

Review Article

Advancements in Fused Deposition Modeling: Materials, Processes, and Emerging Trends in Polymer Additive Manufacturing

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Received 5 April 2025

Revised 16 August 2025

Accepted 17 August 2025

Abstract:

Fused Deposition Modeling (FDM) has become a leading technology in polymer additive manufacturing due to its versatility, cost effectiveness, and accessibility. This review explores the current advancements, material innovations, and emerging trends within FDM, particularly focusing on high performance polymers and composite materials. Key materials like PEEK (Polyetheretherketone), PEI (Polyetherimide), and PPSU (Polyphenylsulfone) are discussed in terms of their mechanical, thermal, and chemical properties, as well as their applications across industries such as aerospace, automotive, and medical devices. The incorporation of fiber and particle reinforced composites has significantly enhanced FDM capabilities, offering improved strength, rigidity, and thermal resistance for demanding applications. Moreover, the integration of Artificial Intelligence (AI) and the Internet of Things (IoT) is poised to revolutionize the FDM process by enabling predictive maintenance, and real time monitoring. However, challenges such as printability, cost, and material limitations continue to hinder broader adoption, especially for high performance composites and advanced materials. The review concludes by highlighting areas for future research, and material development, which are essential for unlocking the full potential of FDM in both prototyping and end use production.

Keywords: *Fused Deposition Modeling (FDM), Polymer Additive Manufacturing, High Performance Polymers, 3D Printing, Artificial Intelligence (AI) in FDM, Internet of Things (IoT) in FDM*

1. Introduction

1.1 Background on FDM

Fused Deposition Modeling (FDM) was developed in the late 1980s by Scott Crump, who sought to overcome the limitations of traditional prototyping techniques. The process was patented by Stratasy in 1989, and initially, it served primarily as a method for rapid prototyping [1]. The ability to produce both functional and visual prototypes directly from digital designs marked a significant breakthrough in product development, shortening the time and cost associated with creating prototypes. Over time, Fused Deposition Modeling (FDM) has expanded beyond prototyping, finding applications in functional part production, custom manufacturing, and low volume production runs [2].

FDM is particularly favored within the additive manufacturing community due to its relative affordability, ease of use, and broad material compatibility. It is commonly used in industries such as automotive, aerospace, medical, and

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consumer goods for a range of applications, from prototyping and tooling to customized and small batch production [3]. The flexibility to print with various thermoplastic materials, including polymers and composites, further enhances the relevance of FDM in today's manufacturing landscape [4].

1.2 Importance in polymer manufacturing

Fused Deposition Modeling (FDM) has emerged as one of the most popular and effective techniques in polymer additive manufacturing, primarily due to its combination of accessibility, flexibility, and cost effectiveness. One of FDM's key strengths lies in its ability to use a wide variety of thermoplastic materials, which are essential in both prototyping and final product production. Common materials used in FDM include widely available polymers like PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), and PETG (Polyethylene Terephthalate Glycol), as well as specialty materials like nylon, TPU (Thermoplastic Polyurethane), and even carbon fiber reinforced filaments [5].

The ability to process such a broad range of polymers allows FDM to cater to a diverse array of industries, including automotive, aerospace, healthcare, and consumer products. This versatility enables manufacturers to select materials with specific properties required for their applications, such as strength, flexibility, impact resistance, or high temperature stability. Additionally, FDM's ability to handle polymer composites filaments infused with reinforcements like carbon fiber or glass fiber enables the production of parts with enhanced mechanical properties, which is particularly valuable for demanding applications [6]. The composite filaments used in this study are based on high-performance polymers such as PEEK, PEI and PPSU, which are known for their excellent mechanical properties and high thermal stability. These materials are also electrically insulating, exhibiting high dielectric strength and low electrical conductivity, making them suitable for applications requiring electrical insulation or protection in demanding environments.

FDM's popularity in polymer manufacturing is also driven by its low cost and accessibility. This makes the technology accessible to small businesses, research labs, and even hobbyists, enabling a wide range of users to take advantage of its benefits [7]. The availability of affordable desktop FDM printers has opened the door to rapid prototyping and short run production without the need for costly tooling or molds [8].

In addition to its affordability, FDM is highly effective for iterative design and small scale production. The quick turnaround times in creating prototypes, coupled with the ability to print customized parts on demand, allows for fast product development cycles and greater design flexibility. This is especially important in industries where rapid innovation and frequent design changes are essential [9]. FDM's capability to create complex shapes with minimal material waste also contributes to its efficiency, further enhancing its value in polymer manufacturing. Overall, FDM's combination of material versatility, cost efficiency, and ease of access makes it a pivotal tool in the field of polymer additive manufacturing, serving a wide range of applications from prototyping to customized, low volume production [10].

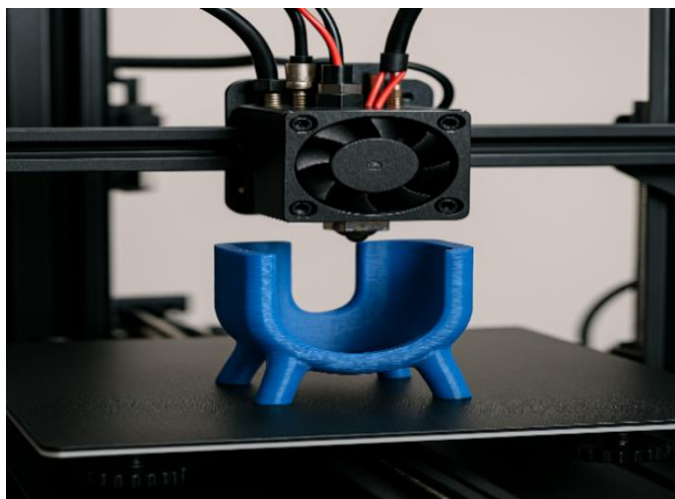


Fig. 1. Schematic Representation of FDM

2. Overview of the FDM process

2.1 Basic principles of FDM

Fused Deposition Modeling (FDM) is an additive manufacturing technique where material is deposited layer by layer to build a 3D object. Fig 1 illustrates the process involves feeding a thermoplastic filament into a heated extruder, which melts the material and deposits it onto a build platform according to a predefined digital model [11]. Each layer solidifies as it cools, and the object is gradually formed by successive layers. FDM is widely used for prototyping and production due to its simplicity, material variety, and ability to create complex shapes. The method's primary limitations include surface finish quality and build speed [12].

2.2 Key parameters affecting FDM performance

Temperature Settings (Nozzle and Bed Temperature): One of the most critical factors in FDM printing is the control of temperature. The nozzle temperature must be set appropriately to ensure that the filament material is heated to its optimal extrusion temperature [13]. If the nozzle is too hot, the filament may become overly liquid, causing issues like stringing or oozing [14]. On the other hand, if the temperature is too low, the filament may not extrude properly, leading to inconsistent deposition and poor layer adhesion [15].

The bed temperature also plays a crucial role in ensuring that the first few layers of the print adhere well to the build platform [16]. A heated bed prevents issues like warping, especially for materials such as ABS and nylon, which tend to contract when cooling. Setting the bed temperature correctly helps in achieving better adhesion and preventing the warping or detachment of parts during printing [17].

Speed and Layer Height: The print speed is another critical parameter that affects both the quality of the printed object and the printing time. Higher print speeds can reduce print time but may result in lower resolution and reduced bonding between layers [18]. Slower speeds, while improving layer adhesion and surface quality, may also increase the print time significantly. Achieving a balance between speed and quality is essential for ensuring that parts are printed with the required mechanical properties, especially for functional parts that must endure stresses or environmental factors [19].

Layer height refers to the thickness of each printed layer. This parameter is a key determinant of the resolution and finish of the part. A smaller layer height results in smoother vertical surfaces and higher resolution but also increases the print time, as more layers are required to form the object. Larger layer heights allow for faster printing but may result in visible layer lines and less detailed parts. Selecting an appropriate layer height is critical, as it directly impacts both the appearance and the mechanical properties of the printed part [20]. In applications where precision and smooth vertical surfaces are required, finer layers are typically preferred.

Infill Patterns and Print Orientation: The infill pattern defines the internal structure of the printed object, and it directly affects the part's strength, weight, printing time, and material efficiency. Common infill patterns include honeycomb, grid, and line, among others. The choice of infill pattern depends on the desired balance between strength, fabrication time, and material usage [21]. A denser infill pattern results in a stronger part but consumes more material and significantly increases printing time due to the greater volume of extruded filament and additional toolpath complexity. Conversely, a more sparse infill pattern reduces material consumption and shortens printing time, but may lead to reduced mechanical performance. Therefore, printing time becomes a critical factor, especially in applications where rapid prototyping or high-throughput production is required, necessitating a careful trade-off between structural integrity and manufacturing efficiency.

Print Orientation: Print orientation refers to the angle at which the object is printed relative to the build platform. This orientation influences not only the appearance of the printed part but also its mechanical properties. Parts printed with layers oriented along specific axes can exhibit markedly different strength characteristics. Previous studies have shown that polymer-jetting specimens printed in XZ, YZ, and vertical orientations exhibited 20–30% higher tensile strength and 15–25% greater hardness than those printed flat in the XY plane, highlighting the significant impact of layer alignment on anisotropic strength. Similarly, it was found that for FDM-printed polymers (ASA, Nylon, ULTEM), side-oriented specimens demonstrated the highest tensile properties, followed by flat prints, while upright (Z-axis) prints showed the lowest performance [34]. Across these works, the trend remains clear: strength is highest

when the load direction aligns with strong intra-layer filaments (X–Y plane), and weakest when load is across inter-layer bonds (Z-axis). Choosing the optimal orientation is therefore critical both for mechanical performance—especially in load-bearing applications—and surface quality. For instance, layers oriented in the XY plane yield better horizontal strength, while Z-aligned layering often produces visible layer lines and weaker inter-layer bonding, requiring additional post-processing [35].

Other Parameters (Support Structures and Cooling): Additional parameters, such as support structures and cooling, can also influence the print quality. Support structures are necessary when printing overhangs or complex geometries that cannot be printed without support. These supports must be carefully designed to ensure they can be removed easily after printing without damaging the part. The type and density of support structures should be selected based on the design and required finish. Cooling is another important factor that can affect the final quality of the printed part. Cooling fans are typically used to rapidly cool the extruded material to help with layer adhesion and reduce warping. Proper cooling is especially important for materials like PLA, which solidify quickly and benefit from immediate cooling, but excessive cooling can cause issues such as warping in materials like ABS. The cooling rate must therefore be optimized based on the material used and the print settings. Together, these key parameters—temperature, speed, layer height, infill patterns, and print orientation—are crucial to achieving high quality FDM prints. Balancing these variables ensures optimal part performance, quality, and efficiency. It is important to consider the specific requirements of each print job, as different applications may require specific adjustments to these parameters [23]. Mastering these settings and understanding their impacts can lead to better print outcomes, improved material use, and enhanced mechanical properties, ultimately contributing to the success of FDM in both prototyping and functional manufacturing.

3. Advanced materials in FDM: a comparative analysis

In recent years, the development and use of high performance polymers in FDM have significantly expanded the scope of 3D printing applications, particularly in industries requiring exceptional mechanical, thermal, and chemical properties. These materials, such as PEEK (Polyetheretherketone), PEI (Polyetherimide), and PPSU (Polyphenylsulfone), offer significant advantages over standard thermoplastics like PLA and ABS, making them suitable for demanding applications in aerospace, automotive, and medical sectors [24]. This section provides a comparative analysis of these advanced materials, focusing on their unique properties, advantages, and challenges when used in FDM.

3.1 High Performance Polymers (PEEK, PEI, PPSU)

PEEK (Polyetheretherketone)

PEEK is considered one of the most advanced and high-performance thermoplastics used in FDM due to its exceptional mechanical properties, including high tensile strength, excellent fatigue resistance, and outstanding wear characteristics. These attributes make it ideal for demanding applications in aerospace and automotive industries, where components must withstand extreme temperatures, mechanical stress, and chemical exposure. PEEK demonstrates excellent thermal and chemical resistance, withstanding continuous use at temperatures up to 250°C and resisting a wide range of chemicals such as acids and solvents. However, its high melting point of around 340°C makes it challenging to print, requiring specialized high-temperature FDM printers and often post-processing to achieve optimal part quality. Despite these challenges, PEEK is widely used for lightweight structural parts in aerospace, high-performance engine components in automotive, and biocompatible medical devices like implants and surgical tools [25].

PEI (Polyetherimide)

Polyetherimide (PEI) is a high-performance polymer commonly used in FDM due to its excellent combination of mechanical strength, dimensional stability, and flame resistance. It offers superior heat resistance compared to standard engineering plastics, maintaining structural integrity at temperatures up to 170°C, and features a low coefficient of thermal expansion (CTE), which enhances dimensional stability under thermal fluctuations. PEI also exhibits strong chemical resistance to fuels, oils, and greases, making it suitable for automotive, electrical, and aerospace applications where non-flammable and chemically resistant materials are essential. Compared to PEEK, PEI is relatively easier to print, requiring a lower extrusion temperature of around 350°C and a heated bed to ensure

proper adhesion and minimize warping, especially for larger components. It is widely used in aerospace for heat- and chemical-resistant interior parts, in electronics for its insulating properties, and in the medical field for sterilizable components [25]. PEI offers an excellent balance of strength, thermal stability, and ease of printability, making it a popular choice in both aerospace and medical sectors. PPSU, on the other hand, is highly valued in medical and aerospace industries due to its excellent chemical and thermal resistance, as well as its ability to endure repeated sterilization.

PPSU (Polyphenylsulfone)

Polyphenylsulfone (PPSU) is a high-performance thermoplastic recognized for its exceptional thermal resistance, impact strength, and chemical stability, making it well-suited for demanding industrial applications. Capable of withstanding temperatures up to 260°C, PPSU also demonstrates strong resistance to a wide range of chemicals, including acids, bases, and solvents, which is particularly valuable in medical and aerospace environments. Its resilience under high temperatures and ability to endure repeated sterilization cycles make it ideal for medical devices, surgical tools, and implants. However, printing PPSU via FDM presents challenges, as it requires high-temperature settings, a heated bed, and careful cooling control to avoid warping or cracking. In aerospace, PPSU is used for components subjected to extreme conditions, such as fluid systems and pressure-exposed tanks, where durability and chemical resistance are critical [17].

Table 1: Comparison of PEEK, PEI and PPSU

Property	PEEK	PEI	PPSU
Thermal Resistance	Up to 250 °C (continuous use)	Up to 170 °C (continuous use)	Up to 260 °C (continuous use)
Mechanical Strength	High tensile and fatigue strength	High strength and impact resistance	High impact strength
Chemical Resistance	Excellent (acids, solvents, oils)	Good (fuels, oils, greases)	Excellent (acids, bases, solvents)
Printability	Difficult (high extrusion temp)	Moderate (requires heated bed)	Moderate (requires temperature control)
Applications	Aerospace, automotive, medical	Aerospace, automotive, medical	Medical, aerospace, food processing
Cost	High (premium material)	Moderate (cost effective for performance)	Moderate (cost effective for high temperature resistance)

3.2 Comparative analysis of high performance materials in FDM: a bar chart overview

Methodology for performance quantification

The performance of the materials was assessed using a 1-10 scoring system based on key properties such as thermal resistance, mechanical strength, chemical resistance, flame resistance, and cost. The scores were determined by a combination of experimental data, literature values, and expert judgment. Thermal resistance was evaluated based on the material’s ability to withstand high temperatures, with higher scores reflecting better performance. Mechanical strength was assessed through tensile strength tests, with higher scores indicating stronger materials. Chemical resistance was tested by exposing the materials to various chemicals, and higher scores represented better resistance to degradation. Flame resistance was determined by combustion tests, with higher scores indicating materials that are more resistant to ignition and flame spread. Cost was evaluated based on market prices, with lower scores assigned to more expensive materials. This approach provided a comprehensive and consistent method for comparing the materials across these critical properties.

Thermal Resistance:

Thermal resistance is a key factor in evaluating a material’s suitability for high-temperature environments, and among high-performance polymers used in FDM, PEEK, PPSU and PEI exhibit notable performance. As shown in Fig 2 PEEK demonstrates excellent thermal resistance, sustaining continuous use at temperatures up to 250°C, making it a preferred choice in aerospace and automotive applications that demand stability under extreme conditions. PPSU

slightly surpasses PEEK in this aspect, withstanding temperatures up to 260°C, and is particularly valuable in medical and aerospace industries where both thermal stability and mechanical strength are essential. PEI, while offering a lower thermal resistance of 170°C, still performs well in many industrial and medical applications where exposure to extreme heat is less critical [26].

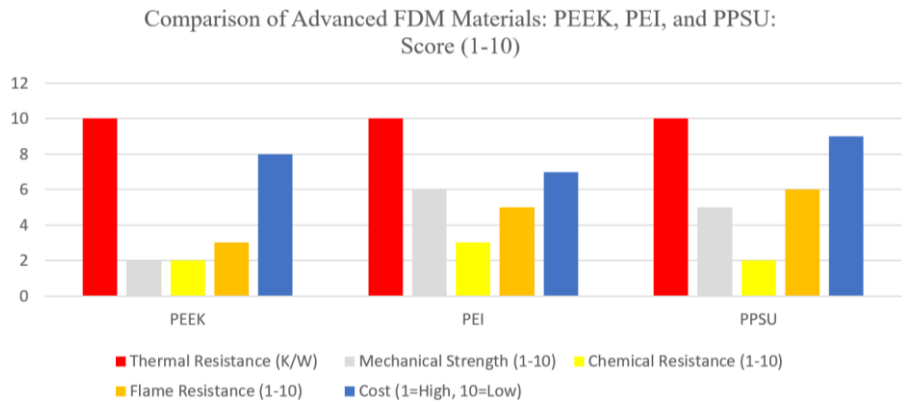


Fig. 2. Comparison of Advanced FDM Materials

Mechanical Strength:

Mechanical strength is a critical property for materials intended for structural and functional components in high-performance applications. Among the evaluated thermoplastics, Fig 2 illustrates PEEK stands out with a mechanical strength rating of 9 out of 10, attributed to its outstanding tensile strength, fatigue resistance, and wear resistance, making it highly suitable for demanding aerospace and automotive parts where durability and long-term performance are essential. PPSU follows with a score of 8 out of 10, recognized for its excellent impact resistance, which is particularly beneficial in medical devices and industrial fluid handling systems requiring resilience against sudden forces. PEI, scoring 7 out of 10, offers solid mechanical properties such as tensile strength and dimensional stability but is comparatively less robust in terms of impact resistance and long-term fatigue performance under stress [26].

Chemical Resistance:

Chemical resistance is a vital factor when selecting materials for applications exposed to aggressive substances such as acids, solvents, and oils. As shown in Fig 2 PEEK demonstrates outstanding chemical resistance with a score of 9 out of 10, enabling its use in harsh environments like chemical processing, aerospace, and automotive sectors. PPSU matches PEEK in this regard, also scoring 9 out of 10, due to its ability to resist a wide range of chemicals, including acids, bases, and solvents, making it ideal for demanding industrial and medical applications. PEI, while offering good chemical resistance with a score of 7 out of 10, is slightly less comprehensive in its chemical protection, performing well against oils, fuels, and greases but falling short of the robustness seen in PEEK and PPSU [27].

Flame Resistance:

Flame resistance is a critical property for materials used in industries such as aerospace, automotive, and medical, where adherence to strict fire safety standards is essential. As shown in Fig 2 PPSU leads in this category with a top rating of 9 out of 10, making it highly suitable for applications requiring exceptional flame resistance, such as aircraft interior components and sterilizable medical devices. PEEK follows with a score of 8 out of 10, offering strong flame resistance suitable for environments where fire safety is important, though not the primary concern. PEI, while inherently flame resistant, scores 7 out of 10, which is adequate for use in aerospace and automotive interiors but may not satisfy the highest flame resistance requirements in more demanding applications.

Cost:

Cost is a critical factor in selecting high-performance polymers for manufacturing, as materials like PEEK, PEI, and PPSU carry premium prices that must be justified by their properties and application requirements. As shown in Fig

2 PEEK is the most expensive, rated 3 out of 10 on the cost scale, with its high price reflecting its superior performance in extreme thermal, mechanical, and chemical conditions, making it suitable only for applications where such capabilities are indispensable. PEI offers a more cost-effective alternative, scoring 6 out of 10, and is widely used in industrial and medical settings where good performance is needed without the extreme demands met by PEEK. PPSU, with a cost rating of 5 out of 10, strikes a balance between performance and affordability, offering excellent flame resistance, chemical stability, and thermal durability, particularly beneficial in medical and aerospace fields. Overall, PEEK stands out in thermal resistance, mechanical strength, and chemical resistance but at a higher cost, while PPSU provides robust flame and chemical resistance with better affordability, and PEI delivers solid performance across categories at a more accessible price point, making it suitable for a wide range of FDM applications.

3.3 Composite materials in FDM: advancements and applications

The integration of composite materials in FDM has significantly enhanced the capabilities of 3D printing, allowing for the production of parts with superior mechanical properties and tailored characteristics. By combining traditional thermoplastics with various reinforcing agents such as fibers, ceramics, and metals, composite materials offer a unique advantage in additive manufacturing. These materials not only retain the versatility and ease of use of standard FDM polymers but also exhibit enhanced properties like increased strength, stiffness, heat resistance, and wear resistance.

Types of Composites in FDM

Composite materials used in FDM generally consist of a base polymer matrix that is reinforced with filler materials. The most common types of fillers include fibers, and particles, each of which contributes different characteristics to the final printed part.

Fiber Reinforced Composites: Fiber reinforced composites are among the most popular types of composites used in FDM due to their ability to improve the strength to weight ratio and stiffness of the base material. These composites combine thermoplastics with fibers such as carbon fibers, glass fibers, aramid fibers (e.g., Kevlar), and natural fibers [28].

- **Carbon Fiber Reinforced Composites:** Carbon fibers, when embedded into a thermoplastic matrix like PLA, ABS, or Nylon, provide high strength, low weight, and excellent dimensional stability. Carbon fiber infused filaments like Carbon Fiber PLA and Carbon Fiber Nylon are widely used in aerospace, automotive, and robotics applications, where both strength and lightness are paramount. The fibers significantly improve the stiffness of the part while maintaining its lightweight nature, making them ideal for applications such as structural parts, robotic arms, brackets, and drone components [26].
- **Glass Fiber Reinforced Composites:** Glass fiber composites offer superior impact resistance and higher rigidity compared to non-reinforced thermoplastics. Filaments such as Glass Fiber Reinforced Nylon (GF Nylon) provide excellent wear resistance and dimensional stability, making them ideal for industrial tooling, machine parts, and high load applications. Glass fibers are also often used in combination with high performance polymers like PEEK to further enhance the mechanical properties of parts intended for extreme environments [26].
- **Aramid Fiber (Kevlar) Reinforced Composites:** Kevlar infused filaments are known for their high tensile strength and abrasion resistance. Kevlar composites can be used to produce parts that are resistant to impact and wear, making them suitable for applications in personal protective equipment, automotive, and defense industries [27].
- **Bio Based Fiber Reinforced Composites:** With a growing demand for sustainable and environmentally friendly solutions in manufacturing, bio based fiber reinforced composites are gaining attention. These composites utilize natural fibers, such as hemp, flax, or jute, combined with biodegradable thermoplastic matrices. These materials offer a renewable alternative to traditional fiber composites and are often used in the automotive and consumer goods industries.

Particle Reinforced Composites: In addition to fiber reinforcement, particles such as metal powders, ceramic particles, or carbon nanotubes are also incorporated into thermoplastics to create composite filaments. These particle based composites offer enhanced thermal conductivity, strength, and resistance to wear.

- **Metal Infused Composites:** Metal filled filaments are gaining popularity in FDM, where a polymer matrix is mixed with fine metal powders like bronze, brass, or stainless steel. These materials are used in prototyping and small batch production for parts that require a metal like finish or properties like conductivity. Once printed, these parts can be post processed (e.g., by polishing or sintering) to further enhance their metallic appearance and properties. Examples of metal filled filaments include Bronze PLA or Stainless Steel PLA.
- **Ceramic Infused Composites:** Ceramic filled filaments are used for creating high temperature resistant parts, such as insulating components and parts that need to maintain their shape under heat. Ceramic composites are typically employed for aerospace or energy generation applications where thermal insulation and strength are needed. Post processing techniques, such as sintering or firing, are often required to fully solidify and enhance the ceramic properties of printed parts [27].

Advantages of Composites in FDM

Composite materials in FDM offer significant advantages by enhancing the mechanical, thermal, and chemical performance of printed parts. Fiber-reinforced composites, in particular, improve tensile strength, stiffness, and fatigue resistance, enabling parts to withstand heavy loads and dynamic stress while also providing superior impact resistance—making them ideal for structural components and functional prototypes. These materials also offer a favorable strength-to-weight ratio, especially when reinforced with carbon or glass fibers, which is highly beneficial in weight-sensitive industries like aerospace and automotive. Additionally, composites contribute to improved thermal stability and chemical resistance, with glass- or carbon-filled polymers exhibiting enhanced wear resistance and heat tolerance, making them suitable for demanding applications such as engine parts, tooling, and aerospace components. Furthermore, FDM composites provide design versatility, allowing engineers to tailor material properties through various reinforcement types and combinations, optimizing performance without the need for traditional manufacturing processes like molding or machining [28].

Challenges of Composites in FDM

Despite their numerous advantages, composite materials used in FDM also present several challenges that must be addressed to achieve optimal results. One of the primary concerns is printability, as fiber-reinforced filaments—especially those with high fiber content—can lead to nozzle clogging or accelerated wear due to the abrasive nature of the fibers, necessitating the use of specialized extruders and hardened nozzles. Additionally, composite filaments, particularly those reinforced with carbon fiber or metal, are generally more expensive than standard thermoplastics, and the need for specialized printing equipment further increases production costs. This makes them more appropriate for low-volume, high-performance applications rather than mass production. Moreover, certain composites, such as metal- or ceramic-filled filaments, often require post-processing steps like sintering, polishing, or firing to achieve their final mechanical properties, adding time, cost, and complexity to the overall manufacturing process [29].

4. Future trends in FDM polymer additive manufacturing

4.1 Emerging trends in composite materials for FDM

- **Hybrid Composites:** Hybrid composites that combine different types of reinforcements such as carbon fibers and metal particles are emerging in FDM. These hybrid materials offer unique combinations of strength, thermal resistance, and conductivity, enabling the creation of parts with multi functional properties. Hybrid composites are expected to gain traction in industries such as electronics, robotics, and automotive.
- **Reinforced Bio Based Composites:** The growing demand for sustainable manufacturing solutions is leading to the development of bio-based composite materials. These composites utilize natural fibers and bio polymers, offering a more environmentally friendly alternative to traditional fiber composites. The use of these materials in FDM could help reduce the carbon footprint of additive manufacturing, making it more aligned with global sustainability goals.
- **Functional Composites:** The integration of functional additives into composites is an emerging trend. For example, researchers are exploring the incorporation of nanomaterials (like carbon nanotubes or graphene) into composite filaments to impart electrical conductivity, enhanced strength, or self healing properties. These innovations could open up new applications for smart manufacturing and advanced electronics.

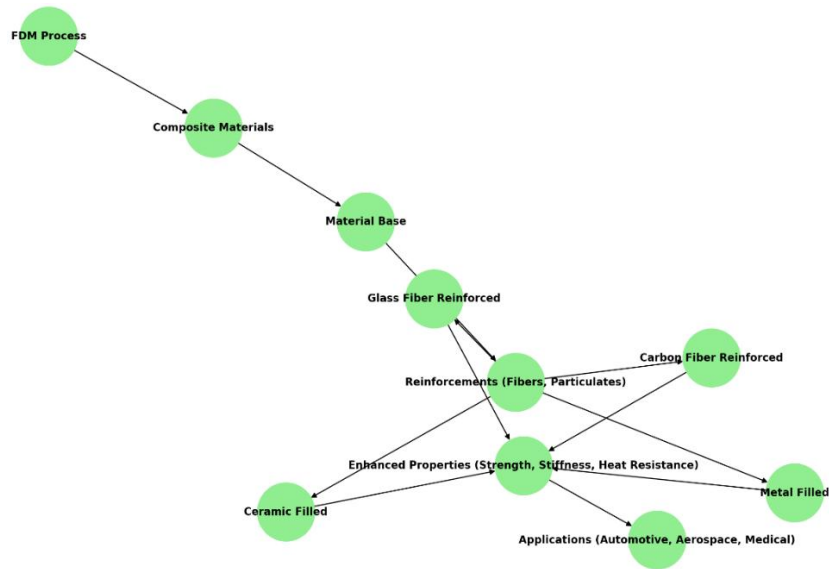


Fig. 3. Composite Materials Integration in FDM

Figure 3 was designed to visually represent the conceptual framework of composite material integration within the FDM process. Although previously referred to as a "flowchart," the figure more accurately serves as a directed concept map, delineating the interrelationships between material inputs, reinforcement types, property enhancements, and their corresponding applications in advanced manufacturing sectors. The diagram begins with the FDM Process, which serves as the foundational node of the framework. From this starting point, the flow proceeds to the incorporation of Composite Materials, indicating the integration of multiple phases (e.g., fiber or particle reinforcements) into a polymer matrix to improve material performance. This leads to the Material Base, representing thermoplastics commonly used in FDM (e.g., PLA, ABS), which are the substrates for further modification. Subsequently, the Reinforcements (Fibers, Particulates) node functions as a pivotal convergence point in the diagram. It encompasses various classes of reinforcements, including Glass Fiber Reinforced, Carbon Fiber Reinforced, Metal Filled, and Ceramic Filled materials. Each of these reinforcement categories is depicted as a branch, signifying the diversification of composite formulations based on functional requirements.

The integration of these reinforcements results in Enhanced Properties, particularly in terms of mechanical strength, stiffness, and thermal resistance. These improved attributes are critical in extending the utility of FDM-fabricated parts to demanding use cases. The diagram culminates in the Applications node, which highlights industrial domains—namely automotive, aerospace, and medical—where such high-performance materials are routinely deployed. To clarify the notion of "flow" within the diagram, directed arrows were employed to indicate the logical and processual transitions from raw material inputs to end-use applications. While the layout is not linear, the directional connections convey the pathway of material evolution within the FDM context. The use of color coding and node sizing was adopted for visual clarity, while relational proximity was maintained to represent functional grouping.

4.2 Automation and AI Integration: Enhancing the FDM Process

The integration of Artificial Intelligence (AI), machine learning (ML), and the Internet of Things (IoT) is ushering in a new era of smart FDM printers capable of significantly improving the efficiency, consistency, and quality of printed parts. These technologies provide advanced capabilities such as predictive maintenance, real time process control, and automated quality assurance, addressing long standing limitations in traditional additive manufacturing methods.

Recent advancements in 3D printing technology have shown significant potential across various industries, from healthcare to manufacturing. The integration of additive manufacturing with AI and IoT has accelerated innovation, enabling the production of highly customized products with reduced waste and faster production times [36]. Studies have highlighted the transformative impact of 3D printing in areas such as biomedical applications, where it facilitates

the creation of patient-specific prosthetics and implants [37]. Additionally, the rise of IoT-enabled 3D printers has led to smarter production processes, where real-time data collection and machine learning algorithms optimize production efficiency and quality [38]. As the technology continues to evolve, its potential for revolutionizing industries, reducing costs, and enabling sustainability remains a key area of interest for researchers and practitioners alike.

Smart FDM Printers: AI and Machine Learning for Predictive Maintenance, Process Control, and Quality Assurance

The integration of AI and machine learning into FDM is revolutionizing the 3D printing landscape by enhancing autonomy, reliability, and efficiency. These technologies minimize the need for human intervention, improve print repeatability, and optimize material usage and part quality. One key application is predictive maintenance, where machine learning algorithms analyze sensor data—such as extrusion rates, motor performance, and temperature patterns—to forecast issues like nozzle clogs, mechanical wear, or thermal irregularities before they lead to machine failure, thereby reducing downtime. Additionally, AI enables real-time process control and optimization by dynamically adjusting parameters like temperature, print speed, and extrusion rate based on sensor feedback, environmental conditions, and material behavior to ensure consistent print quality. Furthermore, AI-driven quality assurance systems utilize computer vision and machine learning to monitor prints in real time, detecting defects such as layer misalignment or extrusion anomalies and enabling automated corrections to maintain dimensional accuracy and part integrity throughout the process [29, 32].

IoT and Real Time Monitoring: Enhancing FDM Performance and Efficiency

As shown in Fig 4 The integration of the Internet of Things (IoT) into FDM has significantly enhanced real-time monitoring, process control, and operational efficiency by enabling data-driven insights and remote accessibility. IoT-enabled sensors continuously track critical printing parameters such as material consumption, temperature fluctuations, layer progression, and environmental conditions, transmitting data to centralized systems or the cloud for analysis and optimization. This allows for proactive decision-making, such as detecting filament shortages, adjusting for environmental influences like humidity, and identifying print deviations early. Additionally, IoT systems facilitate detailed tracking of material usage, supporting waste reduction, automated inventory management, and material traceability for quality assurance. Remote monitoring and control further expand capabilities, allowing operators to manage print jobs from any location—pausing or resuming prints, receiving real-time updates, and performing remote diagnostics to minimize downtime. Moreover, the data collected through IoT infrastructure enables predictive analytics, revealing trends in print failures, estimating the lifespan of critical components, and optimizing energy consumption, ultimately driving greater reliability, efficiency, and performance in FDM printing operations [29–33].

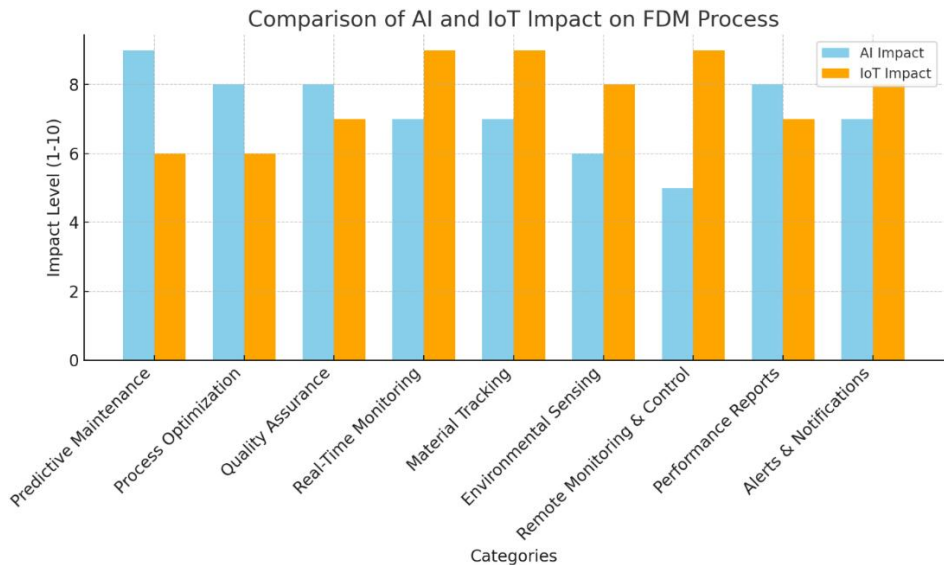


Fig. 4. Comparison of AI and IoT Impact on FDM Process

Table 2: Comparison: AI, ML and IoT in FDM

Technology	AI/ML Integration	IoT Integration
Primary Focus	Process Control, Predictive Maintenance, Quality Assurance	Real Time Monitoring, Material Tracking, Remote Control
Key Advantages	Real time process optimization Predictive failure detection Automated quality assurance	Remote monitoring and control Real time print data analysis Material consumption tracking
Benefits	Improved print accuracy Reduced downtime Higher quality parts	Efficient material usage Remote diagnostics Greater process visibility
Challenges	High initial cost Requires robust data for training models	Need for connectivity Data security concerns

5. Conclusion

5.1 Summary of key points

This review paper explores the significant advancements and challenges in FDM, focusing on breakthroughs in materials, composite materials, and the incorporation of AI, machine learning, and IoT. Noteworthy developments in materials include the development of high-performance polymers such as PEEK, PEI, and PPSU, as well as the emergence of composite materials like carbon fiber, and metal-filled filaments, which have significantly enhanced FDM's capabilities. These materials offer outstanding mechanical properties, thermal resistance, and chemical stability, which are crucial for industries such as aerospace, medical devices. The application of smart materials, including shape memory polymers and conductive materials, also holds great promise, enabling FDM to create components with advanced features like self-healing and dynamic shape-changing capabilities.

The integration of AI and ML has introduced autonomous systems capable of predictive maintenance, process optimization, and real time quality assurance, enhancing the overall efficiency and accuracy of FDM printing. IoT further enhances this by enabling remote monitoring, material tracking, and real time adjustments based on environmental factors, ensuring high quality print results and improved production management. However, challenges still remain in the adoption and full utilization of these advancements. Printability issues, cost constraints, and material limitations need to be addressed for the widespread implementation of high performance composites and smart materials. The high cost of specialized filaments and the technical difficulty of printing with advanced materials hinder their use in mass production. Moreover, the environmental impact of FDM processes, especially in terms of material waste and energy consumption, is an area that requires further research and optimization.

The main contribution of this manuscript lies in its comprehensive examination of the latest advancements in FDM technology, specifically focusing on high-performance polymers, composite materials, and the integration of AI, ML and IoT. Unlike existing review papers, this manuscript emphasizes the emerging role of materials such as PEEK (Polyether Ether Ketone), PEI (Polyetherimide), and PPSU (Polyphenylsulfone), which have not been extensively covered in previous reviews. These high-performance polymers offer outstanding mechanical properties, thermal resistance, and chemical stability, making them ideal for demanding applications in industries such as aerospace, medical devices, and automotive. Additionally, it provides a unique perspective on how AI and IoT are converging with FDM technology to enhance process optimization, predictive maintenance, and real-time quality assurance. This paper addresses critical research gaps, including the technical challenges related to the printability of advanced materials, cost constraints, and the environmental impact of FDM processes. By highlighting these overlooked aspects, the manuscript seeks to offer a fresh and timely contribution to the field, guiding future research to overcome the barriers limiting the widespread adoption of these advanced technologies.

5.2 Call for future research

Despite significant advancements in FDM, several key areas require further research to fully realize the technology's potential. Material development remains a priority, with ongoing efforts needed to create advanced, cost-effective filaments offering improved mechanical strength, heat resistance, biocompatibility, and environmental sustainability, including biodegradable options to reduce ecological impact. Process optimization is another critical focus,

particularly through the use of AI-driven real-time adjustments and smart sensors to enhance print accuracy, repeatability, and efficiency by dynamically adapting parameters during printing. Sustainability is becoming increasingly important as FDM adoption grows, necessitating innovations to minimize material waste, improve filament recycling, and increase energy efficiency, with an emphasis on renewable resources and closed-loop systems. Additionally, the integration of AI, IoT, and machine learning into smart manufacturing systems promises to usher in a new era of autonomous 3D printing, where printers can self-optimize and self-correct, reducing the need for human intervention while improving reliability and performance for critical applications. In conclusion, while FDM has already demonstrated significant potential in various industries, continued research and development are essential to address the current challenges and unlock its full capabilities. By advancing material technologies, optimizing processes, and promoting sustainability, the future of FDM polymer additive manufacturing can lead to more efficient, cost effective, and environmentally friendly production methods, contributing to the broader adoption of 3D printing in both prototyping and end use part production.

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not for profit sectors.

Author Contributions

Author 1: Conceptualization, data analysis, writing original draft, Methodology.

Author 2: Supervision, review & editing.

Author 3: Analysis, Editing and Formatting.

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