

# Mechanical Performance of FDM Printed Thermoplastics: Influence of Process Parameters and Hybrid Carbon Fiber Reinforcement

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## Abstract:

Additive Manufacturing (AM), particularly Fused Deposition Modeling (FDM), has gained significant attention due to its ability to fabricate complex geometries with reduced material waste and high design flexibility. FDM employs a layer-by-layer material deposition process in which thermoplastic filaments are extruded through a heated nozzle to produce three-dimensional components directly from digital models. Despite its advantages, FDM-fabricated parts often exhibit anisotropic mechanical behavior, weak interlayer bonding, and internal defects such as porosity and voids, which limit their structural performance in engineering applications. This paper presents a comprehensive analysis of materials, process parameters, and hybrid reinforcement strategies used to improve the mechanical performance of FDM-printed components. The fundamental principles of FDM, including layer deposition mechanisms and anisotropic characteristics, are first discussed. Subsequently, commonly used thermoplastic materials such as ABS, PLA, PETG, Nylon, and Polycarbonate are studied, with particular emphasis on carbon fiber reinforced thermoplastics (CFRTPs). The reinforcement mechanisms of carbon fibers in thermoplastic matrices are examined to understand their contribution to improved stiffness, tensile strength, and dimensional stability. Furthermore, the influence of critical process parameters—including layer height, infill density, infill pattern, print speed, and build orientation—on the mechanical properties of FDM components is systematically analyzed. The analysis also explores recent developments in hybrid multi-material FDM printing, including dual-nozzle systems, functional gradation strategies, and hybrid material architectures that combine pure thermoplastics with fiber-reinforced composites. Despite the progress in this field, several research gaps remain, including limited investigations on hybrid ABS-carbon fiber structures, insufficient multi-parameter optimization using Design of Experiments (DOE), and a lack of integrated experimental and Finite Element Analysis (FEA) approaches. Additionally, the application of hybrid composite materials using desktop FDM printer's remains relatively underexplored. Future research directions are therefore proposed, focusing on hybrid reinforcement strategies, multi-material additive manufacturing, intelligent process optimization using artificial intelligence, and topology-optimized structural designs. The insights presented in this evaluation aim to provide a comprehensive understanding of current research trends and support the development of high-performance hybrid FDM components for advanced engineering applications.

Keywords: Fused Deposition Modeling (FDM); Additive Manufacturing; Carbon Fiber Reinforced Thermoplastics; Hybrid Multi-Material Printing; Process Parameter Optimization; Mechanical Properties; ABS Composites.

## 1. Introduction

Additive Manufacturing (AM), commonly referred to as three-dimensional (3D) printing, represents a transformative approach to modern manufacturing in which components are fabricated directly from digital models through a layer-by-layer material deposition process. Unlike conventional subtractive manufacturing techniques that remove material through machining or forming operations, AM constructs parts incrementally, enabling complex geometries, reduced material waste, and enhanced design flexibility. Among the various AM technologies, Fused Deposition Modeling (FDM)—also known as Fused Filament Fabrication (FFF)—is one of the most widely adopted techniques due to its cost-effectiveness, operational simplicity, and compatibility with a broad range of thermoplastic materials [1], [2], [3].

FDM operates by extruding thermoplastic filament through a heated nozzle and depositing it layer-by-layer onto a build platform according to a pre-defined digital toolpath. This digitally controlled manufacturing approach allows rapid prototyping, customized production, and the fabrication of geometrically complex parts without the need for molds or specialized tooling [4-8]. Over the past decade, the accessibility of desktop 3D printers and open-source technologies has significantly expanded the use of FDM across research laboratories, industrial environments, and educational institutions [9-13]. As a result, FDM has transitioned from a rapid prototyping technique to a viable method for producing functional components in sectors such as aerospace, automotive, biomedical engineering, and tooling applications [14-18].

Despite these advantages, FDM-fabricated parts often exhibit anisotropic mechanical behavior due to the layer-by-layer deposition mechanism. The bonding strength between successive layers is typically weaker than the strength within a deposited filament strand, which results in reduced mechanical performance, particularly along the build (Z) direction [19-21]. In addition, process-induced defects such as porosity, void formation, and inadequate interlayer adhesion can significantly affect tensile strength, fatigue resistance, and structural reliability of printed components. These challenges become more pronounced when commonly used thermoplastics such as Acrylonitrile Butadiene Styrene (ABS) are employed for load-bearing applications. Although ABS offers advantages such as impact resistance, thermal stability, and good processability, FDM-printed ABS components often demonstrate lower mechanical strength compared to conventionally manufactured counterparts due to weak interlayer bonding and residual stresses generated during cooling [22-26].

To address these limitations, recent research has focused on material reinforcement strategies, particularly the incorporation of carbon fibers into thermoplastic matrices. Carbon fiber reinforced thermoplastics (CFRTs), such as carbon fiber reinforced ABS (CF-ABS), combine the toughness of polymer matrices with the high stiffness and strength-to-weight ratio of carbon fibers. These composite filaments enhance mechanical strength, dimensional stability, and thermal resistance of FDM printed parts, thereby extending their applicability to structural and performance-oriented

components [23-28]. During the extrusion process, short carbon fibers tend to align along the printing path, which can improve load-bearing capability and reduce warpage effects compared with pure thermoplastic materials [29-31].

The growing interest in reinforced and hybrid material systems reflects the broader objective of improving the mechanical reliability of FDM-fabricated components. Several studies have investigated the influence of process parameters—including build orientation, layer thickness, raster angle, and infill density—on the mechanical performance of both ABS and fiber-reinforced composites [28], [32-37]. These studies indicate that optimizing process parameters together with reinforcement strategies can significantly improve the structural performance of FDM components, enabling their use in engineering applications where mechanical strength and durability are critical.

In this context, the present evaluation focuses on the mechanical performance enhancement of FDM printed thermoplastic components through carbon fiber reinforcement and hybrid material strategies. The objective of this paper is to analyze existing research on FDM process parameters, material behavior, and reinforcement approaches that influence the mechanical properties of printed parts. Particular emphasis is placed on understanding the limitations of ABS in FDM systems and evaluating how carbon fiber reinforcement contributes to improved tensile strength, stiffness, and structural reliability. By synthesizing findings from recent studies, this evaluation aims to provide a comprehensive understanding of current research trends and identify key directions for optimizing FDM-based composite manufacturing. [38-45]

## **2. Fundamentals of Fused Deposition Modeling (FDM)**

Fused Deposition Modeling (FDM), also referred to as Fused Filament Fabrication (FFF), is a material extrusion-based additive manufacturing technique that fabricates three-dimensional components through the controlled deposition of thermoplastic material in successive layers. The process converts a digital model into a physical object by depositing semi-molten material along predefined toolpaths generated from sliced CAD data. Due to its operational simplicity, low equipment cost, and compatibility with various thermoplastic materials, FDM has become one of the most widely adopted additive manufacturing techniques in research and industrial applications [46-53].

### **2.1 Working Principle of FDM**

The FDM process begins with the creation of a three-dimensional model using Computer-Aided Design (CAD) software. The model is exported in Standard Tessellation Language (STL) format and subsequently processed using slicing software that divides the geometry into multiple thin layers. The slicing software generates a set of machine instructions, commonly known as G-code, which defines the movement of the printer head and the extrusion parameters required to fabricate the component.

In a typical FDM system, a thermoplastic filament such as Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), or composite materials is fed from a spool into an extruder assembly. The filament passes through a heated liquefier where it is softened or melted slightly above its glass transition temperature. The molten material is then forced through a nozzle and deposited onto a build platform following the path defined by the sliced model. The print head generally moves along the X–Y plane, while the build platform moves incrementally along the Z-axis after each layer is completed, enabling the formation of the final three-dimensional structure [1-6].

The deposited material rapidly cools and solidifies upon contact with the build surface or previously printed layer, forming a thermally bonded interface. Through repeated deposition of successive layers, the object gradually takes shape until the complete geometry is fabricated. This digitally driven manufacturing workflow eliminates the need for molds or tooling and enables the production of complex geometries and customized components [7-11].

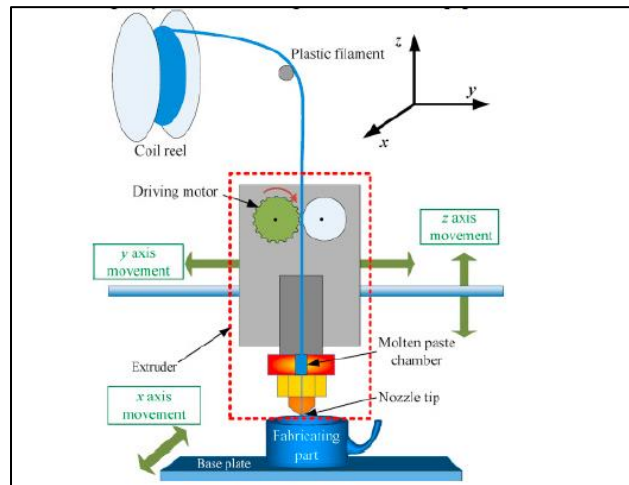


Figure No. 1. Schematic demonstration of the FDM process [5]

Figure No. 1 depicting filament feeding, heating through the extruder, layer-by-layer material deposition on the build platform, and progressive part formation [5].

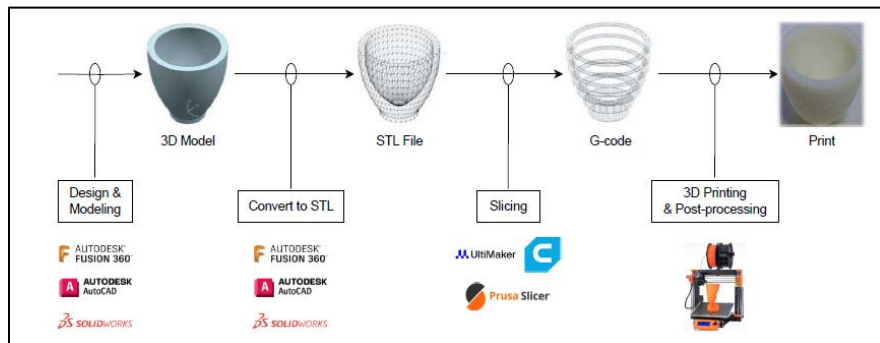


Figure No. 2: Overall workflow of the additive manufacturing process [2]

Figure No.2 shows generalized workflow of the Additive Manufacturing (AM) process—illustrating key stages from CAD modeling, slicing, and material preparation to part fabrication, post-processing, and final application deployment [2].

## **2.2 Layer-by-Layer Deposition Mechanism**

The defining characteristic of FDM technology is its layer-by-layer deposition mechanism, where material is extruded in the form of thin filaments or “roads.” Each deposited strand follows a predefined raster path that determines the internal structure of the printed component. The deposition pattern, raster angle, and infill strategy significantly influence the mechanical behavior, density, and structural integrity of the printed part. [12-17]

During fabrication, the first layer is deposited directly onto the heated build platform to ensure proper adhesion. Subsequent layers are deposited on top of the previously solidified material, where bonding occurs through thermal diffusion between adjacent layers. The bonding quality depends on several process parameters such as nozzle temperature, layer thickness, extrusion speed, and raster orientation. Proper parameter selection promotes sufficient molecular diffusion between layers, resulting in improved interlayer adhesion and mechanical strength. [18-23]

However, imperfect bonding between layers can lead to the formation of voids or micro-gaps, which act as stress concentration points and reduce the structural integrity of the component. These internal defects are common in FDM parts and are considered a major factor affecting mechanical performance, particularly in load-bearing applications [24-32]. The deposition strategy therefore plays a crucial role in determining the final quality and reliability of the printed component.

## **2.3 Anisotropic Mechanical Behavior in FDM**

One of the most significant characteristics of FDM fabricated parts is anisotropic mechanical behavior. Due to the layer-wise construction process, the mechanical properties of printed components vary depending on the direction of loading relative to the printing orientation. In general, strength within the deposition plane ( $X$ – $Y$  direction) is higher than the strength along the build direction ( $Z$ -axis). This occurs because the bonding between adjacent layers is primarily governed by thermal diffusion and is weaker than the continuous filament strands deposited within a single layer. [33-38]

As a result, FDM printed components often exhibit reduced tensile strength, impact resistance, and fatigue life along the  $Z$ -direction compared with conventional manufacturing processes such as injection molding. The anisotropic behavior is further influenced by factors such as raster orientation, layer thickness, infill density, and build orientation, which collectively determine the internal structure and stress distribution of the printed part [39-44].

This directional dependence of mechanical properties presents a significant challenge when FDM is used for structural or load-bearing applications. Consequently, extensive research has been conducted to mitigate anisotropy through optimized process parameters, improved material

formulations, and reinforcement strategies such as carbon fiber incorporation. These approaches aim to enhance interlayer bonding and improve the overall mechanical performance of FDM fabricated components. [45-50]

### 3. Materials Used in FDM

Material selection plays a critical role in determining the mechanical, thermal, and structural performance of components fabricated using Fused Deposition Modeling (FDM). A wide range of thermoplastic polymers and composite materials are currently used in FDM systems due to their ability to melt and solidify repeatedly without significant degradation. Among these materials, engineering polymers such as Acrylonitrile Butadiene Styrene (ABS) and reinforced composites such as carbon fiber reinforced thermoplastics (CFRTPs) are widely studied for structural applications. However, other thermoplastics including PLA, PETG, Nylon, Polycarbonate, and advanced engineering polymers are also frequently employed depending on the functional requirements of the printed component. The evolution of composite filaments has further expanded the applicability of FDM from simple prototyping to high-performance engineering applications. [51-53]

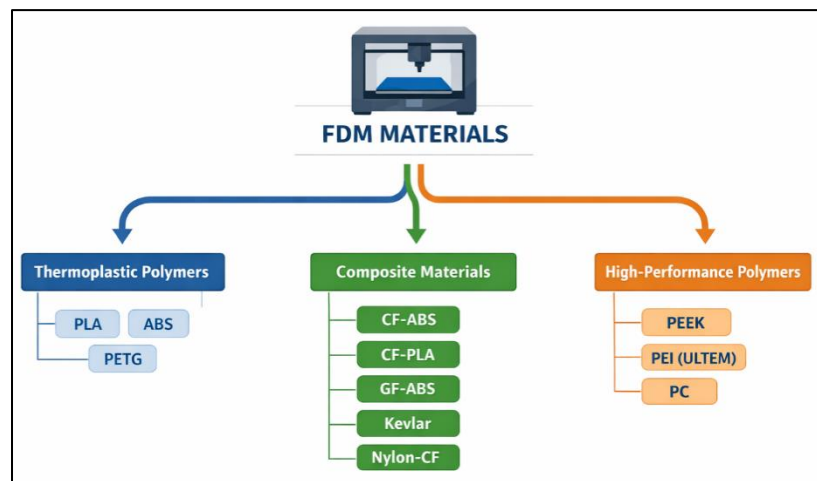


Figure No. 3. Classification of Materials Used in FDM

This Figure no. 3 visually demonstrates the evolution of FDM materials from basic thermoplastics to advanced reinforced and high-performance polymers, reflecting the growing capability of additive manufacturing in structural and industrial applications.

**Thermoplastic Polymers**-These are the most commonly used materials in desktop FDM systems because they melt and solidify repeatedly without significant degradation. Examples include PLA, ABS, PETG, and Nylon, which provide moderate mechanical properties and easy printability. These materials are mainly used for prototyping, functional models, and low-load engineering components.

**Composite Materials** Composite filaments incorporate reinforcing fibers or particles within a thermoplastic matrix to enhance stiffness, strength, and dimensional stability. Examples include carbon fiber reinforced polymers (CF-ABS, CF-PLA), glass fiber composites (GF-ABS), and Kevlar reinforced polymers. These materials are increasingly used in structural components where improved mechanical performance is required.

**High-Performance Polymers** These materials are designed for demanding engineering applications requiring high temperature resistance, strength, and chemical stability. Examples include PEEK, PEI (ULTEM), and Polycarbonate (PC). Such polymers are typically processed using industrial-grade FDM systems with high extrusion temperatures and controlled build environments.

### 3.1 Acrylonitrile Butadiene Styrene (ABS)

Acrylonitrile Butadiene Styrene (ABS) is one of the most widely used engineering thermoplastics in FDM due to its balanced combination of toughness, impact resistance, and thermal stability. ABS typically exhibits a glass transition temperature of approximately 105 °C, which allows consistent extrusion and stable layer deposition during printing. Its moderate strength, good ductility, and resistance to mechanical shock make it suitable for functional prototypes, automotive parts, housings, and industrial components [1-5].

Another advantage of ABS is its compatibility with post-processing techniques such as machining, sanding, and acetone vapor smoothing. These methods help improve surface finish and dimensional accuracy of printed components. Additionally, ABS demonstrates good chemical resistance and durability, which contributes to its widespread use in engineering applications [6-10].

Despite these advantages, ABS printed parts often suffer from anisotropic mechanical behavior caused by the layer-wise deposition process. The bonding strength between layers is typically weaker than the strength within deposited filaments, resulting in reduced tensile strength along the Z-direction. Furthermore, ABS is prone to warping and shrinkage due to thermal contraction during cooling, which may lead to dimensional inaccuracies and interlayer delamination [11-15]. Consequently, reinforcement strategies are often employed to enhance the mechanical performance of ABS components fabricated through FDM.

### 3.2 Carbon Fiber Reinforced Thermoplastics (CFRTPs)

Carbon Fiber Reinforced Thermoplastics (CFRTPs) represent an advanced class of composite materials used in FDM to improve the mechanical properties of conventional thermoplastics. In these materials, short carbon fibers are embedded within a thermoplastic matrix such as ABS or PLA. The presence of carbon fibers significantly enhances the stiffness, strength, and dimensional stability of printed components [16-20].

Carbon fibers possess a high modulus of elasticity and excellent strength-to-weight ratio. When integrated into thermoplastic matrices, they improve the tensile strength and structural rigidity of printed parts while also reducing thermal shrinkage. Studies have reported that CF-ABS composites can increase tensile strength by approximately 15–40 % compared with pure ABS, depending on fiber content and printing parameters [21-27].

However, CFRTP materials introduce certain challenges in FDM printing. The abrasive nature of carbon fibers may lead to nozzle wear and clogging, requiring hardened steel nozzles. Additionally, increased fiber content may cause higher melt viscosity, inconsistent extrusion, and increased brittleness of printed parts [28-33]. Despite these challenges, CFRTP materials are increasingly used in aerospace, automotive, and structural applications due to their superior mechanical performance.

### **3.3 Mechanisms of Carbon Fiber Reinforcement in FDM**

The improvement in mechanical properties observed in carbon fiber reinforced thermoplastics results from several reinforcement mechanisms operating within the polymer matrix during the FDM process. One of the primary mechanisms is fiber alignment along the extrusion direction. As the molten composite filament passes through the nozzle, shear forces orient the short carbon fibers along the deposition path. This alignment creates continuous reinforcement pathways that enhance tensile strength and stiffness along the raster direction [34-40].

Another key mechanism is loading transfer between the polymer matrix and the reinforcing fibers. Carbon fibers act as micro-reinforcement elements that distribute applied stress throughout the composite structure, thereby increasing the modulus and overall structural rigidity of the printed part.

Carbon fibers also improve interlayer bonding and crack resistance. Their presence can bridge micro-gaps between adjacent layers and restrict polymer chain mobility, which reduces crack propagation and enhances structural integrity. Furthermore, carbon fibers possess relatively high thermal conductivity, allowing more uniform heat distribution during printing and improving layer fusion within the composite structure [41-45].

Nevertheless, the effectiveness of reinforcement depends on several factors such as fiber distribution, fiber–matrix adhesion, and processing conditions. Excessive fiber content may cause fiber agglomeration, void formation, and weak interfacial bonding, which can reduce mechanical performance. Therefore, careful optimization of process parameters—including raster orientation, layer height, and extrusion temperature—is required to achieve efficient reinforcement in FDM composites.

### **3.4 Other Thermoplastic Materials Used in FDM**

In addition to ABS and carbon fiber reinforced composites, several other thermoplastic materials are widely used in FDM printing depending on the required mechanical and functional properties.

Polylactic Acid (PLA) is a biodegradable thermoplastic derived from renewable resources such as corn starch. It is widely used in FDM due to its ease of printing, low warping tendency, and good surface finish. However, PLA exhibits relatively low thermal resistance and brittle behavior, limiting its use in high-temperature or load-bearing applications [46-51].

Polyethylene Terephthalate Glycol (PETG) combines the ease of printing associated with PLA and the strength of ABS. It offers good chemical resistance, moderate flexibility, and improved impact resistance, making it suitable for mechanical parts, containers, and protective housings [51-53].

Polyamide (Nylon) is another widely used engineering polymer in FDM. It exhibits excellent mechanical strength, abrasion resistance, and flexibility, making it suitable for gears, bearings, and structural components. However, nylon is highly hygroscopic and requires proper drying before printing to maintain dimensional stability [8-12].

Polycarbonate (PC) is known for its high strength and thermal resistance. It can withstand significant mechanical loads and elevated temperatures, which makes it suitable for automotive and electronic applications. However, polycarbonate requires higher extrusion temperatures and controlled printing environments to prevent warping [15-20].

Advanced high-performance thermoplastics such as Polyetherimide (PEI/ULTEM) and PEEK are also used in industrial FDM systems. These materials exhibit exceptional thermal stability, flame resistance, and mechanical strength, enabling their use in aerospace and medical applications. However, they require specialized high-temperature printers and controlled environments for reliable processing [21-26].

Table No.1: Comparative Properties of Common FDM Materials

Material	Tensile Strength (MPa)	Glass Transition Temperature (°C)	Key Properties	Advantages in FDM	Limitations	Typical Applications
PLA (Polylactic Acid)	60–65	~60	Biodegradable polymer derived from renewable resources	Easy printing, low warping, good surface finish	Low heat resistance, brittle behavior	Prototypes, educational models, consumer products
ABS (Acrylonitrile)	40–50	~105	Tough engineering thermoplasti	Good strength, machinabilit	Warping, shrinkage, anisotropic	Automotive parts, housings,

le Butadiene Styrene)			c with good impact resistance	y, suitable for functional parts	mechanical properties	mechanical prototypes
PETG (Polyethylene Terephthalate Glycol)	50–55	~80	Semi-flexible polymer with chemical resistance	Balanced strength and flexibility, good layer adhesion	Moderate surface finish, lower stiffness than ABS	Containers, mechanical components, protective covers
Nylon (Polyamide)	70–85	~70	High strength, flexibility, and abrasion resistance	Excellent durability and fatigue resistance	Hygroscopic behavior requiring drying before printing	Gears, bearings, structural mechanical components
Polycarbonate (PC)	60–70	~147	High-strength thermoplastic with high temperature resistance	Superior mechanical strength and impact resistance	Requires high printing temperature and controlled environment	Automotive parts, electronics housings
CF-ABS (Carbon Fiber Reinforced ABS)	55–70	~105	ABS matrix reinforced with short carbon fibers	Higher stiffness, reduced warping, improved dimensional stability	Increased brittleness, nozzle wear due to abrasive fibers	Structural components, aerospace prototypes, functional parts

**4. Process Parameters Affecting Mechanical Properties in FDM**

The mechanical performance of components fabricated using Fused Deposition Modeling (FDM) is strongly influenced by process parameters that control filament deposition, bonding between layers, and internal structural configuration. Because FDM constructs parts through a layer-by-layer approach, variations in process parameters directly affect tensile strength, stiffness,

dimensional accuracy, and failure behavior. Key parameters that significantly influence the mechanical properties of FDM components include layer height, infill density, infill pattern, print speed, and build orientation [27-36].

#### **4.1 Layer Height**

Layer height represents the thickness of each deposited layer during the FDM printing process and plays a crucial role in determining interlayer adhesion and surface finish. Smaller layer heights typically improve bonding between layers because they increase the contact area between adjacent filaments, thereby enhancing polymer diffusion. Studies have shown that layer heights within the range of 0.1–0.2 mm produce better tensile strength and improved surface quality due to reduced void formation [9], [18], [19].

Conversely, larger layer heights such as 0.3–0.4 mm reduce printing time but may lead to poor interlayer bonding and increased internal porosity, which negatively affects mechanical strength. Therefore, optimizing layer height is necessary to achieve a balance between mechanical performance and printing efficiency [20-22]

#### **4.2 Infill Density**

Infill density determines the internal material distribution within the printed component and significantly influences its load-bearing capability. Higher infill densities increase structural continuity and reduce internal voids, thereby improving tensile and compressive strength. Research indicates that infill densities of 80–100% provide superior mechanical performance due to enhanced material continuity and reduced stress concentrations [9], [19], [27].

However, increasing infill density also increases printing time and material consumption. Some studies have reported that moderate infill densities (50–60%) may provide an optimal balance between strength, weight, and manufacturing efficiency depending on the intended application [1]

#### **4.3 Infill Pattern**

The infill pattern determines the internal geometric structure of the printed component and governs how stresses are distributed during loading. Common infill patterns include rectilinear, grid, triangular, honeycomb, and cubic structures. Rectilinear and grid patterns generally provide higher tensile strength because they create continuous load paths aligned with the stress direction [1], [9], [15].

Honeycomb patterns are often used in lightweight structures due to their efficient material utilization and energy absorption capability, although they may provide lower tensile strength compared with rectilinear patterns. Advanced infill structures such as cubic or gyroid patterns provide improved isotropic behavior and balanced strength across multiple directions [13], [52]

#### 4.4 Print Speed

Print speed controls the rate at which molten filament is deposited during printing and directly affects bonding between layers and dimensional stability. Slower print speeds allow sufficient time for heat transfer between adjacent layers, resulting in improved interlayer adhesion and better mechanical properties. Studies indicate that moderate printing speeds in the range of 30–50 mm/s provide consistent extrusion and improved bonding [8], [17], [20].

Excessively high printing speeds reduce the time available for layer fusion, which may lead to increased porosity and weaker mechanical performance. Conversely, extremely slow printing speeds may cause overheating or material deformation, affecting dimensional accuracy [21-27].

#### 4.5 Build Orientation

Build orientation is one of the most influential parameters affecting the anisotropic behavior of FDM components. Since the material is deposited layer by layer, the mechanical properties vary depending on the direction of loading relative to the deposition layers.

Experimental studies have shown that build orientation strongly influences tensile performance, where components printed in X or Y orientations generally exhibit higher strength compared to Z orientation due to improved filament alignment and stronger intralayer bonding. In contrast, Z-oriented prints rely primarily on interlayer adhesion, which is comparatively weaker and more susceptible to delamination [10], [28], [30].

Therefore, selecting an appropriate build orientation is essential for maximizing the mechanical performance of FDM printed components, particularly for structural applications where tensile strength and fatigue resistance are critical.

Table No.2: Influence of FDM Process Parameters on Mechanical Properties

Process Parameter	Typical Range / Condition	Influence on Mechanical Properties	Key Observations from Literature	References
Layer Height	0.1–0.4 mm	Controls interlayer adhesion, surface finish, and porosity	Smaller layer heights (0.1–0.2 mm) improve tensile strength and bonding due to increased contact area between layers. Larger layer heights increase void formation and reduce strength.	[9], [18], [19]
Infill Density	20–100%	Determines internal material distribution and	Higher infill density (80–100%) improves tensile and compressive strength by reducing internal voids, but increases print time and	[9], [19]

		load-bearing capacity	material usage. Moderate densities (50–60%) can optimize strength-to-weight ratio.	
Infill Pattern	Rectilinear, Grid, Honeycomb, Triangular, Cubic	Influences stress distribution and stiffness	Rectilinear and grid patterns provide better load transfer and tensile strength. Honeycomb structures are suitable for lightweight applications but may exhibit lower tensile strength.	[1], [9], [15], [52]
Print Speed	30–80 mm/s	Affects bonding time, porosity, and dimensional accuracy	Moderate speeds (30–50 mm/s) ensure proper material fusion and consistent extrusion. High speeds reduce bonding time, causing weak interlayer adhesion and reduced strength.	[8], [17], [20]
Build Orientation	X, Y, Z directions	Governs anisotropic behavior and failure mode	X and Y orientations generally exhibit higher tensile strength due to filament alignment with load direction. Z-oriented prints show weaker strength due to reliance on interlayer bonding.	[10], [28], [30]

## 5. Hybrid Multi-Material Printing

Hybrid multi-material printing has emerged as an advanced manufacturing strategy in Fused Deposition Modeling (FDM) to overcome the mechanical limitations associated with single-material thermoplastic prints. Conventional FDM parts fabricated from a single polymer often suffer from anisotropic mechanical behavior, weak interlayer bonding, and insufficient stiffness for structural applications. To address these limitations, recent research has explored multi-material and hybrid printing approaches, where different materials are strategically combined within a single component to achieve improved mechanical performance and functional customization. These approaches enable the fabrication of components with spatially tailored properties, allowing designers to combine stiffness, strength, and ductility within a single printed structure [5], [28].

### 5.1 Dual-Nozzle Printing Systems

Dual-nozzle FDM systems play a fundamental role in enabling hybrid multi-material fabrication. In such systems, two independent extrusion nozzles are used to deposit different materials during

the printing process. This capability allows the printer to alternate between materials or deposit them simultaneously in predefined regions of the component.

Dual-extrusion systems are commonly used to combine pure thermoplastics (e.g., ABS) with reinforced composite materials such as carbon fiber reinforced ABS (CF-ABS). The use of two materials enables the fabrication of components where one material provides structural strength while the other contributes to flexibility or impact resistance. Additionally, dual-nozzle systems are often employed for printing soluble support materials such as PVA or HIPS, which can be removed after printing to produce complex geometries with internal cavities [5], [28].

The effectiveness of dual-material printing depends on the synchronization of process parameters such as nozzle temperature, extrusion rate, and cooling conditions. Improper parameter matching between materials may lead to weak interfacial bonding, material incompatibility, or thermal mismatch, which can compromise the structural integrity of the printed component. Therefore, careful parameter optimization is necessary when implementing hybrid multi-material printing systems.

## **5.2 Functional Gradation in FDM Components**

Functional gradation refers to the gradual variation of material composition or mechanical properties within a single component. In FDM, functional gradation can be achieved through multi-material deposition, where different materials are selectively placed in specific regions of the part depending on the expected mechanical loads or functional requirements.

For example, reinforced materials such as CF-ABS may be deposited in high-stress regions, while standard ABS may be used in areas requiring greater ductility or reduced material cost. This spatial distribution of materials enables the fabrication of functionally graded structures that exhibit improved strength-to-weight ratios and enhanced structural performance.

Functional gradation also allows designers to optimize mechanical behavior without increasing the overall weight of the component. Studies have demonstrated that hybrid structures with localized reinforcement provide superior tensile and flexural performance compared with components fabricated using a single material. Consequently, functionally graded FDM components have gained significant interest in applications requiring customized mechanical performance, particularly in aerospace, automotive, and biomedical engineering fields [28], [42]

## **5.3 Hybrid Material Strategies in FDM**

Hybrid material strategies involve combining different thermoplastic materials or composites within a single printed structure to enhance overall mechanical performance. One common approach is the use of laminar or sandwich-type structures, where reinforced materials are embedded within a polymer matrix to improve load distribution and structural stiffness. For instance, configurations such as CF/ABS/CF layered structures have been shown to exhibit

improved tensile strength and reduced deformation compared with monolithic thermoplastic prints.

The effectiveness of hybrid material systems is largely influenced by the compatibility between the selected materials and the processing conditions used during printing. Factors such as thermal expansion mismatch, differences in melt viscosity, and interfacial adhesion between materials must be carefully controlled to prevent delamination or internal stresses. Advanced slicing software and optimized toolpath strategies are often required to manage transitions between materials and ensure structural continuity within the printed component [28].

Recent studies have suggested that hybrid multi-material FDM systems provide significant advantages for producing lightweight structural components with tailored mechanical properties. By combining reinforcement materials such as carbon fiber composites with conventional thermoplastics, it becomes possible to design components that achieve both strength and manufacturability. As a result, hybrid multi-material printing is increasingly recognized as a promising approach for next-generation additive manufacturing applications in high-performance engineering sectors [28]

## **6. Research Gap**

Despite significant advancements in Fused Deposition Modeling (FDM) technology and materials, several limitations remain in the current body of research, particularly in relation to hybrid material printing and mechanical optimization. Existing studies have extensively investigated the influence of individual process parameters and conventional thermoplastic materials; however, comprehensive investigations combining hybrid materials, experimental validation, and numerical simulation approaches remain relatively limited. Identifying these gaps is essential for guiding future research toward improving the structural reliability and engineering applicability of FDM-fabricated components.

### **6.1 Limited Research on Hybrid ABS–Carbon Fiber Structures**

Although carbon fiber reinforced thermoplastics have gained increasing attention in additive manufacturing, most studies primarily focus on single-material composite filaments rather than hybrid multi-material structures. While CF-ABS composites have demonstrated improved stiffness and tensile strength compared with pure ABS, limited research has investigated hybrid configurations that combine pure ABS and CF-ABS within the same printed component.

Hybrid material arrangements could potentially exploit the advantages of both materials—maintaining the ductility and processability of ABS while utilizing the high stiffness and strength of carbon fiber reinforced regions. However, the mechanical behavior, interfacial bonding characteristics, and optimal material distribution in such hybrid systems remain insufficiently explored in the literature [5], [28], [46].

## **6.2 Limited Optimization Studies Using Design of Experiments (DOE)**

Several investigations have examined the effect of individual process parameters such as layer height, raster orientation, and infill density on the mechanical performance of FDM components. However, many of these studies rely on single-factor experimentation, which does not adequately capture the interaction effects between multiple parameters.

Although statistical optimization techniques such as Taguchi methods and Design of Experiments (DOE) have been applied in some research, comprehensive multi-parameter optimization for hybrid material systems is still limited. The lack of systematic DOE-based investigations restricts the ability to identify optimal printing conditions for maximizing mechanical performance in hybrid FDM structures [23], [39].

## **6.3 Limited Integration of Experimental and Numerical Approaches**

Another notable gap in the literature is the limited integration of experimental testing with numerical simulation techniques such as Finite Element Analysis (FEA). While experimental tensile and mechanical tests are commonly conducted to evaluate FDM parts, relatively few studies combine these experimental results with simulation-based validation to predict structural behavior under different loading conditions.

The integration of experimental and simulation approaches can provide deeper insights into stress distribution, deformation mechanisms, and failure behavior of printed components. However, only a small number of investigations have attempted to correlate FDM experimental results with FEA predictions, particularly for hybrid composite structures [18], [46].

## **6.4 Limited Investigation Using Desktop FDM Printers**

Many studies on reinforced thermoplastic materials and hybrid printing strategies have been conducted using industrial-grade additive manufacturing systems. However, relatively few investigations focus on the feasibility of implementing these advanced material strategies using low-cost desktop FDM printers.

Desktop FDM printers are widely used in research laboratories, educational institutions, and small-scale manufacturing environments due to their affordability and accessibility. Nevertheless, issues such as inconsistent extrusion, limited temperature control, and dimensional variability often restrict their use in high-performance material studies. Consequently, further research is required to evaluate whether hybrid composite materials such as ABS–CF systems can be reliably processed using desktop FDM platforms [4], [19], [30].

## **6.5 Motivation for the Present Study**

Based on the identified gaps, there is a clear need for systematic research that integrates hybrid material printing, statistical process optimization, and simulation-based validation to improve the mechanical performance of FDM components. The present study addresses these limitations by

investigating hybrid tensile specimens fabricated using ABS and carbon fiber reinforced ABS (CF-ABS) through a dual-nozzle FDM system.

Furthermore, the research combines Design of Experiments (DOE) optimization techniques, experimental tensile testing, and Finite Element Analysis (FEA) to evaluate the structural behavior of the hybrid components. This integrated approach aims to provide a comprehensive understanding of the relationship between material distribution, process parameters, and mechanical performance in hybrid FDM printed structures.

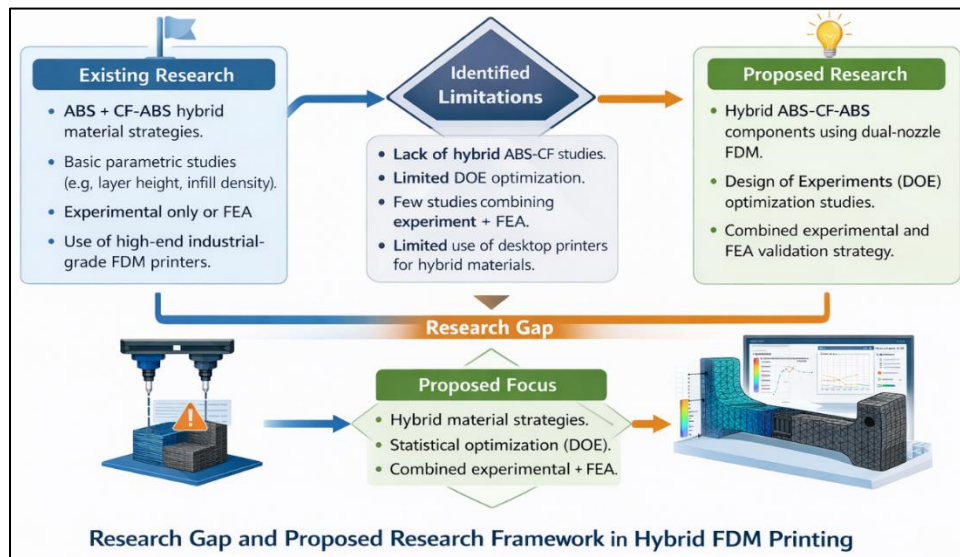


Figure No.4: Research Gap and Proposed Research Framework in Hybrid FDM Printing

## 7. Future Research Directions

Although considerable progress has been achieved in improving the mechanical performance of FDM-printed components, several areas still require further investigation to enhance the reliability and industrial applicability of additive manufacturing systems. Future research should focus on the development of advanced hybrid material strategies, multi-material fabrication techniques, intelligent process optimization methods, and optimized structural designs. These research directions are expected to expand the functional capabilities of FDM and improve the mechanical performance of printed components for high-performance engineering applications.

### 7.1 Hybrid Reinforcement Strategies

Future research should further explore hybrid reinforcement approaches in which multiple reinforcement materials are integrated within a thermoplastic matrix to enhance mechanical performance. While carbon fiber reinforced polymers have shown significant improvements in stiffness and tensile strength, combining reinforcement carbon fibers may provide synergistic improvements in mechanical properties.

Hybrid reinforcement systems may enable the fabrication of components with improved strength, impact resistance, and fatigue performance while maintaining acceptable printability. In particular, combining pure thermoplastics with fiber-reinforced regions within a single structure may allow the development of functionally graded materials that provide optimized mechanical performance in specific load-bearing regions [28], [44]

## **7.2 Multi-Material FDM Printing**

Multi-material additive manufacturing represents one of the most promising directions for future FDM research. Advanced FDM systems equipped with dual or multi-nozzle configurations allow the simultaneous deposition of different materials within a single component. This capability enables the fabrication of components with spatially varying mechanical, thermal, or functional properties.

Future research should investigate improved strategies for controlling the interface between different materials during printing. Issues such as thermal mismatch, bonding compatibility, and material flow synchronization must be addressed to achieve reliable hybrid structures. Additionally, advanced slicing algorithms and toolpath planning techniques are required to ensure accurate material transitions and structural continuity within multi-material prints [5], [28].

## **7.3 Integration of Experimental and Simulation-Based Design**

Future research should also focus on integrating experimental studies with advanced simulation tools such as Finite Element Analysis (FEA) to better understand the mechanical behavior of FDM components. Simulation models can predict stress distribution, deformation behavior, and failure mechanisms before physical fabrication, thereby reducing experimental cost and development time.

Combining simulation-driven design with experimental validation will enable the development of optimized hybrid structures with improved reliability and predictable mechanical performance. Such integrated approaches will be particularly beneficial for designing hybrid multi-material components produced through FDM processes.

## **8. Conclusion**

Fused Deposition Modeling (FDM) has emerged as one of the most widely adopted additive manufacturing technologies due to its cost-effectiveness, material versatility, and ability to fabricate complex geometries directly from digital models. The evaluation presented in this study highlights the fundamental principles of FDM, including the working mechanism of layer-by-layer material deposition and the inherent anisotropic behavior of printed components. While FDM offers significant advantages for rapid prototyping and functional part fabrication, its mechanical performance is strongly influenced by material characteristics and process parameters, which must be carefully controlled to achieve reliable structural properties [21], [23].

The evaluation further examined commonly used materials in FDM, particularly engineering thermoplastics such as Acrylonitrile Butadiene Styrene (ABS) and reinforced composites such as carbon fiber reinforced thermoplastics (CFRTPs). ABS remains a widely used material due to its toughness, impact resistance, and ease of processing; however, it exhibits limitations including anisotropic mechanical behavior, warping, and relatively low stiffness for structural applications. The incorporation of carbon fibers into thermoplastic matrices has been shown to improve stiffness, tensile strength, and dimensional stability, making reinforced composites suitable for high-performance engineering applications [5], [18], [31].

In addition to material considerations, the mechanical performance of FDM components is strongly governed by process parameters such as layer height, infill density, infill pattern, print speed, and build orientation. These parameters directly influence interlayer bonding, internal porosity, and stress distribution within printed components. Among these factors, build orientation has been consistently reported as one of the most critical parameters affecting mechanical performance, where components printed in the X–Y direction generally exhibit higher tensile strength compared with those fabricated in the Z-direction due to improved filament alignment and stronger intralayer bonding [9], [19], [27].

The examination also highlighted recent advancements in hybrid multi-material printing, particularly the use of dual-nozzle FDM systems that enable the integration of different materials within a single component. Hybrid printing strategies, such as combining pure ABS with carbon fiber reinforced ABS, allow the fabrication of functionally graded structures with enhanced mechanical properties and optimized material distribution. These approaches demonstrate significant potential for developing lightweight and high-strength components suitable for aerospace, automotive, and biomedical applications [28]

Despite these advancements, several research gaps remain in the field of FDM manufacturing. Current literature reveals limited studies focusing on hybrid ABS–carbon fiber structures, insufficient multi-parameter optimization using statistical techniques such as Design of Experiments (DOE), and relatively few investigations integrating experimental analysis with simulation-based validation methods such as Finite Element Analysis (FEA). Furthermore, the application of hybrid composite materials using low-cost desktop FDM printers remains underexplored, highlighting the need for further investigation to improve accessibility and practical implementation of advanced additive manufacturing techniques [4], [19], [30].

Future research directions should therefore focus on the development of hybrid reinforcement strategies, advanced multi-material FDM printing techniques, artificial intelligence–based process optimization, and topology-optimized structural designs. These approaches have the potential to significantly enhance the mechanical performance, efficiency, and reliability of additively manufactured components. Additionally, integrating experimental research with numerical

simulations will provide deeper insights into the mechanical behavior of hybrid FDM structures and facilitate the development of optimized manufacturing strategies.

In summary, the advancement of hybrid material systems, optimized process parameters, and intelligent manufacturing techniques will play a crucial role in expanding the capabilities of FDM technology beyond prototyping toward high-performance structural applications. The continued integration of material science, process optimization, and computational modeling is expected to drive the next generation of additive manufacturing solutions, enabling the fabrication of complex and mechanically robust components across a wide range of industrial sectors.

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