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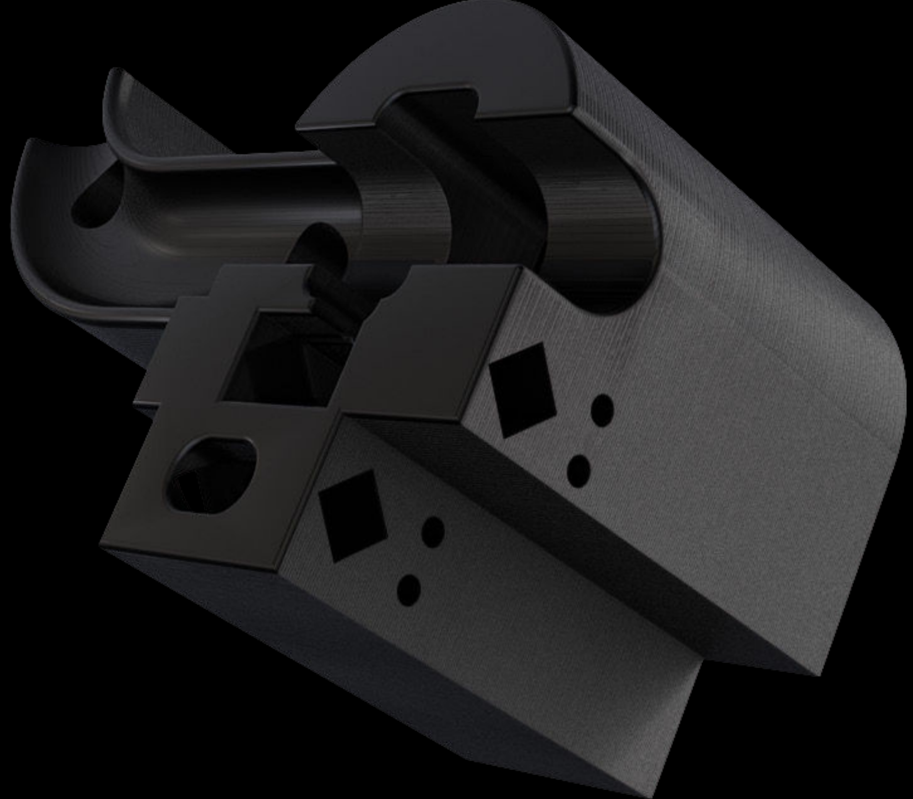


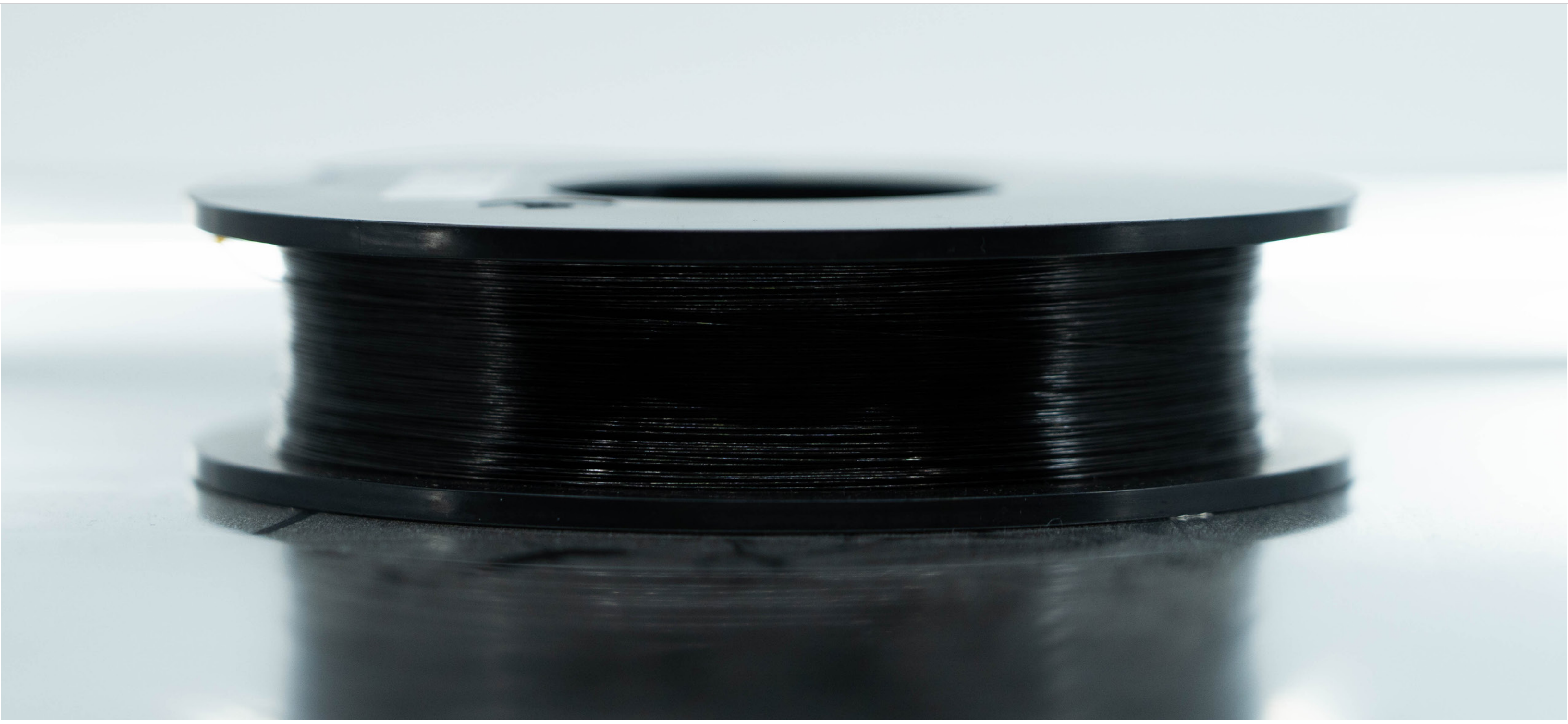
# Carbon Fiber 3D Printing Applications

How Continuous Fiber Reinforcement Opens Up Industrial Use Cases

# Manufacturing Ready

Continuous Fiber Reinforcement (CFR), an innovative technology and unique process from Markforged, is quickly driving the adoption of carbon fiber 3D printing among modern manufacturers.

This white paper takes a deep dive into how you can transform your business with functional 3D printed parts. We'll examine the process advantages of CFR over conventional manufacturing processes, tie those advantages to manufacturing applications, and look at how modern manufacturers are tapping into the benefits of CFR.



# How CFR differentiates itself from conventional manufacturing

Before we dive into applications, let's briefly define CFR. CFR is a process that enables 3D printers to reinforce Fused Filament Fabrication (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. Resulting parts are significantly stronger (up to 10 times stronger than any FFF material), and can replace aluminum parts in-application.

## Process Advantages of CFR 3D Printing

### Complex 3D geometries at less cost

3D printers excel at fabricating complex geometries, thanks to a slicing and printing process that automatically generates machine instructions. In subtractive machines, complexity and cost have an exponential relationship — complex 2D geometries require a 2 or 3 axis CNC mill and 3D geometries require a 3 to 5 axis CNC mill. These machines are expensive to program and operate, leading traditional Design For Manufacturing (DFM) guidance to push for less complex parts. For parts of complex 3D geometries that require strength, only CFR is capable of matching metal strength.

### High customizability

The simple CAD-to-part pipeline enables CFR users to dynamically and quickly alter designs to solve specific problems. With conventional manufacturing, manufacturers face the challenges of having to pick between low cost, one size fits all solutions and ultra expensive one-offs. Small changes typically spawn large cost increases. Fortunately, CFR 3D printing enables users to easily create custom, one-off parts.

**Low barrier to functional parts**

Many 3D printing technologies offer customizability and low cost complexity — the key differentiator of CFR is that it does so with functional parts. When compared to FFF 3D printed parts, CFR-created parts have considerable advantages and characteristics, which include:

+ **Stronger Parts** — CFR enables you to dynamically alter the strength of parts from plastic strength to aluminum strength. This enables users to design and 3D print parts as strong as needed.

+ **Durability** — CFR parts last longer than any other FFF 3D printed parts in application due to the strength, stiffness, and durability of the continuous fibers. In addition, filled plastics boast high wear resistance and toughness.

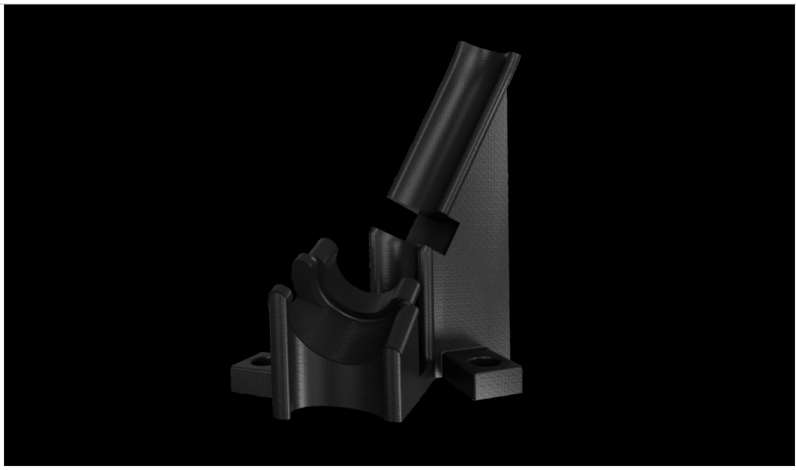
As a result of the functional parts they make, CFR 3D printers bring the means of production closer to engineers in a few key ways:

+ **No waiting on quotes or relying on in-house bandwidth** — Manufacturers don't have to send out a drawing on a part and then wait for a quote or the availability of an in-house machinist.

+ **Automated fabrication process** — No labor is required to fabricate the parts as 3D printers are completely automated.

+ **Point of need parts** — 3D printers are adaptable and affordable enough for most businesses to invest in. Conventional manufacturing usually requires acquisition of expensive machines, outsourcing of parts, and may require a significant amount of space for deployment.

+ **Resistance to heat and chemicals** — CFR parts can resist ambient heat in most manufacturing environments, and the short fiber filled filaments they reinforce are extremely chemically resistant.



# CFR Applications

Now that we've examined some of the benefits, we'll take a look at some CFR applications. We've grouped them into broad categories defined by the functional value they provide to customers. The list is not exhaustive — the technology has broad application compatibility across the manufacturing space.

## Conformal Tools and Fixtures

Modern manufacturers can leverage the free geometric complexity and high functionality of CFR parts to easily fabricate fixtures that can hold complex parts in any orientation they want.

Conformal tools and fixtures can work symbiotically with CNC machines; for example, a conformal tool can be created to enable the CNC machine perform an operation it otherwise could not accomplish. Furthermore, conformal fixtures open up new manufacturing work streams that can be more economical, less complex, and less time-consuming. This can enable production of more complex parts that would otherwise be too expensive to fabricate tooling for.

Conformal tools are also often higher performing than standard tools; this is due to their more complete surface contact to the workpiece they're holding. They can be lighter, stiffer, and stronger than the parts they're replacing. Because of the low cost of 3D printing, manufacturers can fabricate a wide variety of custom conformal tools for the different parts they manufacture.

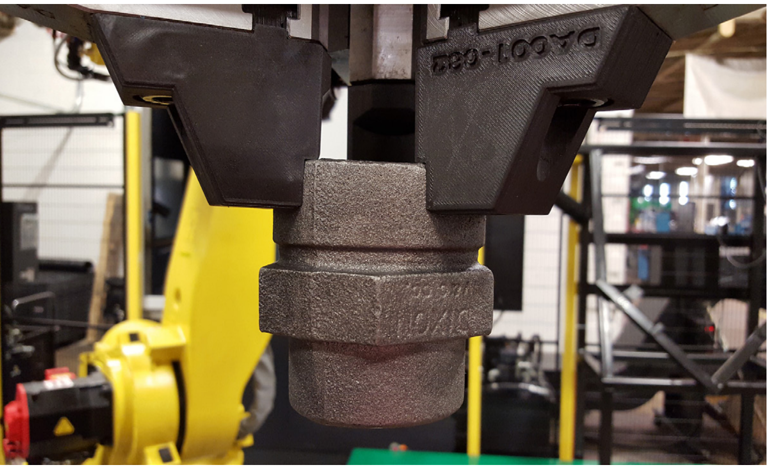
Examples of conformal tools include:

**Soft Jaws**

Conformal tools that hold a workpiece while it's milled, drilled, cut, or otherwise machined.

**End of Arm Tooling (EOAT)**

Interface parts or end effectors such as custom gripper fingers on a robotic arm.



End of Arm Tooling (EOAT)

Forming Tools

**Forming Tools**

CFR parts can be designed and printed in custom geometries to form both steel and aluminum sheet metal parts. Continuous fibers give them the strength and durability to accurately operate for thousands of cycles.

**Go/No-Go Gauges (aka Check Gauges)**

Custom printed parts designed to interface with a manufactured part or assembly to quickly determine if it is in specification.

**CMM Inspection Fixtures**

Expedite and increase repeatability of CMM setup for complex parts with custom CMM fixtures. Used in tandem with an existing modular system, setup can be highly repeatable while retaining customizability.

## Ergonomic and Efficiency Job Aids

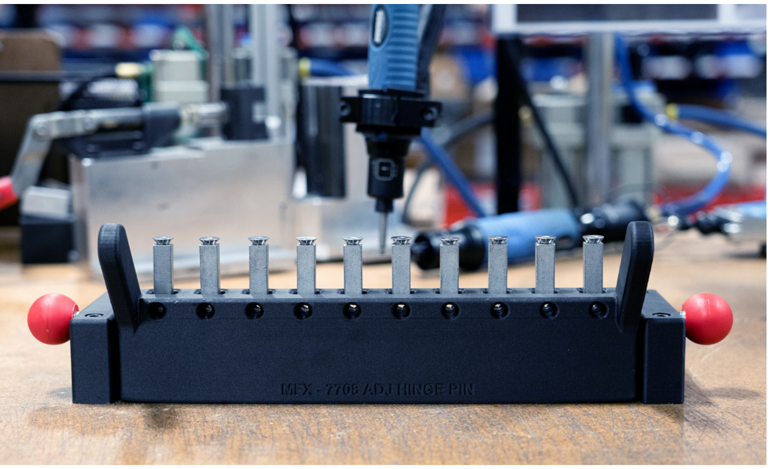
Democratized CFR fabrication enables businesses to print parts that are typically difficult to fabricate. These parts can improve efficiency, connect or integrate other parts, or aid in a manual task. Furthermore, CFR parts can be highly customized to different manufacturing operations and iterated on regularly to incorporate feedback.

**Assembly Fixtures and Trays**

Product assembly is often a highly manual task where small ergonomic gains can lead to massive boosts in efficiency. CFR 3D printing enables businesses to design and produce parts that make their labor force more effective while reducing repetitive strain injuries (RSIs).

**Parts for Manufacturing Cells**

The ability to fabricate functional parts on-demand enables manufacturers to quickly ideate, design, and implement parts for manufacturing cells and factories. Whether these are brackets, sensor mounts, guides, or other parts, these parts lower the lead time, cost and labor associated with CNC fabricated parts.




Assembly Fixtures and Trays

Parts for Manufacturing Cells

Drone Prototype

### Job Aids

CFR 3D printed parts can turn time-consuming manual tasks into simple ones. Internal tooling for some companies can take 8–12 weeks, but with CFR, the time can be reduced to a few days.

## Tools for Iteration

By lowering the barrier to functional parts, CFR makes it easier for modern manufacturers to iterate and produce parts that provide more value at low cost.

### Prototypes

Prototypes are the most common use case for 3D printers. With CFR, users unlock a step change improvement in the capabilities of the prototypes in production. Functional prototypes enable earlier testing and more information leading towards your final part design.

### Bridge tooling

Like prototypes, tools often require several iterations and significant effort before they're locked in. CFR 3D printed early run tooling can produce preliminary parts, which give manufacturers valuable information into how their manufacturing processes will work before they build at scale.

## Replacement Parts

Many critical parts are no longer supported by their original manufacturers, or would take too long to obtain due to supply chain restrictions. Another pain point for manufacturers is dealing with parts that were flimsy and not up to standards needed. CFR 3D printing enables the technological means and agility required to quickly and easily fabricate functional replacement parts in a wide variety of geometries — either as replacements, or as improvements to the original. Replacement parts are not bound to a single application — they can take the form of tooling, fixturing, or end use parts, extending equipment lifetime and enabling a culture of continuous improvement. Overall, the rigidity of CFR means that the parts are durable, strong, affordable to print, and up to the task.

## What makes up a functional part?

By definition, functional refers to a part's ability to meet its design intent. Each of the requirements below is a common functional requirement for a 3D printed part. We've defined each requirement, included how both short fiber filled polymers and CFR address the requirement, and highlighted which technology has a greater impact. Markforged parts feature both technologies, with a short carbon fiber filled polymer reinforced with continuous fibers.

The primary driver of a each functional requirement is highlighted

| Functional Requirement | Description | Short Fiber Filled Polymer | Continuous Fiber Reinforcement |
|---|---|---|---|
| **Stiffness** | The degree to which a material deforms under load | Short fibers increase the stiffness 1.5x-3x relative to conventional polymers. | Continuous fibers increase stiffness 20x relative to conventional polymers. |
| **Strength** | Maximum load the material can withstand before yielding | Adding short fibers marginally improves tensile and flexural strength of materials. | Continuous fibers increase strength up to 10x further. |
| **Durability, Impact** | A material's ability to resist breakage and absorb energy during shock loading | Nylons are known for their durability and fracture resistance under impact. The addition of short fibers further improves wear resistance. | Continuous fibers increase the magnitude of forces that parts are able to withstand before catastrophically deforming. |
| **Durability, Wear** | A material's ability to resist gradual removal or deformation of surface material from friction | Short fibers increase abrasion resistance of polymers, making them last longer in abrasive environments. | Fiber is only exposed after the exterior of a part is worn through — however in extreme cases, it can provide abrasion resistance when exposed. |
| **Accuracy** | How close a part is to toleranced dimensions, both immediately after printing and after time in application | Short fibers improve the bulk CTE of materials, which improves printed accuracy and mitigates print defects. | CFR does not impact initial part accuracy, but prevents dimensional creep common in plastics over time. |
| **Heat Resistance** | A material's response to elevated temperatures in application | Short fibers help stabilize the material at elevated temperatures, thus reducing warp. | High Strength High Temperature (HSHT) and other long fibers withstand heat far better than matrix polymers, pushing HDT up to 145C. |

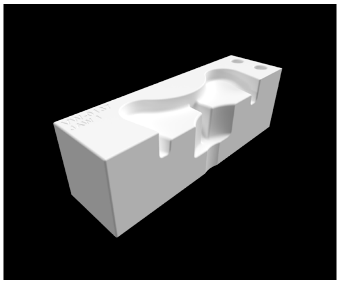
The primary driver of a quality is highlighted

| Functional Requirement | Description | Short Fiber Filled Polymer | Continuous Fiber Reinforcement |
|---|---|---|---|
| **Chemical Resistance** | How a material responds to exposure to adverse chemicals found in manufacturing environments | Nylon-based fiber filled polymers are resistant to most solvents and lubricants used in manufacturing. | CFR has limited effect, as fibers are not typically exposed to chemicals. |

## How do functional requirements map to applications?

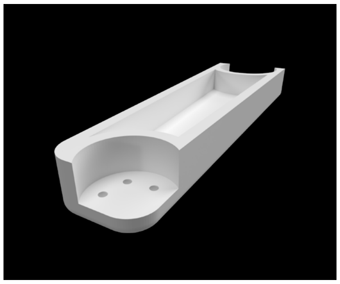
"Functional" is not a singular term in manufacturing — different applications carry different functional requirements. Below, we map the functional requirements met by 3D printing to common applications. We've split requirements into **Critical** and **Recommended**, where critical implies a requirement held by nearly all parts in this application, and recommended implies a less important or universal requirement. It's important to note that even within specific applications there's variety, and this should serve as a general guide.

(C=critical, R=recommended, N=not commonly required)



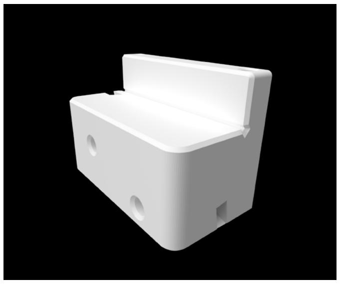
### Soft Jaws

| | |
|---|---|
| Strength & Stiffness | C |
| Impact | R |
| Wear | R |
| Accuracy | C |
| Heat Resistance | R |
| Chemical Resistance | C |



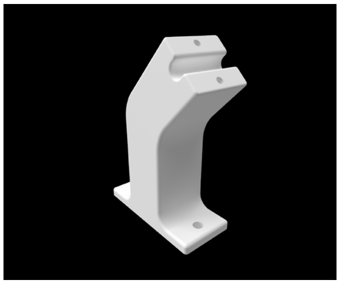
### End of Arm Tooling

| | |
|---|---|
| Strength & Stiffness | C |
| Impact | C |
| Wear | C |
| Accuracy | R |
| Heat Resistance | R |
| Chemical Resistance | R |



### Assembly Fixtures

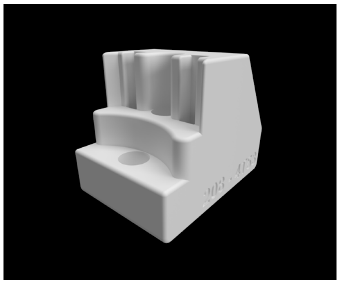
| | |
|---|---|
| Strength & Stiffness | R |
| Impact | R |
| Wear | R |
| Accuracy | C |
| Heat Resistance | N |
| Chemical Resistance | N |



### Welding Fixtures

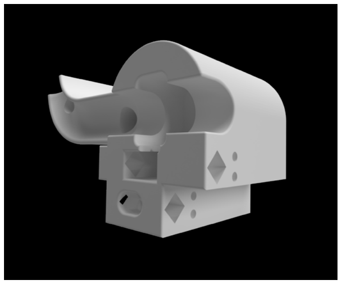
| | |
|---|---|
| Strength & Stiffness | C |
| Impact | N |
| Wear | R |
| Accuracy | R |
| Heat Resistance | C |
| Chemical Resistance | N |

(C=critical, R=recommended, N=not commonly required)



## CMM Fixtures

| | |
|---|---|
| Strength & Stiffness | C |
| Impact | N |
| Wear | R |
| Accuracy | C |
| Heat Resistance | N |
| Chemical Resistance | N |

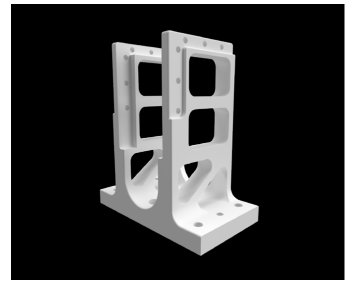


## Check Gauges

| | |
|---|---|
| Strength & Stiffness | N |
| Impact | N |
| Wear | R |
| Accuracy | C |
| Heat Resistance | N |
| Chemical Resistance | N |

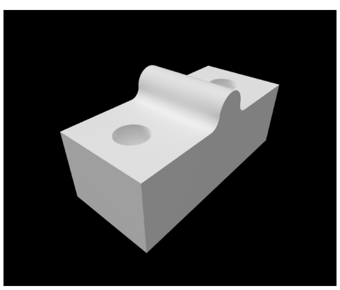
## Housings

| | |
|---|---|
| Strength & Stiffness | R |
| Impact | C |
| Wear | C |
| Accuracy | R |
| Heat Resistance | N |
| Chemical Resistance | N |



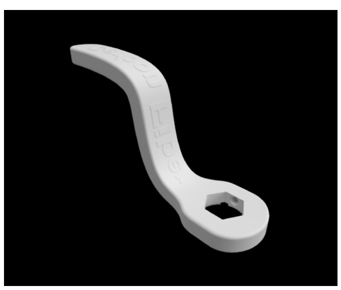
## Brackets

| | |
|---|---|
| Strength & Stiffness | C |
| Impact | R |
| Wear | N |
| Accuracy | C |
| Heat Resistance | R |
| Chemical Resistance | R |



## Forming Tools

| | |
|---|---|
| Strength & Stiffness | C |
| Impact | R |
| Wear | C |
| Accuracy | R |
| Heat Resistance | R |
| Chemical Resistance | N |

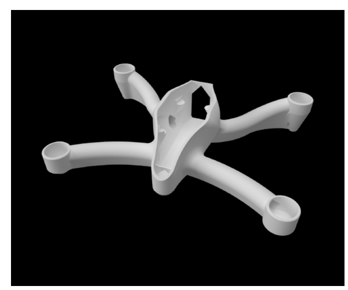


## Custom Hand Tools

| | |
|---|---|
| Strength & Stiffness | C |
| Impact | R |
| Wear | C |
| Accuracy | R |
| Heat Resistance | N |
| Chemical Resistance | N |

## Sensor Mounts

| | |
|---|---|
| Strength & Stiffness | C |
| Impact | C |
| Wear | N |
| Accuracy | C |
| Heat Resistance | R |
| Chemical Resistance | N |



## Functional Prototypes*

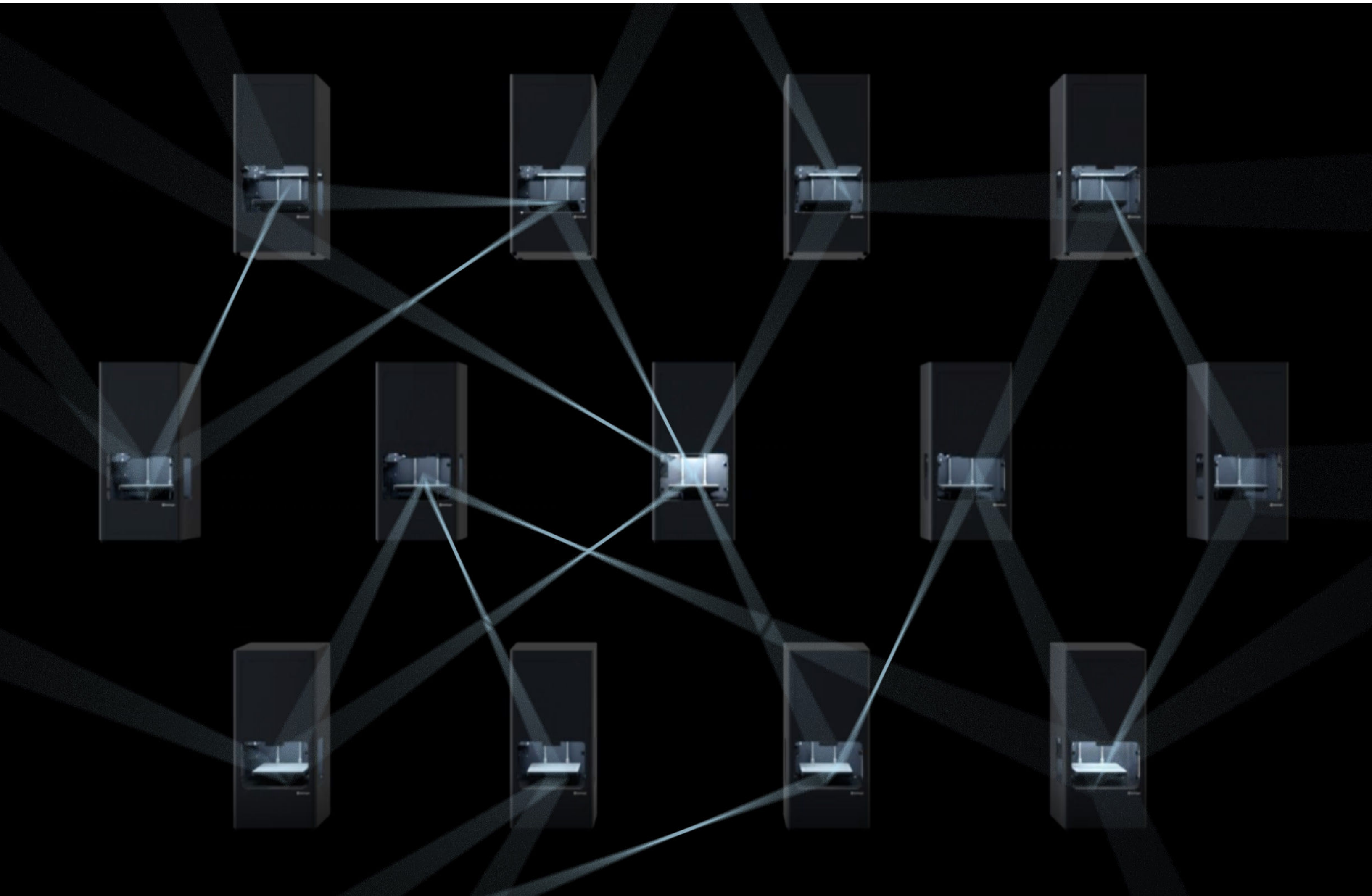
| | |
|---|---|
| Strength & Stiffness | R |
| Impact | R |
| Wear | R |
| Accuracy | R |
| Heat Resistance | R |
| Chemical Resistance | R |

*Functional prototypes do not have a set group of requirements.
Depending on what the prototype is for, it may be subject to any of the key functional requirements.

# The CFR Difference

Markforged is the first company to offer 3D printers capable of reinforcing parts with continuous fibers, which enables composite parts robust enough to replace machined metal. The advantages and benefits of CFR, as covered, have opened up the potential for various applications that have helped the modern manufacturer transform their business.

**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. The platform can drive competitive advantages by making your entire operation more agile and efficient.



Markforged

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.

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