Carbon Fiber 3D Printing

An Introductory Guide

The Rise of Carbon Fiber

While carbon fiber 3D printing has been around for the better part of a decade, it has rapidly risen to prominence in the last few years. Today, many incumbent 3D printer manufacturers are rushing to capitalize on the term "carbon fiber 3D printing" but not all carbon fiber is created equal.

This white paper covers the basics of carbon fiber in the 3D printing space — where we'll define the different types, examine the challenges, benefits, implementation considerations, and more. Within carbon fiber printing, we'll take a deep dive into the benefits of Carbon Fiber Reinforcement (CFR) from Markforged.

Carbon Fiber Basics

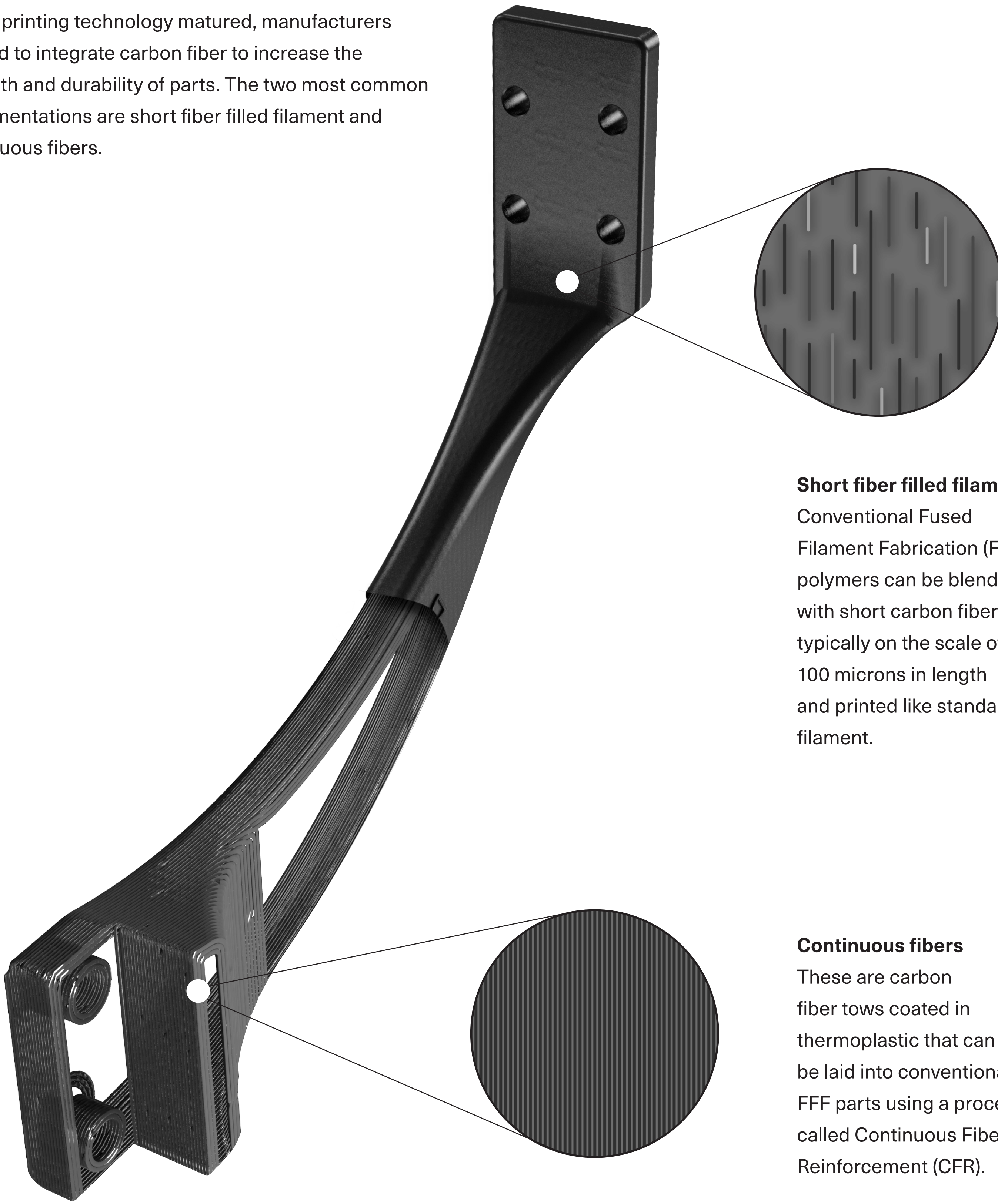
What are Carbon Fibers?

Carbon fibers are made up of carbon atoms organized into long, thin crystalline structures 5-10 microns in diameter. These fibers can be used by themselves or in tows, which are several thousand individual fibers bundled together. In modern manufacturing, carbon fiber is almost always combined with other materials to form a composite. When joined with a thermoplastic or thermoset resin matrix, carbon fiber tows can take various forms for use in engineering applications. Most commonly, they are wrapped around mandrels to form tubes, pulled through dies for pultrusions, or woven together into tapes and fabrics. This combination creates strong, custom geometries that can be used in aerospace, automotive, military, and other industries.

The combination of carbon fiber's enhanced mechanical properties and resistance to heat and chemicals make it ideal for advanced fabrication. Carbon fiber boasts high stiffness and tensile strength at a far lower relative density than steel and aluminum. Because of its very high strength to weight ratio, carbon fiber is widely used in the aerospace and automotive industries.

Carbon Fiber in 3D Printing

As 3D printing technology matured, manufacturers worked to integrate carbon fiber to increase the strength and durability of parts. The two most common implementations are short fiber filled filament and continuous fibers.



Short fiber filled filament
Conventional Fused Filament Fabrication (FFF) polymers can be blended with short carbon fibers, typically on the scale of 100 microns in length and printed like standard filament.

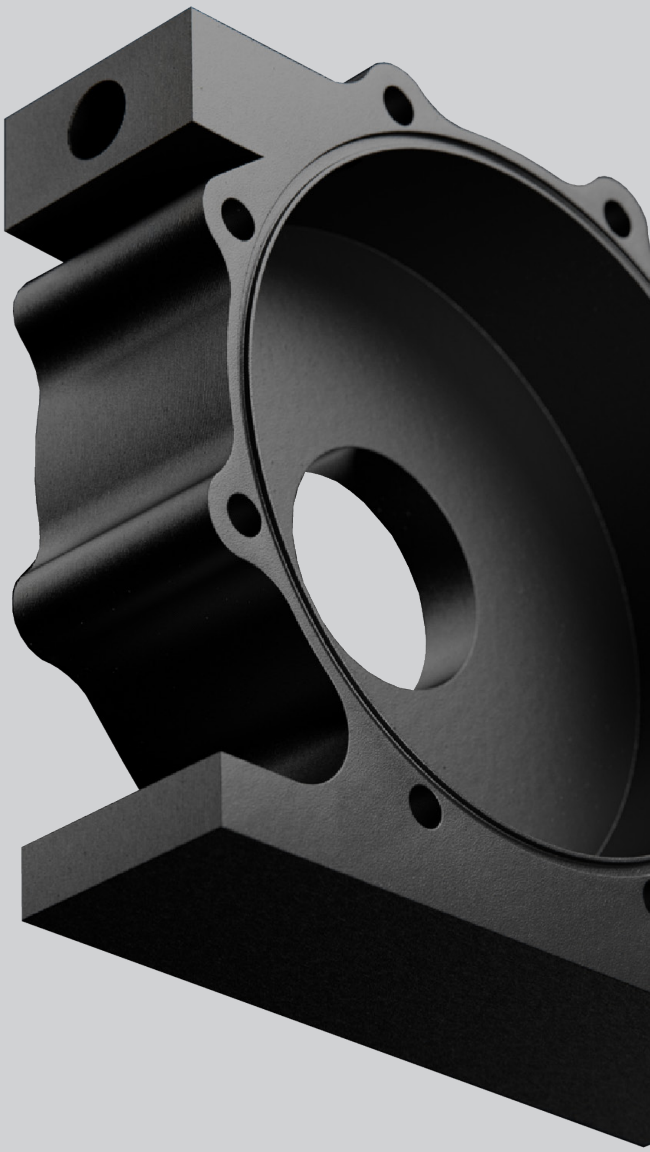
Continuous fibers
These are carbon fiber tows coated in thermoplastic that can be laid into conventional FFF parts using a process called Continuous Fiber Reinforcement (CFR).

Short Fiber Filled Filaments

Background

Short fiber fillers, such as glass fibers and carbon fibers, have been used for decades in the injection molding industry to improve the material properties of thermoplastics. To create these filled filaments, manufacturers blend polymer feedstock with filler materials, forming them into pellets. These pellets are sent through an extrusion line that further blends, joins and stretches them into a filament. The filament is then spooled and used. In the 3D printing industry, the most common application of this process is short carbon fiber filled filament using either nylon or ABS plastic as a base material.

It's important to note that not all fillers are fibers meant to enhance mechanical properties; in fact, some are used to improve flowability, aesthetic appearance, or even to lower cost.




With the right carbon fiber content, short fiber filled filaments can achieve unparalleled surface finish.

Short carbon fiber filled filaments are typically composed of between 5-35% carbon fiber by weight that is uniformly distributed. These fibers are short fibers that are either milled or chopped from fiber tows, with sizes ranging from 5-10 microns in diameter and 50-250 microns in length.

The flow characteristics of the material extrusion process, both in filament production and in printing, will align the fiber filler in the print direction. This means the improvements to tensile and flexural strength tend to align with the part's outer shell.

Key Benefits

+ **Marginal increase in strength/stiffness**
  This translates directly to stronger, stiffer parts.

+ **Improved thermal stability**
  Carbon fiber has a low coefficient of thermal expansion and can help reduce warping during the printing process. Additionally, it helps printed parts resist distortion in hot environments.

+ **Greater printed part accuracy**
  The combined increase in mechanical and thermal stability means that carbon fiber filled parts are capable of achieving greater dimensional accuracy than their unfilled counterparts.

Challenges

Short carbon fibers provide significant benefits that scale to their volume proportion. As a result, you might wonder why all commercial filaments aren't filled with the maximum possible amount of carbon fiber. The reason is that carbon fiber presents a number of challenges to both the material production process and the printing process, which include:

- **Filament uniformity can be negatively impacted** if the volume of stiff filler material increases beyond a certain point, which may cause poor surface finish and quality defects during printing.

- **Carbon fiber filled filaments are abrasive** and can quickly wear out printer extrusion components designed for generic unfilled FFF filaments. This can be mitigated with hardened components and routine maintenance, but increases equipment cost.

- **Too much fiber content can also obstruct material flow** and increase the risk of clogging the nozzle, rendering a machine unusable until maintenance is performed.

Many filament manufacturers choose to ignore these drawbacks and add as many short carbon fibers as physically possible to their filled filaments. The resulting parts gain strength at the expense of surface finish and machine reliability.

Carbon Fiber Reinforcement (CFR) from Markforged enables us to design our filled filament Onyx in a way that mitigates these failure modes. While most filled filament manufacturers optimize their material for strength at the cost of printability, we've optimized Onyx for dimensional accuracy, surface finish, and printer reliability. We're able to do this without sacrificing final part strength because of the strength and stiffness of the continuous fibers used in CFR, which are introduced below. The results are increased accuracy in parts, bulk stiffness and strength, more aesthetically pleasing surface characteristics and overall reliably printed results.

Continuous Fibers

Background

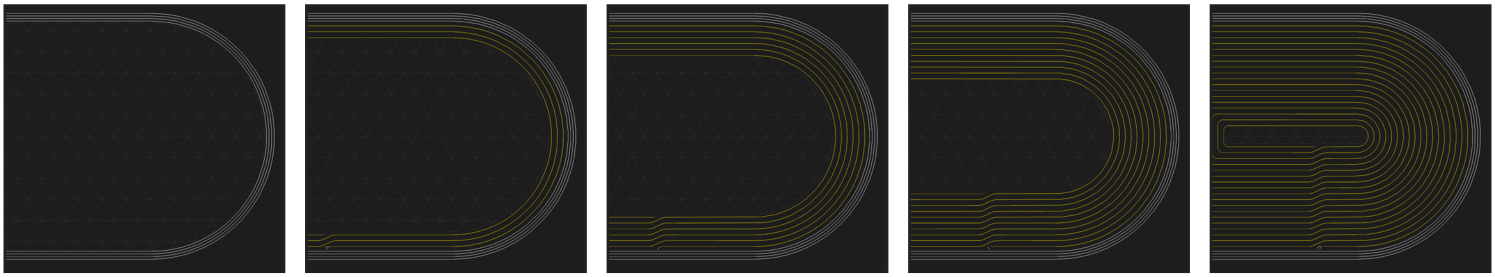
Continuous carbon fibers are long carbon fiber tows coated in thermoplastic. These fiber tows are then laid into thermoplastic FFF parts using the CFR process. During this process, the thermoplastic coating is thermally fused to the part by extruding the material through a heated nozzle. Fibers can be laid in a wide variety of 2D orientations within each layer of the 3D printed part.

The strength of parts reinforced with continuous carbon fiber is comparable to that of parts made by conventional composite layups. In filled filaments, the discontinuities between short fibers cause mechanical loads to transfer through the matrix polymer, which limits the associated boost in mechanical properties to an incremental one. In CFR parts, tensile and flexural loads are applied to long fiber tows with minimal loading of the matrix polymer, leading to elevated bulk mechanical properties. Parts can be reinforced in many different ways to optimize for different loading conditions.

Continuous Fiber Reinforcement technology extends beyond carbon fibers with materials that include continuous fiberglass, Kevlar®, and High Strength High Temp Fiberglass.

Dynamic Continuous Fiber Content

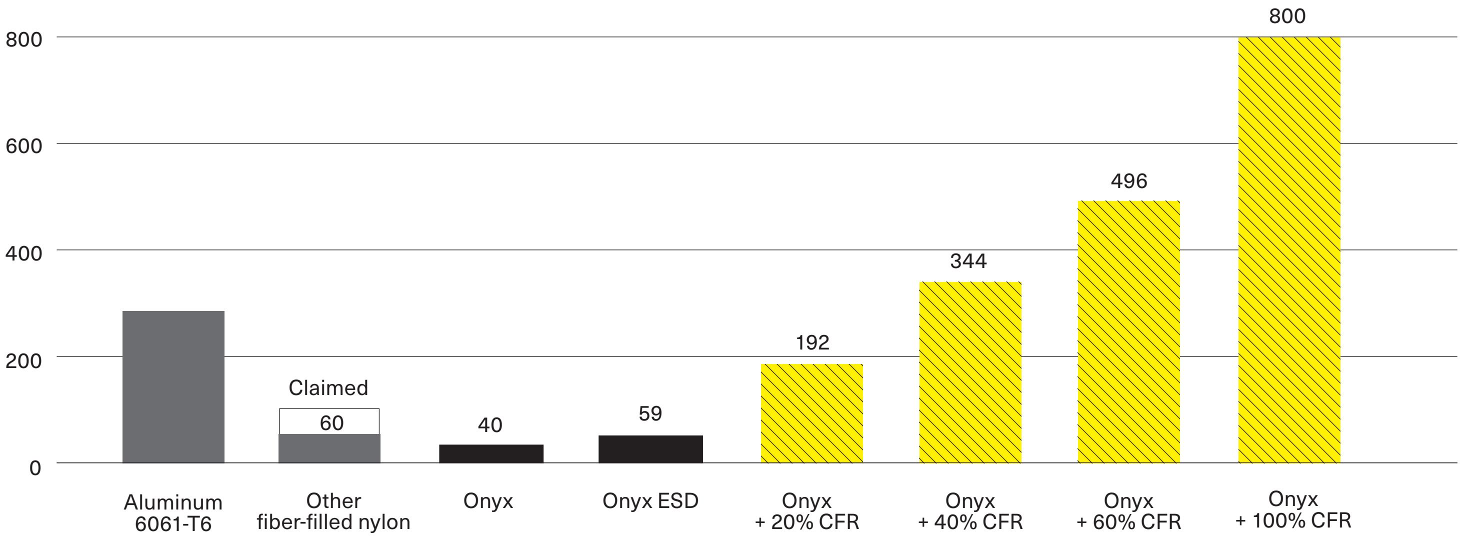
Using CFR, a user can dynamically control the amount of fiber in the part in two ways — by altering the amount of fiber in a layer and designating how many layers are reinforced. This control enables engineers to 3D print parts exactly as strong as they need them.



Onyx | Onyx + 20% CFR | Onyx + 40% CFR | Onyx + 60% CFR | Onyx + 100% CFR

Tensile Strength (MPa)

Conditioned to ASTM D638 Specifications



Key Benefits

Continuous fibers enable a step-change improvement in part properties as opposed to the incremental improvement afforded by filled filaments. Advantages of continuous fibers include:

+ **Capable of achieving similar strength to aluminum,** a continuous carbon fiber reinforced part has the ability to replace machined components in application.
+ **Enhanced stiffness, impact resistance, heat resistance, and durability** are possible through a range of specialty continuous fiber reinforcement materials including Kevlar and Fiberglass.
+ **Continuous fibers complement filled filaments.** As an example, Markforged uses short carbon fiber in Onyx to improve accuracy and surface finish of printed parts, and continuous carbon fiber for a tenfold boost in strength and stiffness.

Implementing Continuous Fibers

Unlike filled filaments, continuous fibers are implemented by users through an additional process called Continuous Fiber Reinforcement (CFR). CFR allows flexibility in how users can implement continuous fibers in their parts; and, in doing so, users have more control over how much carbon fiber to put into parts. While it’s possible to fill parts indiscriminately with continuous fibers, the best results come with strategic placement of fiber tows based on loading conditions. An optimized part provides the same desired outcome using less material, which also reduces the time and cost of fabrication.

Control is a key benefit when considering continuous fibers. This control can be exercised in two key ways:

1. Determining whether or not to place continuous fibers within each layer of the part
2. Determining a reinforcement strategy for each reinforced layer

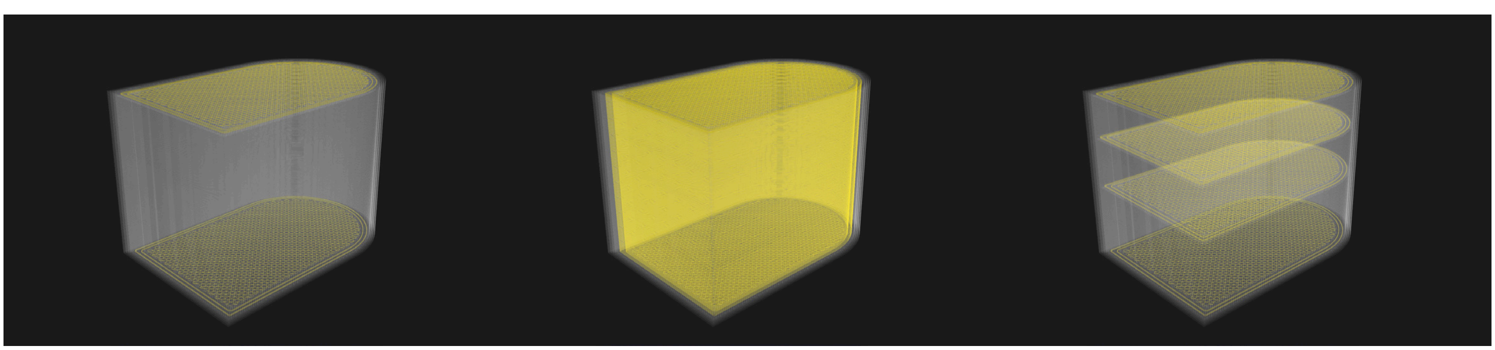
Examples of continuous fiber techniques commonly utilized for parts include:

Sandwich panel
Like a conventional composite laid up part, adds continuous fibers to the top and bottom. Under most flexural loading conditions, stress concentrations are highest at the surface of a part. Sandwich panels are used to resist forces in the Z direction.

Shell
Like a sandwich panel, but uses loops of continuous fibers inside the walls of each layer. Shell reinforcement places continuous fibers at the perimeter of each layer to resist loads along the XY plane.

Striped
Sandwich panel with added “stripes” of continuous fibers at key areas of part. Stripes can be used in tall sandwich panels to distribute loads, which reduces the risk of infill buckling.

Sandwich panel Shell Striped



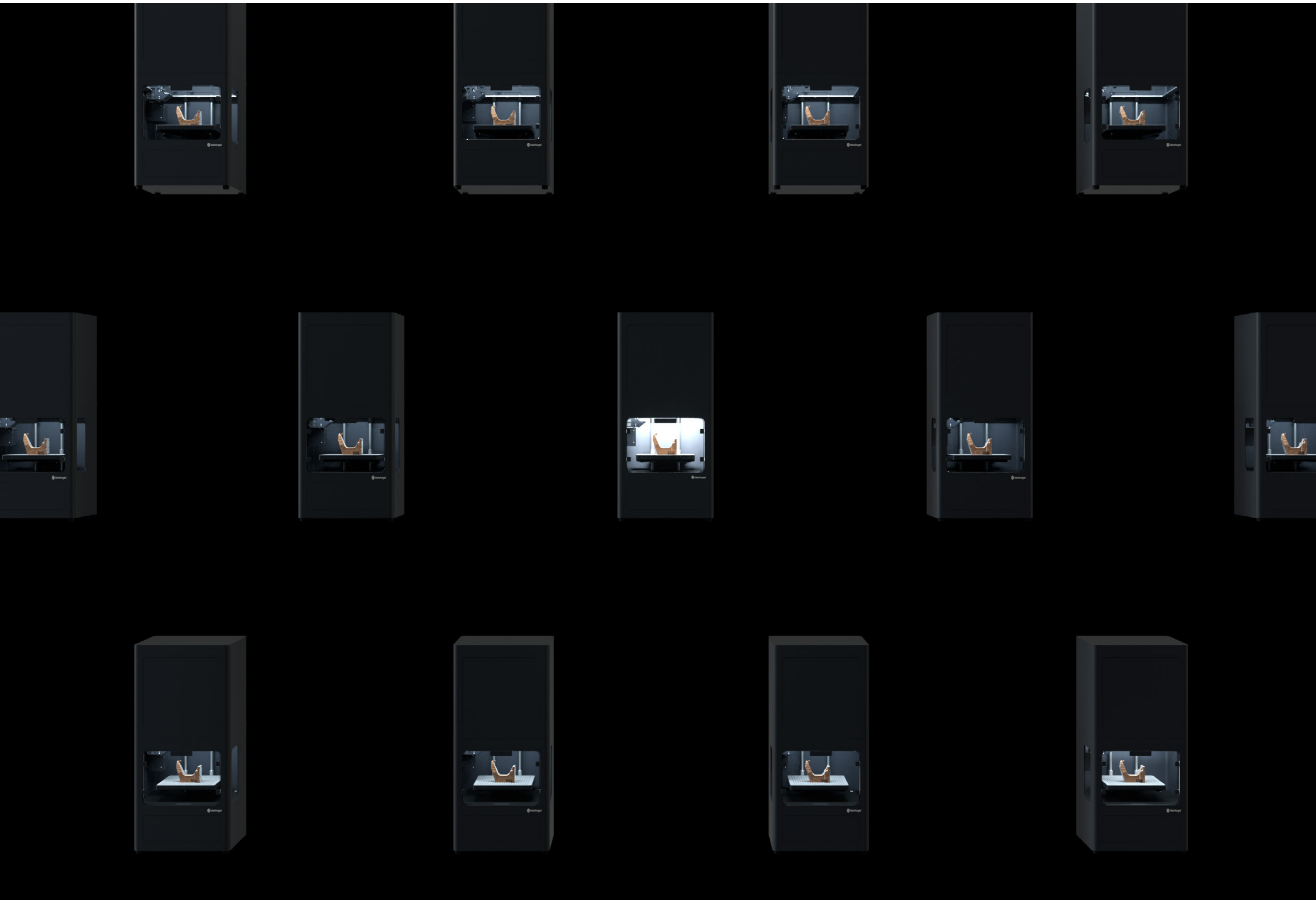
Conclusion

Now that you're armed with the basics, key definitions, benefits and considerations, your organization can be best prepared when deciding how to invest in the right carbon fiber 3D printing solution.

Partnering with a leader in continuous fiber printing technology can help you adapt evolving business needs that involve 3D printing. Continuous carbon fiber is Markforged's unique, ultra-high-strength material — when laid into a composite base material like Onyx, it can yield parts as strong as 6061-T6 Aluminum. It's extremely stiff and strong, and can be automatically laid down in a wide variety of geometries by Markforged 3D printers.

The Digital Forge from Markforged 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.



Markforged transforms manufacturing with 3D metal and carbon fiber printers, capable of producing parts tough enough for the factory floor. Engineers, designers, and manufacturing professionals all over the world rely on Markforged metal and composite printers for tooling, fixtures, functional prototyping, and high-value end-use production. Founded in 2013 and based in Watertown, Massachusetts, Markforged has about 300 employees globally, with $137 million in both strategic and venture capital. Markforged was recently recognized by Forbes in the Next Billion-Dollar Startups list, and listed as the #2 fastest-growing hardware company in the U.S. in the 2019 Deloitte Fast 500.