

3D Printing Fundamentals

\$21 Billion

As the global 3D printing market is expected to reach 21 billion U.S. dollars globally in 2021¹, various industries — from manufacturing, automotive, aerospace, healthcare, robotics, education, and more — are tapping into the numerous opportunities and innovations.

This guide will cover the fundamentals, and examine the promise and reality of the technology.

¹[Statista, 3D Printing Forecast](#)

The Promise of 3D Printing

The buzz around 3D printing reflects its enormous disruptive potential, which is based on key tangible benefits over conventional fabrication.

Native digital fabrication — 3D printing was one of the first digital native fabrication methods at its inception. While modern CNC milling is now entirely digital, its genesis is rooted in analog practices. In application, digital native technologies provide smoother part fabrication workflows. Furthermore, due to its digital foundations, 3D printing technology is well-suited for integration with cloud based infrastructure, artificial intelligence (AI), and future-facing technologies/platforms.

Democratized fabrication — 3D printing carries the promise of accessibility and affordability. Commercially available 3D printers could transform the garage hobbyist into someone capable of fabricating near net-shape parts.

Complexity and customization as less cost — In subtractive manufacturing, any complexity in a part (such as curved or uniquely-shaped geometries) adds cost in the form of increased machine time and steps required. Additive manufacturing has an automated prep and fabrication workflow that enables complexity free of cost.

The Reality of Fused Filament Fabrication Printing

3D printing has immense potential, but the technologies that have dominated the space have faced challenges since their invention. First, fabricating robust parts is difficult because 3D printing is reliant on thermoplastics that are not robust enough to survive loads typically encountered by functional parts. Second, 3D printers have a history of being less reliable than conventional subtractive technologies. The last decade, however, has seen significant accuracy and reliability improvements and new processes designed to yield functional parts. Overall, the outlook is very bright.



Defining key terms

Additive Manufacturing (AM) is where a part is made by adding material, and 3D printing is a subset of additive manufacturing. In 3D printing, a 3D printer makes a three-dimensional object by starting from a 3D CAD (computer-aided design) file.

Fused Filament Fabrication (FFF) is an industry-standard 3D printing process in which thermoplastic-based filament is heated and extruded through a nozzle in discrete layers to create a part. Some FFF filaments are “filled” with micro carbon fibers, but the resultant part strength is similar to plastic.

Carbon Fiber Reinforcement (CFR) is a process that enables 3D printers to reinforce FFF parts with continuous fibers. A CFR capable machine uses two extrusion systems: one for conventional FFF filament, and a second for long strand continuous fibers. Continuous fibers are laid down in-layer, replacing FFF infill where specified. The resulting parts are significantly stronger (up to 10 times stronger than any FFF material) and can replace aluminum parts in-application.

Today, FFF is the dominant incumbent 3D printing technology. However, CFR delivers on the category benefits of FFF by eliminating key part weaknesses. While FFF parts are typically limited by the strength of weak polymers, CFR parts are strong enough to replace machined aluminum in key manufacturing operations.

Fused Filament Fabrication printers: A closer look

Fused Filament Fabrication printers are the most common 3D printing technology due to their simplicity, affordability, variety, and maturity. They exist all up and down the cost spectrum — from \$200 machines that are preferred by casual users to production-grade machines that cost hundreds of thousands of dollars. As the technology advances it's been adopted by more industries.

How a Fused Filament Fabrication 3D printer works

In this section, we'll discuss the processes, printers, and parts of FFF.

Here's a breakdown of how an FFF printer creates a part after the initial design phase:

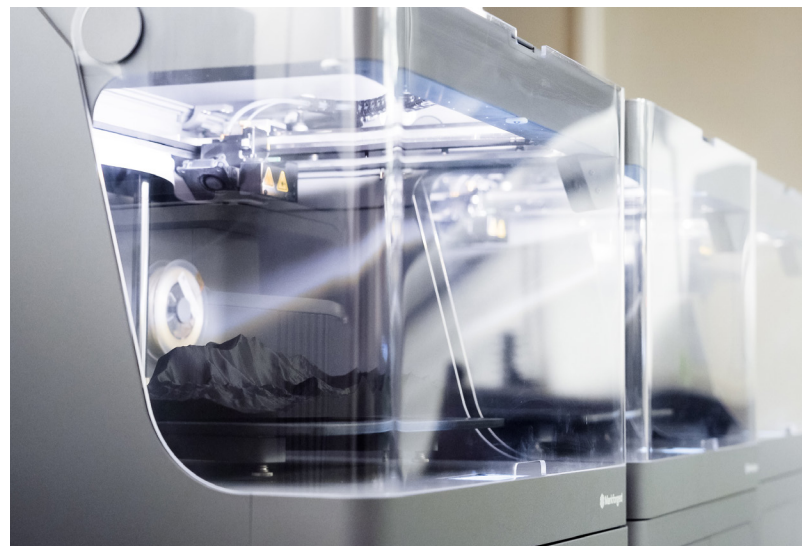
1. The printer software slices parts into discrete layers, then builds a toolpath for each layer. The toolpath serves as an automatic blueprint for the machine to follow.
2. A printing system heats and extrudes material (like a glue gun) out of a nozzle while precisely following the toolpath. On the first layer, the machine deposits material directly onto the print bed.
3. Once a layer is completed, the printer lowers its print bed one layer from the print head and starts printing the next layer. This process continues until a print job is complete.
4. After the print is complete, a user can remove the part from the print bed and use it.

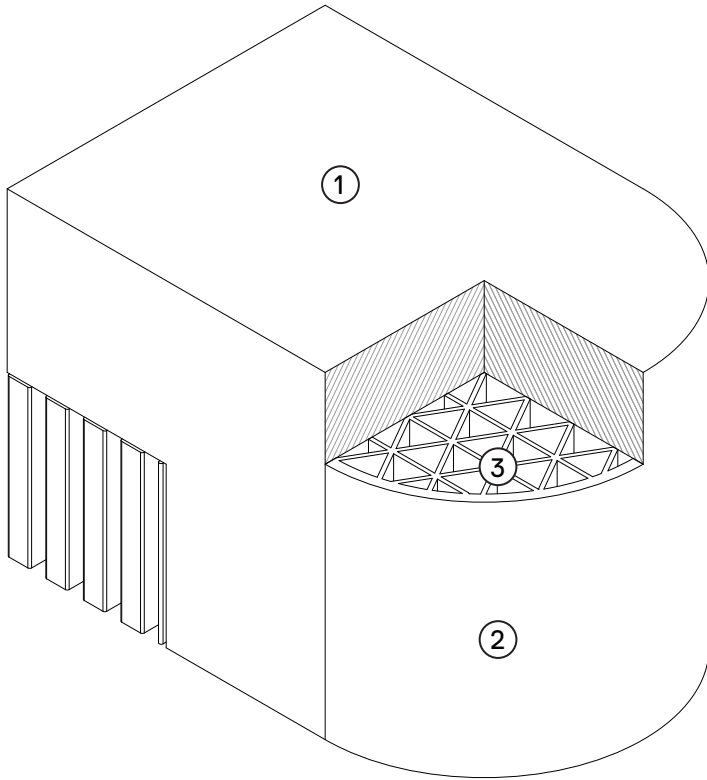
Key systems in a Fused Filament Fabrication 3D printer

Print head/extrusion system — The core part of an FFF printer where the system heats and extrudes material out of a nozzle.

XY motion system — The system that moves the print head on the printing plane via a typical XY gantry. A precision motion system precisely controls the location of the print head.

Print bed — Also known as the stage or build plate, the print bed is the surface an FFF part is built up from. It's typically attached to a Z axis motion system, which controls how far the print bed is from the part.

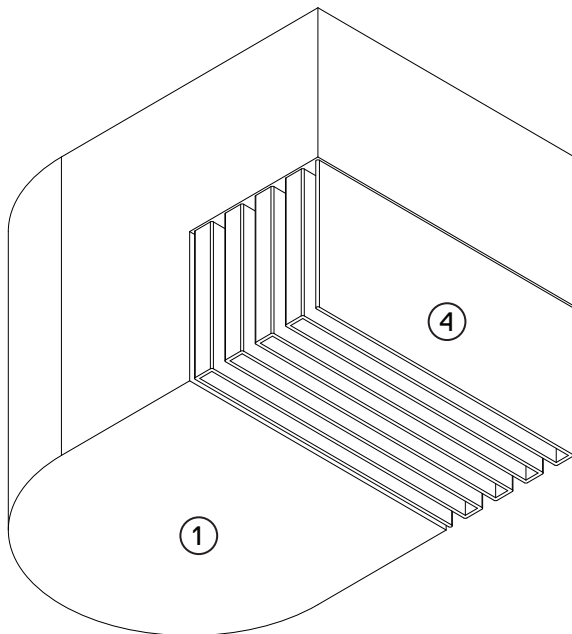




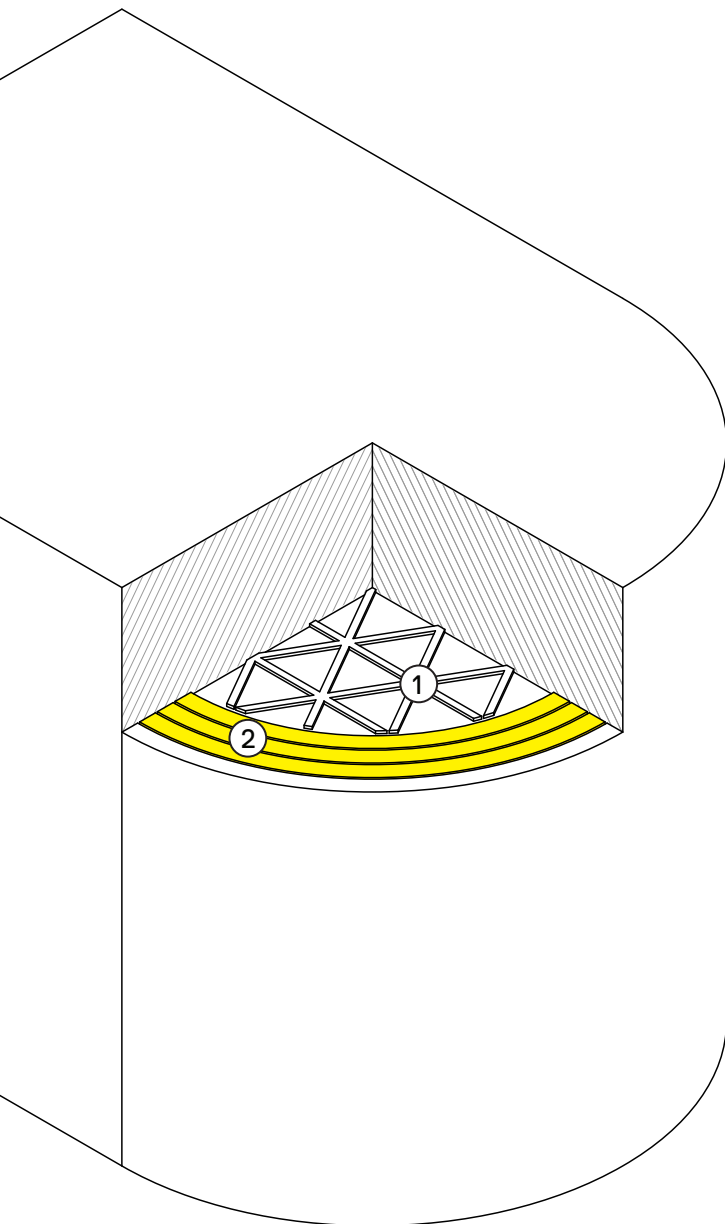
Fused Filament Fabrication: The anatomy of a 3D printed part

An FFF printer builds parts using four key elements:

- ① **Floors and roofs**
Floors refer to the bottom and roofs to the top of the part. Floors and roofs of an FFF printed part are multiple layers each; they are printed via a back and forth pattern that alternates in direction for each layer.
- ② **Walls**
Walls refer to the external “shell” outside of an FFF printed part and are commonly printed 2-4 beads thick.
- ③ **Infill**
Infill is the structure that makes up the inside of the part. While it’s possible to print solid parts, the clear majority of FFF printed parts are printed with a lattice infill.
- ④ **Support material**
Support material is used for printed part geometries that have cantilevered overhangs or bridged structures. So, in that manner, the 3D printer will print support materials that serve as a scaffold for the part. This support material is either a peel-away structure or a soluble support (made from a secondary material) that will dissolve in a solvent bath to remove. It is also important to note that the support material is sacrificial.



Bottom view



① **Conventional infill**

In areas where fiber is not inserted into a part, the printer lays down conventional FFF infill.

② **Continuous fibers**

Where specified, a CFR capable printer replaces conventional FFF infill with continuous fibers.

Continuous Fiber Reinforcement: The basics and advantages

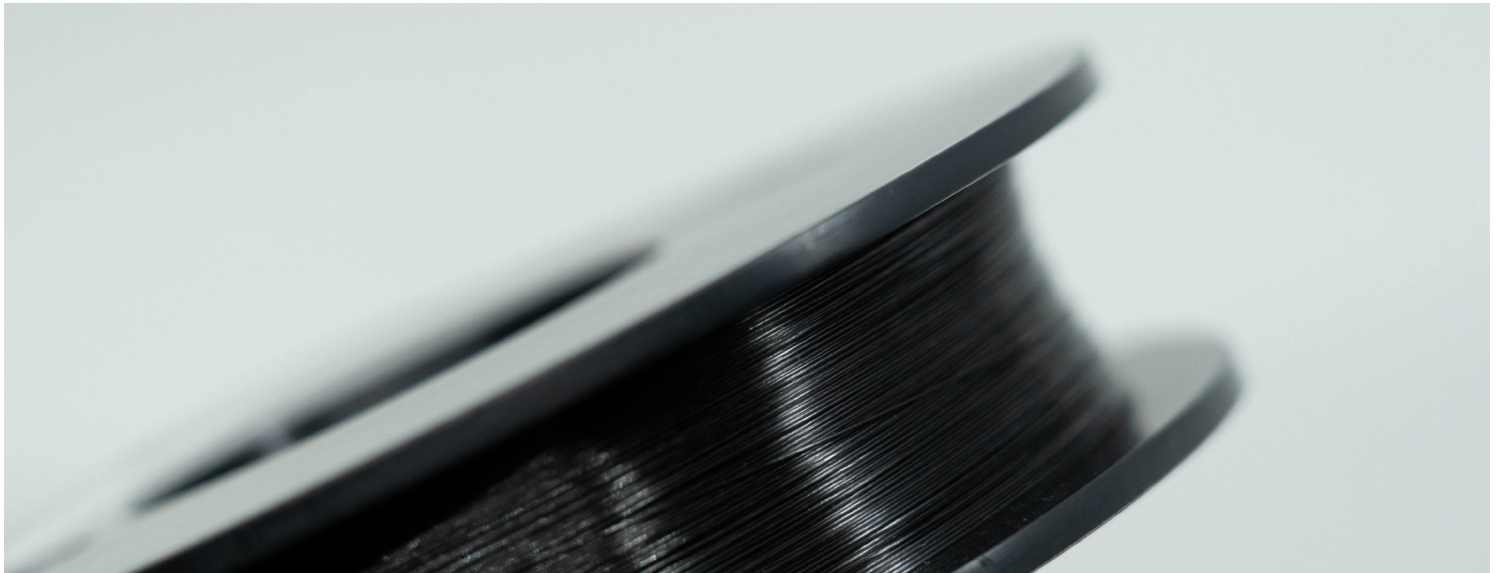
While FFF printing has made its mark on the 3D printing industry, the technology faces the challenge of printing parts that are beyond the plastic strength. In this section, we'll examine how CFR works, differences, and similarities to FFF.

A closer look at CFR

CFR augments traditional Fused Filament Fabrication (FFF) technology, enabling Markforged's printers to reinforce FFF parts with continuous fibers. A CFR-capable machine uses two extrusion systems for two unique materials: one for conventional FFF thermoplastic filament, and a second for long-strand continuous fibers. Continuous fibers are laid down in-layer, replacing FFF infill.

CFR levels of control

Continuous fibers can make a huge difference in material properties even when used sparingly. CFR printers also enable users to systematically control the placement, distribution, and orientation of fibers in a part but also allow for granular control on a layer-by-layer basis.



How The Digital Forge from Markforged will transform your organization

The Digital Forge is the intuitive Additive Manufacturing platform for modern manufacturers—bringing the power and speed of agile software development to industrial manufacturing. Composed of hardware, software, and materials working seamlessly on a unified platform, it's purpose-built to integrate into your existing manufacturing ecosystem and eliminate the barriers between design and functional part.

Digital Forge adopters reap immediate benefits through massive time and money savings on parts. Through increased adoption, the platform can drive competitive advantages by making your entire operation more agile and efficient.

Partner with an industry leader

While FFF is the industry's incumbent technology, it still has limitations. Adopting continuous fiber reinforcement solutions can unlock more opportunities, potential, and value.

Markforged is rapidly innovating and meeting the evolving challenges of modern manufacturers by continually improving our hardware, software, and material platforms. Partnering with an industry leader like Markforged will immediately open up a broad swath of capabilities today and enable you to face the challenges of tomorrow.