties of PETG+CF**

SI. No	Flexure Stress [MPa]	Maximum Force [KN]	Modulus(Automatic Youngs)[MPa]	Flexural Stress at Yield(offset 0.2%)[MPa]	Flexural strain(Displacement) at Yield (offset 0.2%0[%]
1	29.81	0.04	1404.76	25.59	2.29
2	48.77	0.07	2144.03	38.99	2.26
3	52.96	0.08	2464.22	42.14	2.16

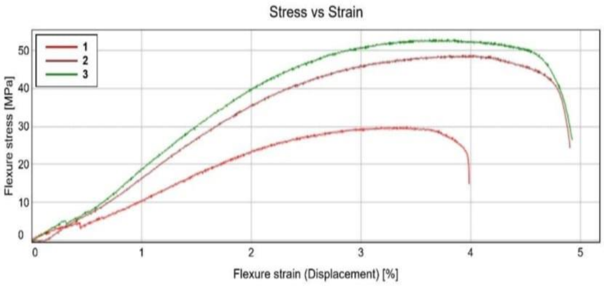

Figure 9 Flexural stress Vs Flexural Strain Graph

We have taken three different Thickness in this experiment. They are as follows 0.8mm, 1.6mm and 2.4mm.The below graph (Figure 9, 10& 11) shows the test results for three Thickness .in such a diagram 1 is shell thickness 0.8mm, 2 is Shell thickness of 1.6mm, 3 is Shell thickness of 90mm [19].

Figure 10 Before Flexural Testing of the Specimen

Figure 11 After Flexural Testing of the Specimen

Standard organizations such as ASTM (American Society for Testing and Materials) or ISO (International Organization for Standardization) often provide guidelines for the dimensions of specimens used in various testing methods, including flexural testing. Table 2 shows the Flexural Properties of PETG+CF.

6.3. Impact Test

The 1.6mm orientation helps resist delamination by providing a cross-ply structure that helps prevent the propagation of cracks between layers. The 1.6mm orientation typically results in a good balance between strength and toughness. Longitudinal fibers contribute to strength, while transverse fibers contribute to toughness. Table 3 shows the Impact Properties of PETG=CF.

Table 3 Impact Properties of PETG=CF

S.no	Material 1 (0.8 mm) (J)	Material 2 (1.6 mm) (J)	Material 3 (2.4 mm) (J)
1	36	39	38

The 1.6mm orientation helps resist delamination by providing a cross-ply structure that helps prevent the propagation of cracks between layers. The 1.6mm orientation typically results in a good balance between strength and toughness. Longitudinal fibers contribute to strength, while transverse fibers contribute to toughness. Figure 12 shows the Impact Stress Grap.

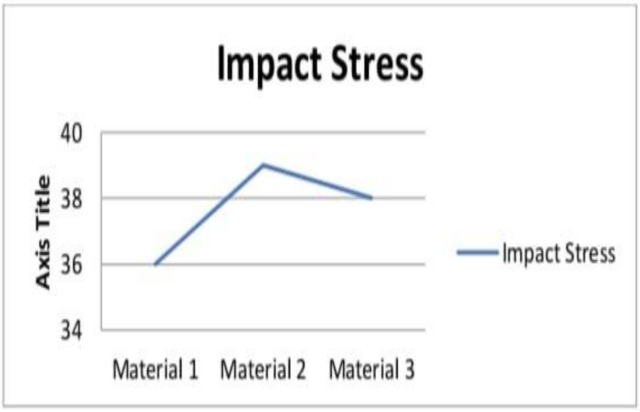

Figure 12 Impact Stress Grap

Conclusion

The investigation into the impact, flexural, and tensile properties of PETG carbon fiber composites with a 0.8mm shell thickness in Fused Deposition Modeling (FDM) processing has yielded valuable insights. The results suggest that the 0.8mm shell thickness parameter can serve as a practical and effective choice for producing PETG carbon fiber composites with enhanced mechanical characteristics in FDM applications. The consistent and positive performance across these three critical mechanical tests suggests that a 1.6 mm shell thickness in PETG carbon fiber composites is a viable and effective configuration for achieving a balanced combination of impact resistance, flexural strength, and tensile properties. The composite material demonstrated commendable mechanical characteristics across the three testing modalities. Systematic experimentation and analysis, it has been determined that this specific shell thickness significantly influences the overall performance of the composite material. The impact testing revealed an enhanced resistance to external forces, showcasing improved toughness and durability. In flexural testing, the 2.4 mm shell thickness demonstrated superior bending strength and stiffness, contributing to the material's structural integrity.

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