Chapter 2

Fused Deposition Modeling (Fdm): Theory, Application, and Innovative Approaches

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Fused Deposition Modeling (FDM), one of the most widely used additive manufacturing technologies, has gained significant attention due to its cost-effectiveness, flexibility in material selection, and ease of use. This method involves the layer-by-layer deposition of thermoplastic filaments melted through a nozzle to fabricate three-dimensional objects based on digital models. FDM is extensively utilized in both industrial and academic settings for prototyping and producing functional components across various sectors, including automotive, aerospace, biomedical engineering, and education. The process enables the creation of complex geometries that are difficult to achieve with traditional manufacturing methods, while also minimizing material waste. However, despite its advantages such as rapid prototyping, simplicity, and compatibility with a wide range of materials—including PLA, ABS, PETG, and fiber-reinforced composites—FDM has inherent limitations. These include anisotropic mechanical properties, surface roughness, limited dimensional accuracy, and potential printing errors such as warping, layer shifting, and nozzle clogging. Several process parameters, such as layer height, nozzle temperature, infill percentage, and build platform temperature, significantly influence the final product's quality and mechanical performance. Optimization of these parameters is crucial for improving part strength, dimensional accuracy, and surface finish. Recent advancements aim to enhance FDM's capabilities through innovations like continuous fiber reinforcement, 4D printing, and the use of recycled materials. This review highlights the theoretical background, working principles, materials, parameters, challenges, and application areas of FDM technology. It also emphasizes the importance of ongoing research in material development, process optimization, and system design to expand FDM's applicability beyond prototyping into serial production and high-performance industries.

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1. INTRODUCTION

Additive manufacturing, which refers to the production of three-dimensional (3D) objects, is a process in which materials are deposited layer by layer—i.e., through successive addition—to create physical 3D models. This method is based on dividing the model into thin layers and then fabricating the object stepwise, layer by layer, according to these divisions. Additive manufacturing offers numerous advantages as a modern fabrication technique, particularly due to its capability to produce highly complex geometries, including both micro- and macro-scale components that are otherwise difficult to manufacture. In this production method, the prototyping process is notably fast, and it also allows for the design and realization of customized products tailored to individual needs [1].

Fused Deposition Modeling (FDM), one of the most prominent additive manufacturing technologies and processes, has gained widespread visibility due to its relatively low cost, operational flexibility, and the ability to process a broad range of materials. Although FDM is often perceived as a recently developed technology, its origins date back to the late 1980s when it was first developed and commercialized by Stratasys Inc. In 1984, Charles Hull, a physics professor, became the first person to develop an advanced 3D printer [2]. The introduction of color printing began in 1995 with the development of the first color 3D printer. Around 2007, the proliferation of open-source platforms accelerated the development of 3D printers, followed shortly by the emergence of desktop or personal 3D printers.

By 2010, 3D printing had begun to see rapid growth driven by increased media exposure, rising industrial demand for prototypes, academic acceptance, decreasing costs, and an expanding variety of printable models and materials [3]. One of the primary factors contributing to this growth was the significant material waste associated with conventional subtractive manufacturing methods, such as chip formation and scrap generation [4]. In contrast, additive manufacturing involves minimal material loss during the production process.

2. PRODUCTION PROCESS

3D printing technology provides the opportunity to produce customized products that meet personal needs. Various techniques are available for both industrial and personal 3D printers, including Stereolithography (SLA), Digital Light Processing (DLP), and Fused Deposition Modeling (FDM). Among these, FDM (Fused Deposition Modeling) is the most used technique in personal applications. In this method, filament materials are used as raw material.

As seen in Figure 1, computer-aided design software capable of creating 3D models is required for production with 3D printers. Among the most widely used programs are SolidWorks and AutoCAD. Additionally, web-based platforms such as Tinkercad, 123D Design, and Google SketchUp also offer accessible modeling capabilities. Alternatively, ready-to-print models can be obtained by scanning a person or object using 3D scanners. Once the model generation process is completed, the file must be converted into the STL (Standard Tessellation Language) format, which is the standard file format used in 3D computer-aided design, before being transferred to the 3D printer for manufacturing. After the transfer, a slicing process is carried out to divide the model into layers. Following this, the sliced data is transferred to the machine via an SD card, and the 3D printing process is performed based on this information [5].

Figure 1. Production process of 3D printers

Table: FDM Manufacturing Parameters [15]

Yığma modelleme (prototipleme) özellikleri	
Weight of Produced Part (kg)	0.1-10
Minimum Cross-section (mm)	1.2-100
Capability of Producing Complex Shapes	High
Tolerance (mm)	0.3-2
Surface Roughness (μm)	75-100
Economic production quantity	1-100

3. COMPONENTS OF FDM SYSTEMS

The FDM printing machine and its components, consisting of mechanical and electronic components, are shown in Figure 2. These components and their descriptions are given below.

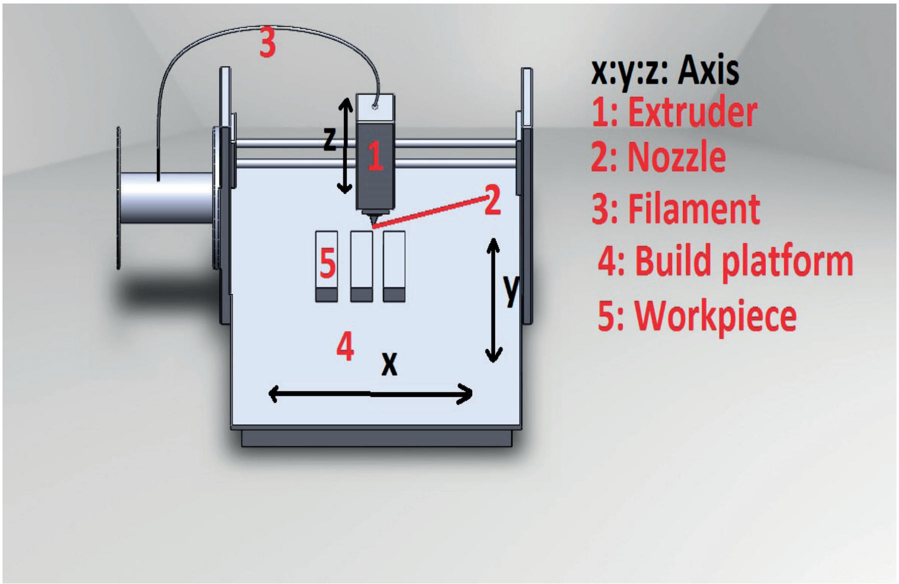

Figure 2. Schematic representation of production with FDM

Nozzle and Hotend: The part where the filament is melted, typically made from brass or stainless steel.

Extruder: The system responsible for feeding the filament into the hotend. It can be either direct drive or Bowden type.

Build Platform (Heated Bed): Ensures proper adhesion of the first layer and reduces warping issues.

Stepper Motors: Control movement along the X (left-right), Y (forward-backward), and Z (up-down) axes.

Cooling Fans: Facilitate rapid cooling of printed layers, thereby improving print quality.

Control Board: The main board that coordinates all components and serves as the interface between hardware and software.

4. MATERIALS USED (FILAMENTS)

There are many types of filaments used for 3D printing. In FDM (Fused Deposition Modeling) 3D printers, the raw material used is thermoplastic filament. Each type of filament has distinct properties and is manufactured in various dimensions and diameters. These filaments, which are sold in spool form, are wound like a thin thread around a reel and then loaded into the 3D printer [8].

The filament processing mechanism can be briefly described as follows: The filament is pulled toward the hot end by the drive gears connected to the motor. It is then heated until it reaches a liquid or semi-liquid state. After being held at this state for a short period, the melted or semi-molten filament is extruded through the nozzle located at the print head. Following this, temperature control is performed via an indicator panel that shows whether the desired temperature has been reached. Finally, the molten material is deposited onto a heated build platform within a controlled chamber, where the three-dimensional object is formed layer by layer, completing the printing process [9]. The filament workflow is illustrated in Figure 3.

Among the most commonly used materials in 3D printing are polypropylene (PP), acrylonitrile butadiene styrene (ABS), polyethylene (PE), polylactic acid (PLA), thermoplastic polyurethane (TPU), high-impact polystyrene (HIPS), polyvinyl alcohol (PVA), polycarbonate (PC), nylon (PA), polycaprolactone (PCL), PETG, and polyether ether ketone (PEEK). These materials are widely preferred due to their suitable mechanical properties, cost-effectiveness, and ease of printability [10,11,18,19,20].

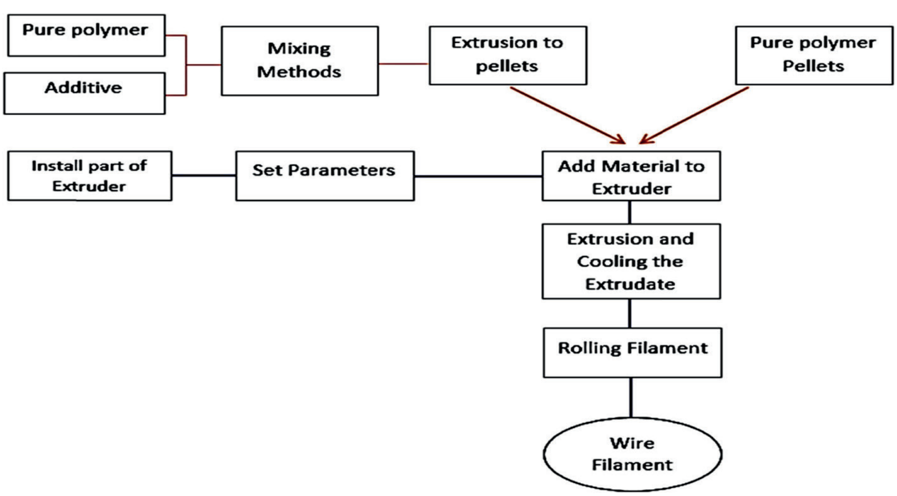

Figure 3. Filament workflow [16].

5. ADVANTAGES AND DISADVANTAGES OF THE FDM PROCESS

Some of the advantages of the Fused Deposition Modeling (FDM) process can be listed as follows:

Simple Setup Procedures: The setup operations are relatively straightforward. It involves loading the filament spool and heating the device to the desired temperature.

No Special Training Required: The system is user-friendly and does not require any specialized training for operation.

Easy Post-Processing: Removing the printed part and cleaning the machine after the printing process is very simple.

Fast Printing Speed: Compared to conventional manufacturing methods, the printing speed is significantly faster. This is mainly due to the rapid heating of the nozzle to the required temperature, which accelerates the production process.

High Print Resolution: In terms of print clarity, FDM provides better resolution than traditional manufacturing techniques [6].

- Simplicity and Ease of Use
- Ease of Maintenance
- Lower Cost Compared to Other 3D Printing Technologies
- Less Material Waste
- Variety of Build Styles and Patterns
- Ability to Manufacture Components with Various and Complex Geometries

However, there are also several disadvantages associated with the FDM process:

- Rough or Grainy Surface Finish
- Limitations in Product Size
- Material Shrinkage During Cooling
- Relatively Low Build Speed Compared to Some Other Methods
- Anisotropic Mechanical Properties
- The mechanical strength varies depending on the direction of the layers.

- Reduced Mechanical Strength Compared to Conventional Manufacturing Technique [7]

The quality of materials produced by 3D printers can be categorized into three main stages: pre-processing (preparation phase), processing (printing phase), and post-processing [14]. In the FDM material production process, various issues that arise in composites, along with all factors affecting the quality and performance, are illustrated in detail in Figure 3.

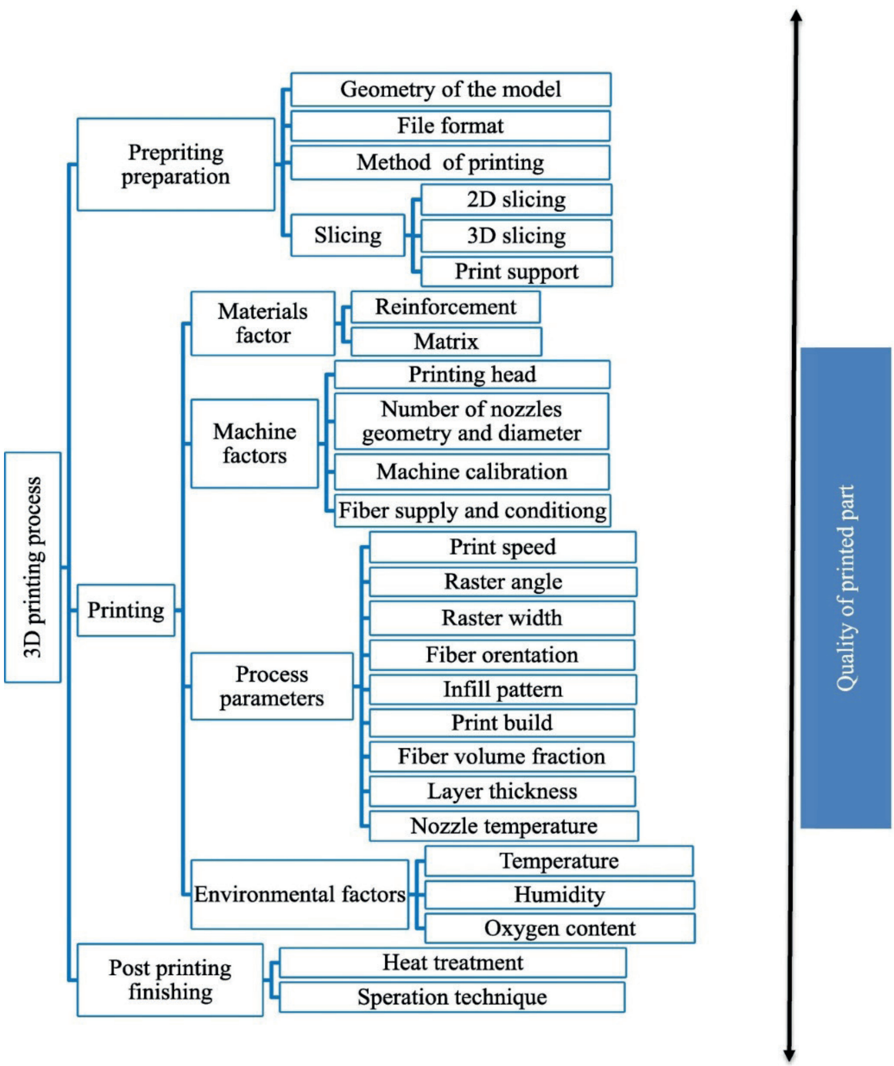

Figure 4. List of preparatory, machine, process and environmental factors affecting quality of 3D printed composites [13].

6. PRINTING PARAMETERS AND THEIR EFFECTS

Key parameters affecting the success of FDM printing include:

Layer Height: Thinner layers result in higher resolution.

Nozzle Size and Temperature: Varies depending on the material type.

Heated Bed: Affects initial layer adhesion.

Infill Percentage: Influences structural strength.

Support Structures: Necessary for overhanging surfaces.

Below are examples of printing parameters for different composite materials found in literature:

Table 2. Print Parameters for PLA Composites [8]

Print parameter	**Value**
Nozzle size	0.8 mm
Layer height	0.15 mm
Top and bottom solid layers	2
Perimeter	2
Filling pattern	Rectilinear
Filling angle	45
Infill percentage	80%
Infill overlap	21%
Nozzle temperature	200°C
Heated bed	45°C

Table 3. Print parameters for ABS reinforced CFRP composites [12].

Print parameter	**Value**
Nozzle size	0.35 mm
Layer height	0.2 mm
Top and bottom solid layers	1.2-1.5
Perimeter	2
pattern Filling	Rectilinear
Filling angle	45
Infill percentage	100%
Nozzle temperature	230°C
Heated bed	45°C

Table 4. Print parameters for PA12 composites [17].

Print parameter	**Value**
Nozzle size	0.4 mm
Layer height	0.2 mm
Printing speed	30 mm/s
pattern Filling	Rectilinear
Filling angle	45
Infill percentage	100%
Nozzle temperature	250°C
Heated bed	120°C

7. COMMON ERRORS AND SOLUTION PROPOSALS

Clogging: Nozzle cleaning should be performed carefully, and it is recommended to clean the nozzle after every printing operation. In addition, using high-quality filaments should be prioritized to prevent clogging.

Warping: This issue can be mitigated by increasing the build platform temperature or by using a brim structure during printing

Layer Shifting: The tension of the printer's belt mechanisms should be checked regularly to avoid misalignment between layers.

First Layer Issues: Proper bed leveling should be ensured, and accurate Z-offset calibration must be performed for optimal first-layer adhesion.

STL File Errors: During the conversion to STL format, complex geometries, such as topological objects, may cause errors. Therefore, it is essential to verify and validate the STL file before printing [21].

8. INDUSTRIAL AND EDUCATIONAL APPLICATIONS

Parts produced via Fused Deposition Modeling (FDM) are primarily used for prototyping but have also found applications across various industrial sectors today. Some of the most common application areas include:

Automotive Industry: FDM is frequently used in the production of assembly jigs, crash-test plastic components, and prototype parts.

Aerospace Industry: In aircraft manufacturing, FDM is utilized to reduce the weight of structural components while enhancing their mechanical strength. It is also employed in the cost-effective production of lightweight parts for expensive aerospace systems [22,23].

Biomedical Field: Due to its ability to produce customized medical devices, FDM has rapidly gained popularity in this sector. It is widely used in the fabrication of orthopedic implants, prosthetics, and various dental products related to oral health [24].

Education: 3D printing plays a crucial role in education, particularly in engineering and design disciplines. It facilitates the development of analytical thinking and practical skills among students, from primary to secondary schools. At the university level, 3D printers are extensively used in engineering education and project-based learning. Moreover, numerous academic studies focus on the mechanical, thermal, and tribological properties of materials produced via FDM technology [25].

9. RESULTS AND EVALUATION

In this section of the book, Fused Deposition Modeling (FDM), one of the most widely used methods in additive manufacturing, is discussed in detail. FDM is a fabrication technique based on the principle of extruding thermoplastic filaments through a nozzle after heating, followed by building the desired object layer-by-layer. It is currently employed extensively by both individual users and industrial sectors.

The main advantages of the FDM method include low equipment costs, ease of use and maintenance, minimal material waste, the ability to produce highly complex geometries, and compatibility with a wide range of materials. Due to these characteristics, FDM holds significant importance in prototyping and design processes. It is actively utilized across various fields such as automotive, aerospace, biomedical engineering, and education, where it is used to manufacture lightweight structural components, prosthetics, dental products, educational tools, and many other items.

When considering its limitations, several disadvantages can be identified, including rough surface finish, anisotropic material behavior, restrictions on part size, relatively slow production speed, and mechanical properties that are generally inferior compared to those achieved by conventional manufacturing techniques. Additionally, printing errors encountered during the process—such as nozzle clogging, warping, and layer shifting—are critical quality control issues that can potentially be resolved through parameter optimization.

FDM technology has rapidly expanded due to the increasing availability of open-source software, the growing variety of filament materials, and the transformation of 3D printers into consumer-level devices. In the future, advancements such as the incorporation of continuous fiber-reinforced composites, 4D printing technologies, and the utilization of recycled materials are expected to further enhance the capabilities of FDM. Ongoing research in these areas aims to enable FDM not only for prototyping but also for serial production applications.

In conclusion, FDM occupies a significant place within the field of additive manufacturing due to its accessibility, flexibility, and cost-effectiveness. However, for the technology to produce higher quality, durable, and functional parts in the future, further research is required in areas such as material science, process parameter optimization, and system design. As the technology continues to expand into educational and academic settings, it is expected to play a pivotal role in shaping the manufacturing methods of the future.

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