

1 A Survey of Fused Deposition Modeling 2 (FDM) Technology in 3D Printing 3

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8 **ABSTRACT**

9 This survey provides a thorough examination of Fused Deposition Modeling
10 (FDM), a prevalent 3D printing technology known for its accessibility and versatility.
11 FDM has emerged as a transformative tool across various industries, including
12 healthcare, aerospace, automotive, and education. This paper reviews recent
13 advancements in FDM technology, focusing on material innovations, process
14 optimization, and application areas. We analyze the benefits and limitations of FDM,
15 including print quality, speed, cost-effectiveness, and environmental impact.
16 Furthermore, we explore emerging trends and future directions in FDM research,
17 highlighting the potential for enhanced customization, sustainability, and integration
18 with other manufacturing technologies. This survey aims to provide a comprehensive
19 understanding of FDM's current landscape and its implications for future developments
20 in 3D printing.

21 *Keywords:* 3D printer, Fused Deposition Modeling, Sustainable FDM,
22 Automotive Industry.

23 **1. Introduction**

24 **3D Printing and Its Types**

25 3D printing, or additive manufacturing, is an innovative technology that
26 builds objects layer-by-layer, transforming digital designs into tangible products.
27 Originally introduced in the 1980s, it has evolved significantly to become a
28 cornerstone in various industries due to its adaptability, speed, and potential for
29 cost-effective, custom manufacturing. Today, 3D printing is widely utilized in
30 sectors such as aerospace, healthcare, automotive, and consumer goods. This
31 technology has not only streamlined production but has also empowered
32 designers and engineers to produce prototypes and end-use parts with
33 unprecedented precision, directly from CAD models.

34 The **main advantage** of 3D printing lies in its ability to create complex shapes
35 without the need for molds or cutting tools, distinguishing it from conventional
36 subtractive manufacturing methods. Through different techniques, each with
37 unique capabilities and materials, 3D printing can meet a wider range of
38 application needs [1].



Fig.13dprinter.

Source: <https://www.rennd.com/blog/polyjet-3d-printing/>

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1.1. Types of 3D Printing Technologies

Several primary types of 3D printing technologies have emerged, each suited to specific purposes and materials:

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1.1.1. **Fused Deposition Modeling (FDM)**: This technique, among the most accessible forms of 3D printing, uses thermoplastic filaments that are heated and extruded layer-by-layer. FDM is popular for rapid prototyping and is commonly used in consumer-grade and industrial machines due to its simplicity and affordability.

1.1.2. **Stereolithography (SLA)**: SLA printing employs a UV laser to selectively harden liquid resin into solid parts with high precision and fine detail. This method is ideal for applications requiring smooth surfaces and intricate detail, such as dental models and medical devices, making it especially popular in the healthcare industry.

1.1.3. **Selective Laser Sintering (SLS)**: This technique uses a high-powered laser to sinter powdered material, typically nylon or polymers, into durable, functional parts. SLS is particularly valuable in industrial applications where strength and complex geometries are required, as it does not require additional support structures during printing.

1.1.4. **Multi-Jet Printing (MJP)**: In MJP, multiple printheads deposit material droplets, which are then cured to form highly detailed parts with a high degree of accuracy. MJP is commonly used in jewelry design, engineering models, and any application where refined detail and multi-material capabilities are advantageous.

2. INTRODUCTION FUSED DEPOSITION MODELING

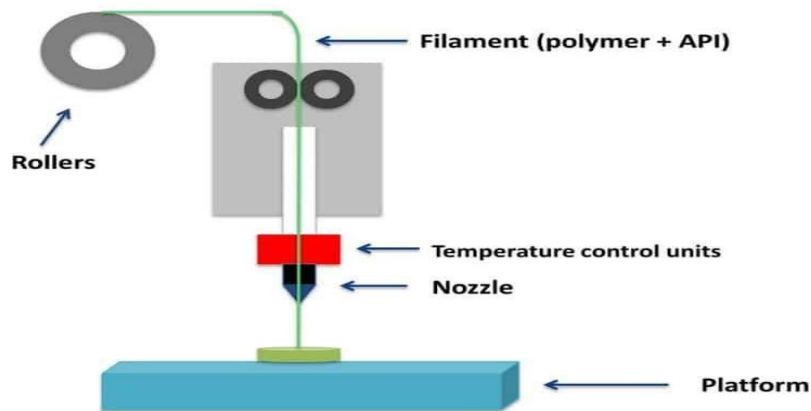


Fig.2.FDM3DPRINTER

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Source: <https://biohub3d.com/que-tipos-de-impression-3d-tenemos-guia-completa/>

66 Fused Deposition Modeling (FDM) has gained significant traction as a prominent
67 additive manufacturing technology since its inception in the late 1980s. This technique
68 involves the layer-by-layer deposition of thermoplastic material to create three-
69 dimensional objects, making it highly versatile for various applications. The advantages
70 of FDM include its cost-effectiveness, ease of use, and the ability to produce complex
71 geometries that are often difficult to achieve with traditional manufacturing methods. As
72 a result, FDM has found applications across diverse sectors, including healthcare for
73 prosthetics and implants, aerospace for lightweight components, and education for
74 prototyping and design projects [2].
75 Recent advancements in materials science have expanded the range of thermoplastics
76 that can be used in FDM, including biodegradable options and composite materials
77 that enhance mechanical properties [3]. Moreover, improvements in printing
78 technology, such as increased resolution and speed, have further enhanced the
79 practicality of FDM for industrial applications [4]. Despite its advantages, challenges
80 remain, particularly concerning the mechanical properties of printed parts and the
81 limitations of certain materials [5].
82 This survey aims to provide a comprehensive overview of the current state of FDM
83 technology, including recent innovations, applications, and future trends. By
84 synthesizing findings from recent literature, this paper seeks to highlight the potential
85 of FDM as a transformative technology in modern manufacturing.

86 **3. RECENT ADVANCES IN FDM**

87 The diverse applications of FDM technology across various fields highlight its
88 potential for innovation in medicine, environmental science, and engineering.
89 Continued advancements promise to enhance the capabilities and efficiency of 3D
90 printing. The study [6] investigates the emissions of ultrafine particles from FDM
91 printers, particularly focusing on the inhalation exposure risks for children and adults. It
92 utilizes dosimetry models to estimate particle deposition in the respiratory tract,
93 highlighting the health risks associated with frequent use of FDM printers. The review
94 in [7] discusses the FDM process, emphasizing the rheological properties of
95 thermoplastic materials used in 3D printing. It covers the importance of these
96 properties in ensuring printability and the overall performance of printed objects. In
97 paper [8] reviews the applications of FDM in the pharmaceutical industry, focusing on
98 the production of drug delivery systems and the challenges faced in implementing this
99 technology in medical applications. In review [9] highlights various 3D printing
100 technologies, including FDM, and their applications in medicine. It discusses the
101 potential for personalized medicine and the challenges of regulatory approval. The
102 structured review [10] examines the use of 3D printing in drug formulation, focusing on
103 FDM technology and its ability to create customized drug delivery systems. The
104 research [11] explores the potential of FDM in creating tablets with customizable
105 release profiles, demonstrating the technology's application in personalized medicine.
106 The [12] discusses the applications of 3D printing, including FDM, in surgical planning
107 and the production of surgical instruments in the field of otolaryngology. The pilot study
108 [13] reviews the use of FDM in podiatry, focusing on the production of custom orthotics
109 and the benefits of personalized treatment. The [14] evaluates the current state of 3D
110 printing technologies, including FDM, in the production of surgical instruments,
111 discussing the potential for customization and efficiency. The [15] study presents a
112 novel application of FDM in creating water filtration systems, showcasing the versatility
113 of 3D printing in addressing environmental issues.

114 **4. APPLICATIONS OF FDM 3D PRINTING IN MODERN** 115 **MANUFACTURING**

116 **4.1. Prototyping and Product Development**
117 FDM 3D printing is widely used for rapid prototyping, which accelerates the
118 product development cycle by enabling manufacturers to quickly produce physical
119 models of product designs. This method allows companies to evaluate, modify,
120 and validate designs at a lower cost and faster turnaround than traditional methods
121 in the automotive industry, prototyping with FDM helps test form and fit, allowing for
122 multiple iterations without incurring high expenses [16].

123 **4.2. Tooling and Fixtures**
124 Manufacturers use FDM to produce custom tools, jigs, and fixtures, which are
125 essential in assembly lines to maintain accuracy and efficiency. This application
126 improves operational efficiency by reducing lead times for tools, lowering material
127 costs, and allowing for easy adjustments in design based on specific
128 manufacturing needs. Boeing and other companies, for instance, employ FDM for
129 fabricating custom tooling, enhancing flexibility in production [17].

130 **4.3. End-Use Parts Volume Production**
131 FDM is becoming increasingly viable for low-volume production runs of end-use
132 parts, especially for custom or complex shapes that would be more costly to
133 produce through traditional methods. This approach is particularly useful in
134 industries like medical and aerospace, where customization and precision are
135 critical. FDM allows for on-demand manufacturing, reducing inventory and storage
136 costs [18].

137 **4.4. Educational and Research Applications**
138 Applications are valuable in educational institutions and research labs for
139 instructional purposes and experimentation with complex designs. In these
140 environments, FDM enables hands-on experience in manufacturing techniques,
141 supporting students and researchers in fields such as engineering, product design,
142 and medical sciences [19].

143 **5. ADVANTAGES AND LIMITATIONS OF FDM 3D PRINTING**

144 **5.1. Advantages of FDM 3D Printing**
145 **5.1.1. Cost-Effectiveness** FDM is one of the most affordable types of 3D printing,
146 both in terms of equipment and material cost. The method uses
147 thermoplastic filaments, which are relatively inexpensive and widely
148 available. This cost-effectiveness has made FDM accessible for small
149 businesses, educational institutions, enabling rapid prototyping and small-
150 scale manufacturing without high investments [20].

151 **5.1.2. Use and Accessibility: FDM printers are known for their ease of use,**
152 requiring minimal technical expertise compared to other 3D printing
153 technologies. This accessibility makes FDM suitable for educational
154 environments, allowing students and new users to experiment and learn 3D
155 printing techniques without extensive training. Additionally, FDM printers are
156 compatible with a variety of materials, enhancing versatility in applications
157 ranging from product design to engineering [21].

158 **5.1.3. Viability:** FDM allows for highly customized designs and geometric complexity
159 that would be challenging with traditional manufacturing methods. This
160 flexibility supports innovation in fields like medical device production and
161 aerospace, where unique geometries are often required. With FDM, custom
162 parts can be produced on-demand, significantly reducing lead times and
163 inventory requirements [22].

164 **5.1.4. Sustainable FDM:** It reduces waste by only using the necessary amount of
165 material to build an object, contrasting with subtractive manufacturing

166 methodsthatgenerateexcess material.Additionally,bio-basedandrecycled
167 filamentsarebecomingmorecommon,furtherenhancingFDM'srolein
168 sustainablemanufacturing practices[23].

169 **5.2. Limitationsof FDM3DPrinting**

170 5.2.1. **SurfaceFinishandAccuracy:**FDMprintingcanleadtoactivelylow-
171 resolutionfinishes,withvisiblelayerlinesthatmayrequirepost-processing
172 forsmoothnessandaestheticappeal.Whileadvancementsareimproving
173 accuracy,FDMisgenerallylessprecisecomparedtostereolithography
174 (SLA)orselectivelasersintering(SLS),makingitlessidealforapplications
175 demandinghighdetailorsmoothsurfacetextures[24].

176 5.2.2. **Limited Material Strength:** Although FDM supports a range of
177 thermoplastics,includingABSandPLA;itisgenerallylimitedinproducing
178 partsthatrequirehighstrengthordurability.PartscreatedwithFDMare
179 oftenweakeralongthelayerlines,andwhilecompositeslikecarbon-fiber-
180 reinforcedfilamentsexist,theyaremoreexpensiveandmaystillnotmatch
181 thestrengthprovidedbyothermanufacturingmethods[25].

182 5.2.3. **SlowPrintingSpeedfor LargeParts:** TheAyerapproachofFDMcanlead
183 tolongproductiontimes,especiallyforlargerormoreintricateparts.For
184 industrial-scaleapplicationsrequiringhighthroughput,FDMmaynotbethe
185 mostefficientchoice.TechnologieslikeSLSomulti-jetfusionareoften
186 preferredforlargerproductionrunsduetotheirfasterspeedsandabilityto
187 handlemorecomplexgeometries[26].

188 5.2.4. **WarpingandMaterialConstraints:**CertainthermalinFDM,likeABS,are
189 pronetowarping,whichcanaffectdimensionalaccuracyandcausepart
190 failures.Warpingtypicallyresultsfromunevencooling,especiallyinlarger
191 parts,makingtheprocesssensitiveenvironmentalconditionsanddesign
192 features.MaterialconstraintsalsolimitFDM'suseinapplicationsrequiring
193 specificmaterialproperties,suchaschemicalresistance[27].

194 **6. CASE STUDIES AND REAL-WORLD EXAMPLES OF**
195 **FDM 3D PRINTING**

196 **6.1. Automotive Industry: Prototyping at Ford Motor Company**

197 Ford Motor Company has been a pioneer in using FDM for prototyping and testing
198 new vehicle parts. Ford uses FDM to create prototype parts, which allow the team to
199 assess design accuracy, functionality, and fit before committing to production. This
200 approach has resulted in significant reductions in lead time and prototyping costs. Ford
201 has reported that FDM-based prototyping enables a 40% faster turnaround for parts
202 and contributes to its goal of reducing product development time across its vehicle
203 lineup [28].

204 **6.2. Healthcare: Custom Prosthetics and Orthotic Devices**

205 In the healthcare industry, FDM has been instrumental in producing custom
206 prosthetics and orthotic devices tailored to individual patient needs. Startups like
207 Limitless Solutions utilize FDM to create prosthetic limbs for children, providing a low-
208 cost, highly customized solution that traditional manufacturing methods cannot easily
209 achieve. The FDM process allows for fast adjustments based on growth or specific
210 patient feedback, ensuring optimal comfort and functionality [29].

211 **6.3. Aerospace: Tooling at Boeing**

212 Boeing has incorporated FDM 3D printing to produce jigs, fixtures, and other
213 essential tooling components. Using FDM for these applications enables Boeing to
214 quickly produce lightweight, durable, and cost-effective tooling. In a notable
215 example, Boeing used FDM to produce assembly aids for aircraft fuselage assembly,
216 which reduced tooling production time by 60% and resulted in substantial cost savings.
217 The company continues to explore FDM applications to improve operational efficiency
218 and reduce weight on non-critical flight components [30].

219 **6.4. Consumer Products: Customizable Wearables by Adidas**

220 Adidas has embraced FDM technology to develop customizable footwear and
221 wearable accessories. With FDM, Adidas can rapidly prototype new designs and
222 create custom insoles that match individual customer requirements for fit and comfort.
223 The company has also leveraged FDM to explore sustainable product lines,
224 incorporating biodegradable materials in the production of prototypes and specialized
225 footwear. This application underscores FDM's potential in creating personalized
226 products and promoting eco-friendly manufacturing [31].

227 **6.5. Education and Research: University Engineering Projects**

228 FDM is widely adopted in educational institutions to support engineering and design
229 projects. For example, at MIT, students use FDM 3D printing to create components for
230 robotics, biomedical devices, and mechanical prototypes, which allow them to
231 experiment with real-world engineering challenges in a low-risk environment. Studies
232 show that hands-on experience with FDM significantly improves students'
233 understanding of design principles and manufacturing processes, making it a vital
234 educational tool [32].

235 **7. Mechanical Properties of FDM Parts**

236 **7.1. Tensile Strength**

237 FDM parts generally exhibit good tensile strength, which refers to the material's
238 ability to resist tension and withstand stretching forces. The tensile strength varies based
239 on material choice, layer height, and print orientation, with filaments such as ABS and
240 carbon-fiber-reinforced materials yielding higher strength in specific orientations. For
241 example, studies in 2024 show that optimized layer bonding and fiber-reinforced
242 materials significantly enhance tensile strength, making FDM suitable for functional
243 prototypes and end-use parts.

244 **7.2. Layer Adhesion and Anisotropy**
245 A limitation in FDM is the anisotropy of printed parts, where mechanical
246 properties vary based on print direction. Parts are generally stronger along
247 the layer lines, while strength between layers may be weaker. Research in
248 2024 has made strides in optimizing layer adhesion through new print
249 strategies and advanced materials, reducing this anisotropy and thus
250 expanding the range of FDM's industrial applications.

251 **7.3. Fatigue Resistance**
252 FDM parts also exhibit moderate fatigue resistance, depending on material
253 choice and print parameters. This is essential in applications where repeated loading
254 occurs, as in machine components or prosthetic devices. Studies reveal that nylon-
255 based filaments exhibit higher fatigue resistance, suitable for parts under cyclic
256 loading [33].

257 **8. FUTURE TRENDS AND IMPLICATIONS FOR THE** 258 **MANUFACTURING INDUSTRY**

259 **8.1. Expansion of Material Options**
260 Future advancements in FDM materials are likely to enhance the mechanical,
261 thermal, and chemical properties of printed parts. Research is ongoing to develop
262 high-strength, bio-based, and composite filaments that expand the range of
263 applications for FDM, making it more competitive with traditional manufacturing.
264 Companies are exploring carbon-fiber-reinforced thermoplastics, conductive
265 filaments, and biodegradable polymers, which could make FDM viable for highly
266 specialized sectors such as aerospace, medical, and electronics [33].

267 **8.2. Integration with Smart Manufacturing and IoT**
268 Integrating FDM technology with the Internet of Things (IoT) and smart
269 manufacturing systems will enable more autonomous, connected manufacturing
270 processes. IoT-enabled FDM printers could improve efficiency by providing real-
271 time monitoring, predictive maintenance, and data-driven insights, reducing
272 downtime and material waste. This shift aligns with Industry 4.0, where
273 interconnected machines enhance the scalability and adaptability of manufacturing
274 operations, allowing for seamless on-demand production [34].

275 **8.3. Increased Customization and On-Demand Production**
276 FDM's role in on-demand, customizable production is expected to grow as
277 industries prioritize personalized products. This trend is particularly evident in the
278 medical and wearable sectors, where tailored devices and products are essential.
279 As FDM becomes more efficient and reliable, companies will increasingly adopt it
280 for short-run manufacturing and custom items, minimizing the need for large
281 inventories and improving the flexibility of supply chains [35].

282 **8.4. Sustainability and Eco-Friendly Manufacturing**
283 With sustainability becoming central to manufacturing, FDM's potential for waste
284 reduction and use of biodegradable materials support eco-friendly practices.
285 Future trends may see the development of entirely circular FDM manufacturing
286 systems, where materials can be reused or composted. This approach aligns with
287 global efforts to reduce carbon emissions, providing companies with sustainable
288 options for prototyping and low-volume production [36].

289 **8.5. Advancements in Multi-Material and Multi-Color Printing**
290 Future FDM systems are expected to incorporate multi-material and multi-color
291 capabilities, allowing for more complex and functionally integrated parts. Multi-
292 material FDM printers can integrate conductive, flexible, and rigid materials into a
293 single print, opening up possibilities for electronics, biomedical devices, and
294 robotics. This evolution would broaden FDM's applicability, making it an integral
295 technology in industries that require highly functional, mixed-material components
296 [37].

297 **9. CONCLUSION**

298 FDM 3D printing has established itself as a valuable technology in modern
299 manufacturing, enabling rapid prototyping, cost-effective production, and highly
300 customizable solutions across industries such as automotive, healthcare, and

301 aerospace. The advantages of FDM—its affordability, ease of use, and design
302 flexibility—have made it an accessible option for businesses and educational
303 institutions alike. However, limitations related to surface finish, material strength, and
304 production speed highlight areas where continued innovation is essential.
305 Case studies demonstrate the real-world impact of FDM, from custom prosthetics to
306 lightweight aerospace tooling, showcasing its potential to revolutionize manufacturing
307 practices. Looking ahead, the integration of advanced materials, IoT capabilities, and
308 sustainable practices are likely to drive FDM's evolution. These advancements will
309 empower manufacturers to meet the demands for on-demand production and eco-
310 friendly practices, positioning FDM as a key technology in the era of Industry 4.0.
311 Ultimately, while FDM will complement rather than replace traditional manufacturing,
312 its role will continue to expand, offering new opportunities for innovation,
313 customization, and efficiency in the manufacturing industry.

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technology

319 Details of the AI usage are given below:

- 320 1.
- 321 2.
- 322 3.

323

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