Metal FFF 3D Printing

A step-by-step guide for process and considerations

Powerful & Accessible

While conventional metal 3D printing processes are still not ready for mass adoption, new ones — like metal fused filament fabrication (metal FFF) — are accessible, affordable and easy-to-use. Various industries, from automotive to aerospace, have tapped into this adaptable technology to produce a myriad of functional parts. Metal FFF, which is based around metal injection molding (MIM), uses a three-step process: print, debind, and sinter. Markforged has built a holistic system to make the process simple and accessible to everyone.

This white paper takes a deep dive on the metal FFF process, examines Markforged's approach to metal FFF, and key considerations when considering adopting the technology.

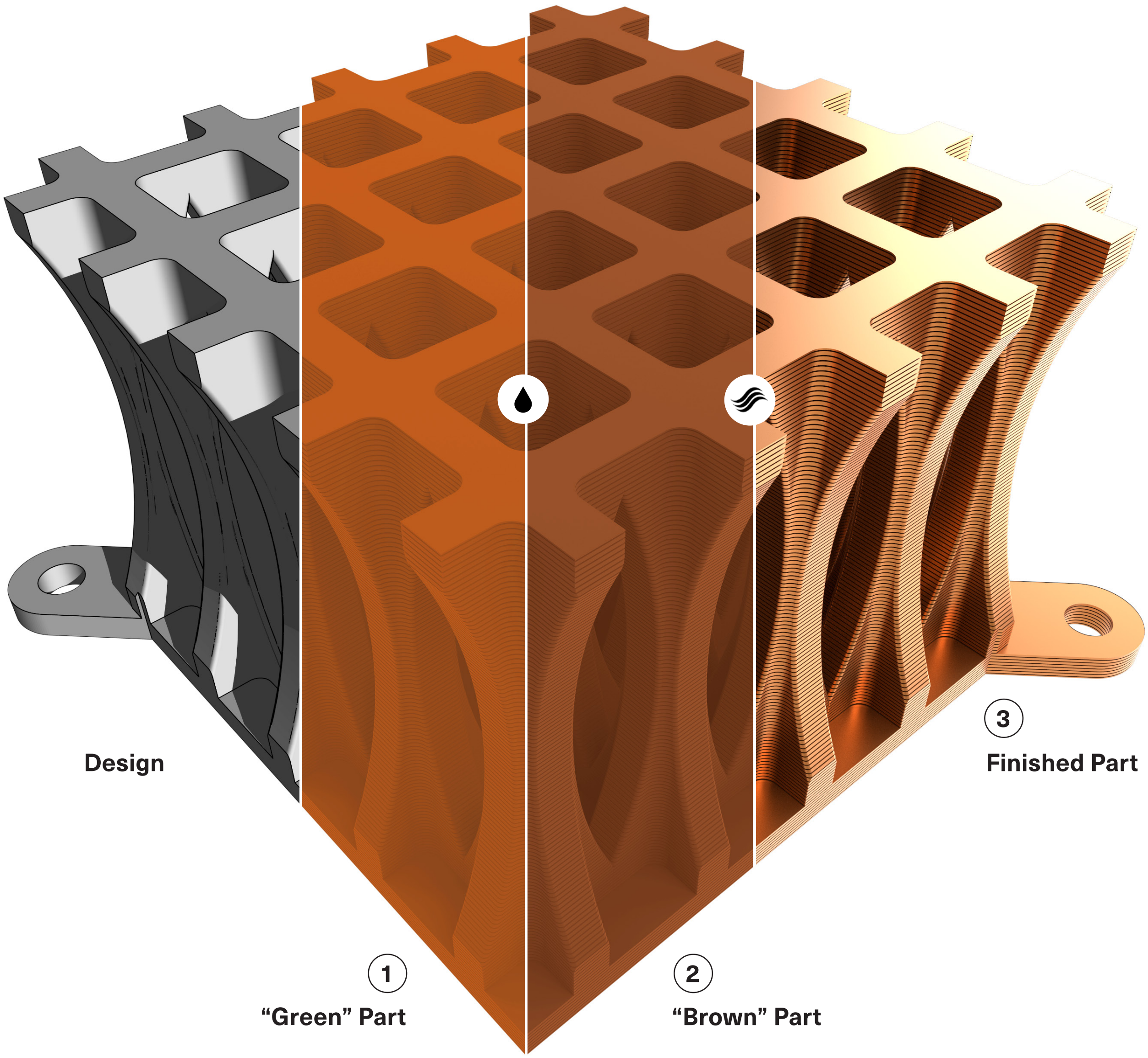
End-use metal parts printed in 17-4 stainless steel.

Metal FFF Printing

A metal FFF 3D printer is a highly specialized FFF printer optimized to print MIM feedstock. The printer doesn't print finished metal parts; instead it yields green parts that must be debound and sintered before using. "Green" parts are always scaled up 15-20% from the final part dimensions to account for repeatable and predictable shrinkage during sintering.

3-Step Printing Process

Before we cover them in detail, let's quickly define the three steps of metal FFF 3D printing.



1 Printing

Metal powder bound in plastic is printed a layer at a time into the shape of your part. Parts are scaled up to compensate for shrinkage during the sintering process. The resultant parts are known as **"green" parts**.

2 Debinding

After printing, "green" parts are placed into the debinding station, which uses an organic solvent to dissolve most of the plastic binding material. After washing they are known as **"brown" parts**.

3 Sintering

Washed "brown" parts are placed in a furnace, where they are heated with a material-specific profile — first to burn away remaining binder, then to solidify metal powder into a **finished part**.

A Familiar Process

A metal FFF printer uses a nearly identical process to conventional FFF printers, with the exception of using a vacuum-sealed print sheet instead of a conventional print bed.

The steps a user takes include:

+ Slicing parts on a software platform
+ Placing a vacuum-sealed print sheet on the print bed
+ Starting the printing process
+ Removing the printed part from the printer after the vacuum disengages
+ Peeling the “green” part off the print sheet

Dual Extrusion Optimized with MIM Feedstock

Dual extrusion machines are common in 3D printing however, a metal FFF printer has been optimized differently: MIM filament in one nozzle and ceramic interface filament in the other nozzle.

One extrusion nozzle is designed to print MIM feedstock, which is metal powder bound in a two-part plastic binding material. This material forms the part itself, as well as the supports and raft, which raise the part off of the print sheet. Markforged currently offers six different commercial-grade materials: 17-4 PH Stainless Steel, H13 Tool Steel, Copper, Inconel, A2 Tool Steel, and D2 Tool Steel.

The other nozzle prints ceramic release material, which provides the interface surface between part and support/raft. It’s important to note how critical the release material is to the process. Without a release material, parts that require supports could not be printed. The sintering process turns this material into powder, which enables the part to be easily separated from supports.

Metal FFF printing is best for custom, low-volume, high-value functional and end-use part applications.

Part Size and Infill

Ideal parts for metal FFF range from fingernail to fist size, but larger parts can be printed. Metal FFF parts are typically much larger than MIM parts, which are extremely small. The metal FFF printing process is optimized for small MIM parts so, as a result, the wash times go up exponentially as parts get larger. With solid parts, the wash time can be extremely long above a certain thickness.

Most metal FFF printed parts utilize closed cell infill. While it is possible to print solid parts, doing so introduces several complexities and constraints.

Metal FFF Debinding

The debinding step removes the majority of the binding material and yields a “brown” part ready for sintering. The “green” part is first placed into a heated solvent bath in a wash station using a degreasing solution to dissolve the primary binding material. Markforged metal FFF machines use the Wash-1, a solvent based debinding solution. It primarily uses Opteon SF-79 as a solvent, a high-performance fluid designed to offer superior cleaning power, higher efficiency, and safety in an environmentally sustainable way.

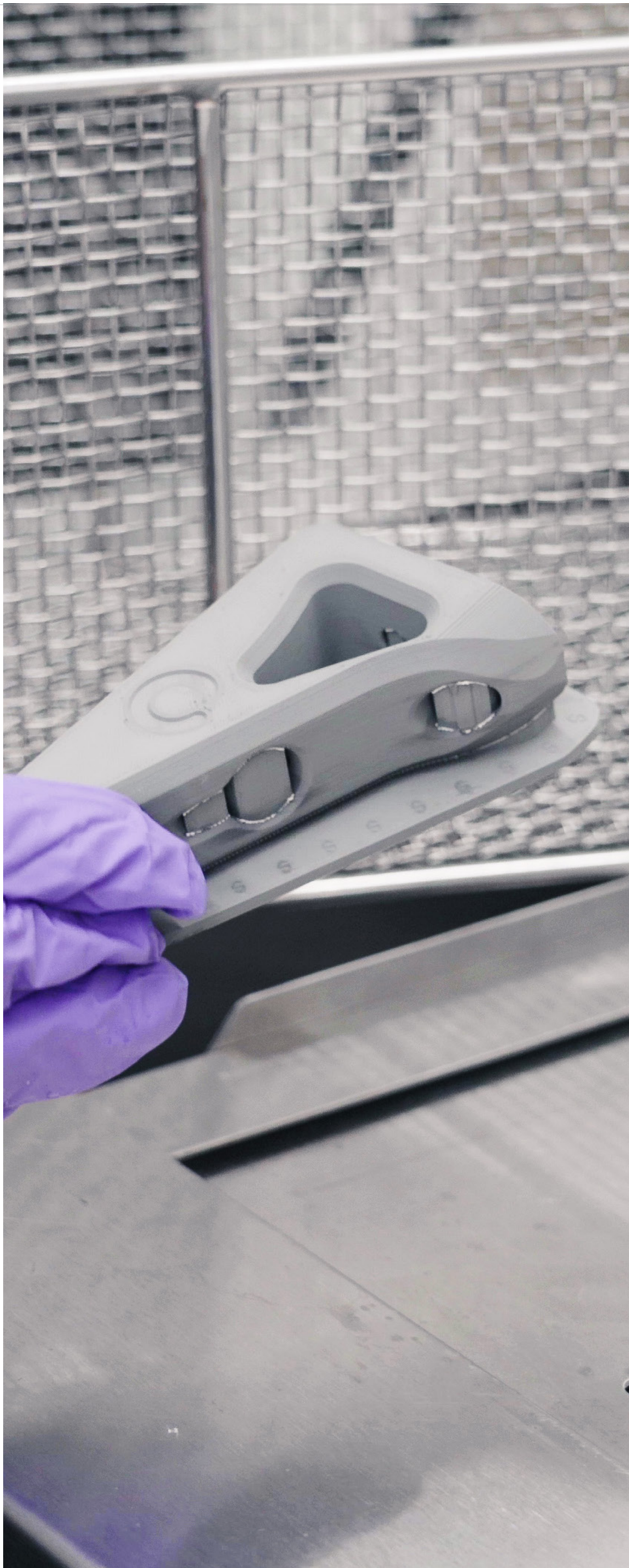
Using the Metal FFF Debinding System

The metal FFF debinding machine is fairly simple to use and requires only basic PPE (i.e. safety glasses, laminate film gloves).

The steps a user takes include:

+ Adding “green” parts to a washing basket, lowering it into the machine with the solvent, and closing the lid
+ Opening the lid, after the specified washing time, and removing the parts from the washing basket
+ Placing the parts in an air drying chamber in the wash station
+ Removing the part parts from the wash station station once the parts are dried

So, what happens to a part during washing? The debinding solvent bath dissolves the primary binding material in the green part. As it dissolves binding material, the solvent opens up microscopic fluid pathways into the part, which enables the solvent to flow deeper and dissolve more.



Metal FFF Debinding Considerations

In this section, we'll cover considerations pertaining to part thickness, solid vs. closed cell infill, and environmental health safety concerns.

Part thickness — Wash time correlates to the maximum thickness of the part, not the size or weight of the part. To determine thickness, we use the inscribed circle method that determines the largest diameter sphere you could fully fit within the bounds of the part.

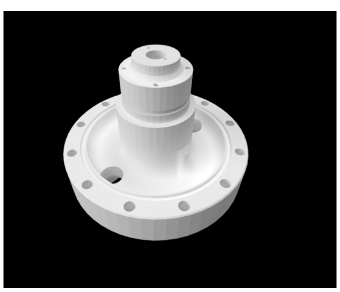
Solid vs. closed cell infill — Wash time has an exponential relationship with solid part thickness, which constrains the max part size. As a result, solid parts must be small or only have thin features. By using closed cell infill, you can print larger and thicker parts while maintaining manageable wash times.

EHS considerations — Debinding systems are fairly simple and safe to operate. They are typically connected to a house ventilation system. The key solvent, Opteon SF-79, is widely used in industry — though other solvents are also available. Exposure to users is limited well below OSHA recommended levels during machine operation; exposure in a typical operation is 40x below the recommended levels and more than 2x below during maximum exposure. Opteon SF-79 is also classified as a non-flammable liquid.

Solvent Bath vs. Furnace as a Primary Debinding Step

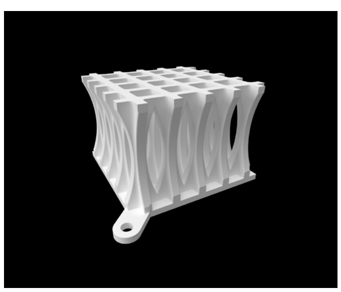
While it is possible to fully debind MIM parts in a sintering furnace, that approach brings several challenges. One impact of this approach is time. A sinter-based debinding process is 6 to 10 times slower than solvent-based debinding, according to Randall German, a leading expert on MIM-based debinding and sintering processes. In addition, a furnace-only debinding cycle increases in time exponentially as part size increases, severely impacting part-in-hand times.

Cycle Time for Different Parts



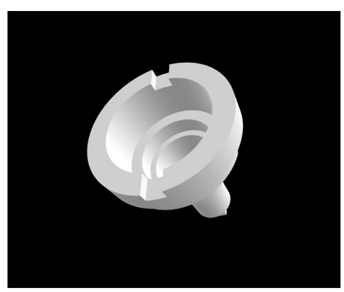
Injector Nozzle

Print Time	2d 15h
Wash Time	14h
Sinter Time	1d 6h
Final Part Mass	377g



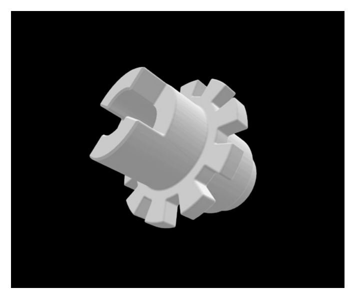
Heat Sink

Print Time	18h
Wash Time	12h
Sinter Time	1d 6h
Final Part Mass	207g



Chuck Prototype (Shukla)

Print Time	17h
Wash Time	12h
Sinter Time	17h
Final Part Mass	72.6g



Window Hardware Prototype

Print Time	4h
Wash Time	12h
Sinter Time	17h
Final Part Mass	13.5g

Metal FFF Sintering

In this section, we'll cover the critical final step of the metal FFF printing process: sintering.

Sintering involves removing the "brown" parts from the debinding step, burning out the remaining binder, and then sintering the part at a near melting temperature. All of this is done in a precise, controlled atmosphere. The automated process is extremely complex and requires precise control of a high energy environment.

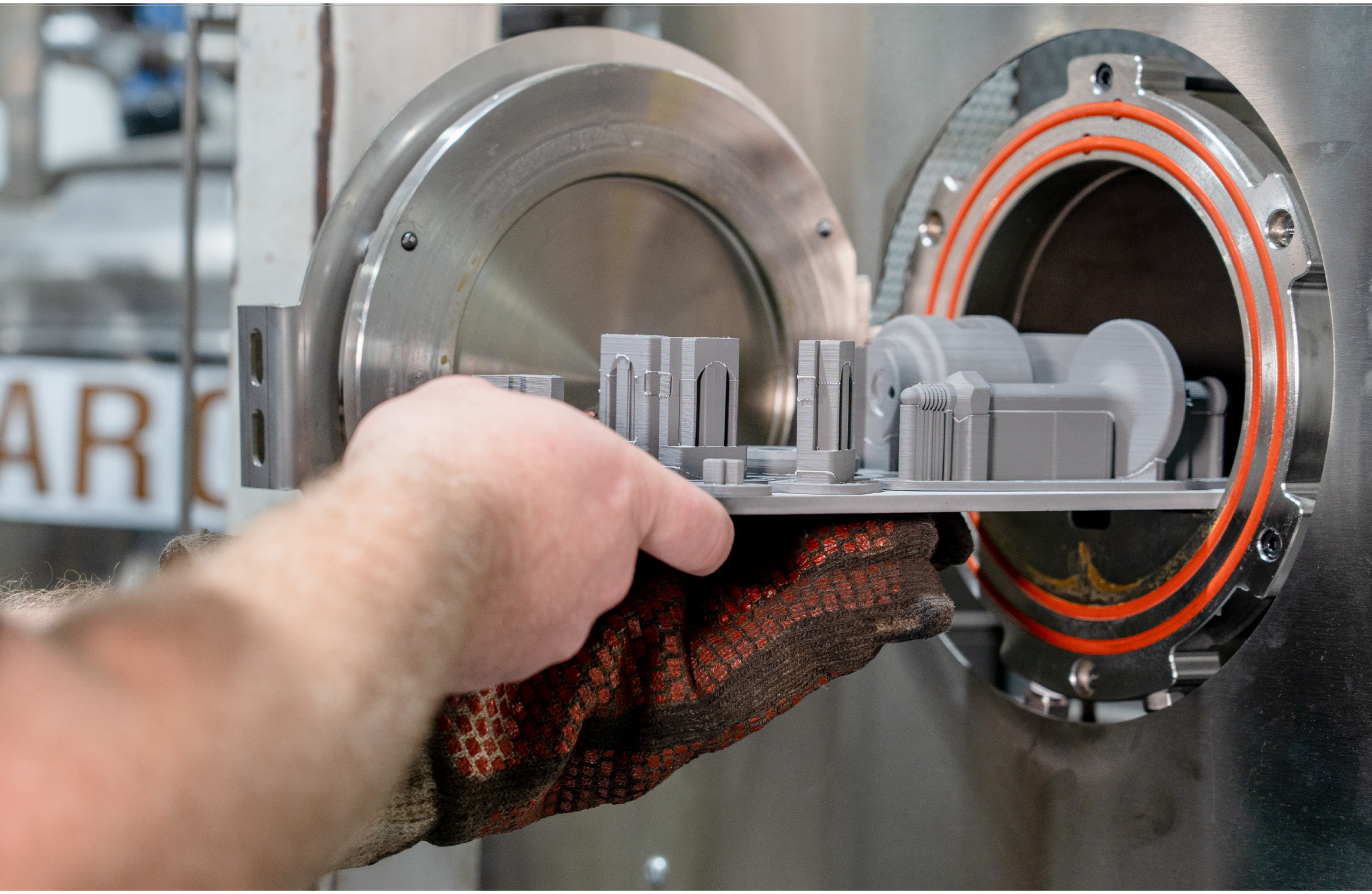
Using the Sintering Furnace

A user operating a sintering furnace follows these simple steps:

1. First adding parts to the setter plate
2. Placing the setter plate into the furnace
3. Closing the furnace door
4. Starting the sintering process
5. Running the process to completion

Markforged sintering furnaces typically complete a sintering cycle in 17 to 30 hours.

The sintering process involves several key stages. First, the part is heated to an intermediary temperature to burn out the remaining binding material — which exits the part through the micro-pathways created during the solvent debinding process. Second, the part is heated to the sintering temperature where it shrinks from the larger "green" or "brown" size to the final part size. Solid geometries coalesce to 95%+ porosity while the closed cell infill remains. The ceramic interface material turns to dust, which enables users to easily separate the part from the raft and supports.



Finished stainless steel parts are removed from the furnace.

Metal FFF Sintering Considerations

Metal FFF sintering furnaces are more complex than regular furnaces because MIM-based furnaces need to operate in inert environments at specific temperatures. This is because of the nature of the feedstock and how this specific sintering process works.

The difficulty and constraints scale exponentially with the size of the part. Larger parts should be designed for additive manufacturing.

Debinding and sintering require high levels of precision and control. Precise atmospheric composition and a carbon free retort prevents parts from being contaminated during the high-energy sintering cycle. Precise and predictable temperature control mitigates part deformation and cracking, and enables predictable part shrinkage.

Post-processing

After parts are sintered, they are fully metallic and can be post processed in whatever way a user sees fit. Common post processing processes are heat treatment, tumbling for surface finish, and machining.

EHS and Facility Considerations

Sintering furnaces are optimized for a shop or lab environment. They require a basic ventilation drop and three phase power. Consumable components are designed to be easily swapped. Metal FFF sintering furnaces use a combination of inert and mix gas, which can be sourced globally.

Markforged

Partner with Markforged, an innovator in metal 3D printing

Metal 3D printing is an ever expanding space with a wide range of solutions, capabilities, and maturities. Aligning where the technology is at right now with your needs can tell you how you should invest in the technology. It's important when deploying solutions that you partner with a technology vendor like Markforged who has the expertise and experience within metal 3D printing.

Markforged delivers this with Metal X, an accessible end-to-end metal 3D printing solution designed to yield functional metal parts. The Metal X is the most intuitive, simple to use metal 3D printer available today. Print a wide range of materials from stainless steels to copper with minimal training on a closed workflow. The Metal X is designed to be safe to use and accessible for all fabricators. It costs 5-10 times less than powder base metal 3D printing systems and requires no dedicated operator, no powder management system, and minimal PPE. Markforged combines best-in-class software, materials research, and an advanced motion system to deliver industrial-grade parts reliably.

markforged.com