

Metal 3D Printing Fundamentals



Primed for Takeoff

In recent years, metal 3D printing has risen to prominence as a fabrication method of the future. The technology has shown promise and generated hype — however, until recently it didn't provide enough value for most businesses to consider adopting. Today, metal 3D printing has become more accessible, scalable, and robust.

This white paper aims to separate truth from myth surrounding metal 3D printing, cover the different types of processes, how they work, benefits and considerations. Overall, you'll gain strategic and tactical insights on the benefits of adopting metal 3D printing.



3D printed Inconel 625 crucible clips from Nieka Systems.

Commonalities in Metal 3D Printing

Metal 3D printing technologies, while diverse in method and media, share two key commonalities: powder-based metal media and a high-energy event during the printing process. Let's examine some distinctions in each process.

Powder Metal Media

Most metal 3D printing media contain metal powder: either raw or as a base. While a few technologies utilize a metal wire feedstock, these are the exception, not the norm.

So, why do metal printers generally use powder? Additive manufacturing on a fundamental level involves the deposition of material in a precise manner. While plastic filaments can be easily heated and extruded through a nozzle, the high melting temperature of most metals makes extrusion infeasible. The equipment would be nearly impossible to manufacture, as there are few, if any, materials that could survive prolonged contact with molten metal. Some wire-fed metal printers rely on electric arc-welding to form parts, but the welding process produces crude surfaces that are only usable after machining. The large thermal gradients generated during the welding process also introduce high levels of internal stress, which results in severe warping.

Powder metal based processes, on the other hand, prevent key 3D printer components from ever interacting with molten metal. In some processes this works by having the 3D printer apply extremely localized energy with a laser — in other processes, the 3D printer itself uses a low energy process, and high energy sintering is done in furnaces after the fact.

Loose Powder vs. Bound Powder

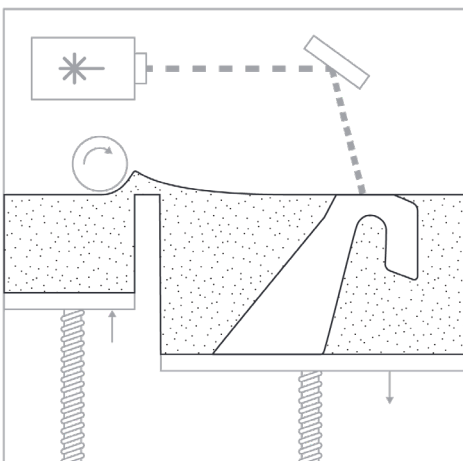
The use of loose powder is common among many metal 3D printers. However, these powders are hazardous materials that bring significant safety and handling concerns. Due to its high flammability and respiratory risk, it must be handled in controlled environments. Loose metal powder printers require special PPE and dedicated rooms that have closed ventilation and filtration. Another challenge is the swapping of materials, which requires hours of specialized labor.

Bound powder is a technology used by metal FFF. Bound powder is safer and less flammable than loose powder. Unlike loose powder, it doesn't require specialized PPE or dedicated rooms to deploy. Bound powder solutions necessitate extra steps in order to remove binding material and sinter the printing media into fully metal parts.

High Energy Event

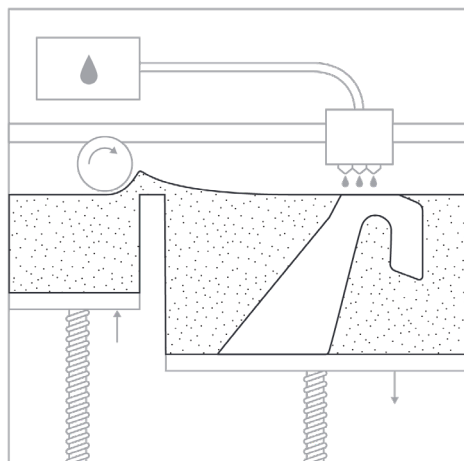
In order to additively manufacture parts, 3D printers need to alter the phase of the printing media at some point during the process. Plastics — which have relatively low melting temperatures between 200C and 400C — are far simpler to print compared to metals, which typically have melting points in the 1100 to 1400C range. These high melting points mean that any metal printing technology must include a high energy process at some point during manufacturing.

Loose Powder

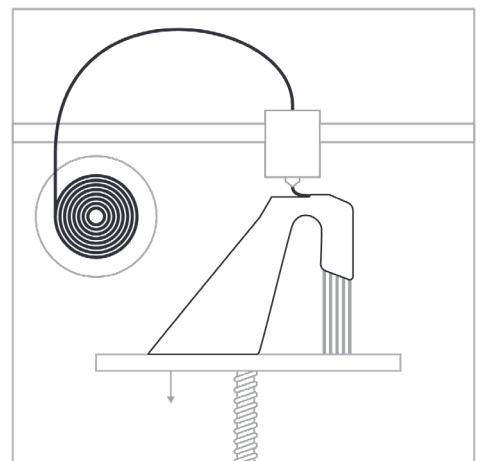


Powder Bed Fusion

Bound Powder



Binder Jetting



Metal FFF

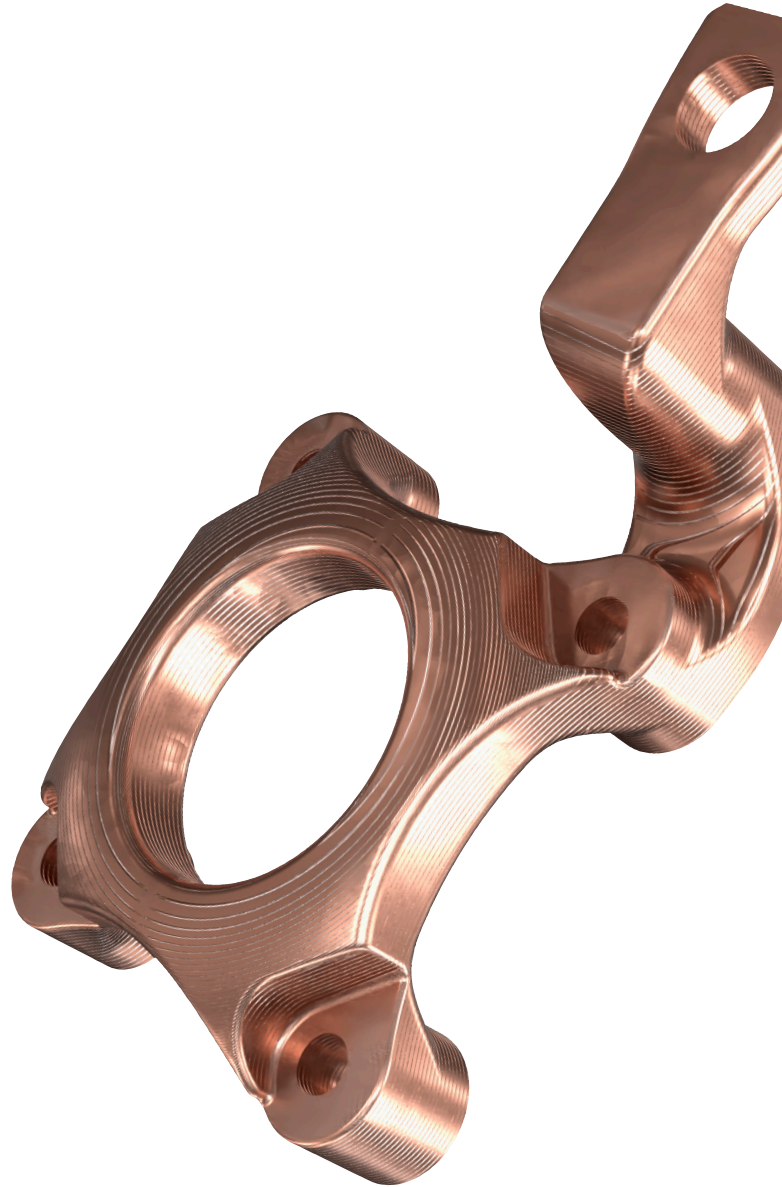
Sinter During Printing

Sinter After Printing

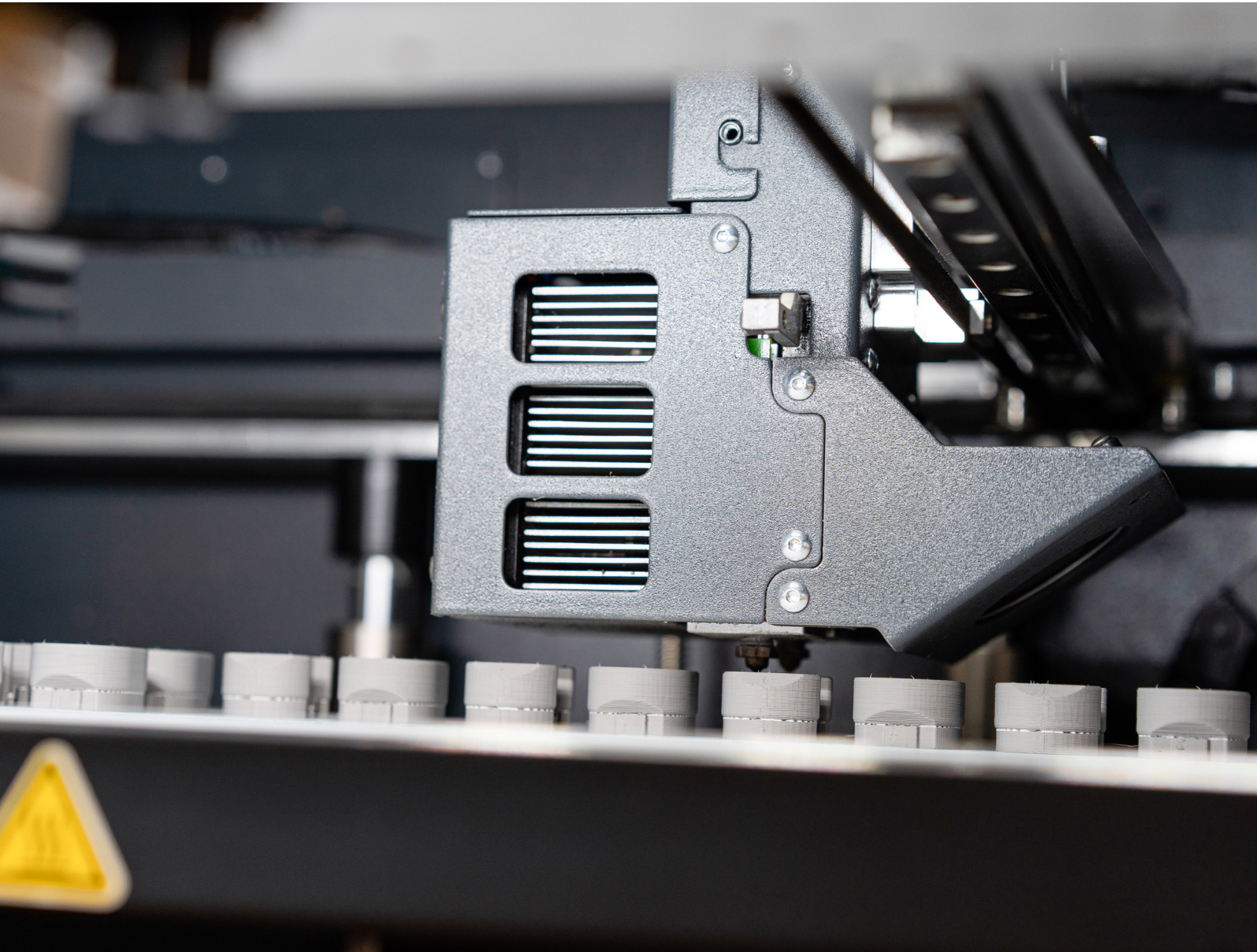
A high energy process is constant — however, you can sort metal 3D printing processes by when and how they apply it:

During printing, as a means to form the part: Some printing processes build parts by metallogically fusing them together, usually by means of a laser. These high energy processes that happen during printing are precise and isolated, with only the specific section of a part currently being printed subject to the process. As a result of this isolated high energy process, many parts incur internal stresses that must be thermally cured after printing.

After printing, as a means to metallogically fuse an already formed part: In other processes, the part is formed using a low energy process, then metallogically fused after printing using a high energy sintering furnace. This process works for both loose powder and bound powder based machines. Using a sintering furnace has advantages and disadvantages — parts sintered do not typically have internal stresses, but do require an additional step in the process.



Sintering transforms a lightly bound part into a full metal part. To do this, the temperature is ramped up slowly to burn away the trace amounts of remaining binding material. As the temperature ramps up closer to the melting point of the material, the metal particles fuse together to create a strong metal part.



A metal FFF machine printing a variety of window and door hardware prototypes.

Metal 3D Printing Processes

While there are a variety of specific metal 3D printing processes, we'll look at the three leading types: metal Fused Filament Fabrication (FFF), powder bed fusion, and binder jetting. We'll cover how each works, key considerations, where these technologies are at today, and long term views.

Metal FFF

Metal FFF, which is also known as Bound Powder Extrusion, represents the most accessible and safe metal 3D printing technology on the market today.

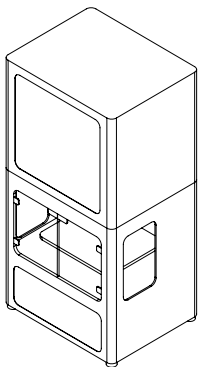
This process uses bound powder feedstock made from metal injection molding media (metal powder bound together in waxy polymers). Bound Powder Extrusion systems use a debinding system and a sintering furnace to turn printed parts fully into metal. Due to their accessibility, Bound Powder Extrusion machines are an ideal fit for a wide variety of manufacturing applications.

How Metal FFF Works

Metal FFF is a three-step process that uses bound powder and a post-printing, high energy process called sintering — which turns printed parts fully into metal. Due to their accessibility, Bound Powder Extrusion machines are an ideal fit for a wide variety of manufacturing applications.

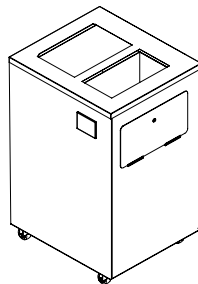


Heatsink 3D printed in pure Copper.



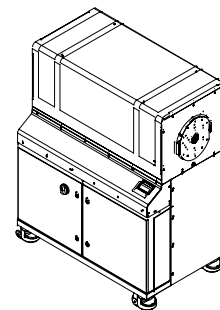
① Print

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.



② Wash

After printing, “green” parts are placed into the wash station, which uses a debinding fluid to dissolve most of the plastic binding material.



③ Sinter

Washed “brown” parts are placed in a furnace, where they are heated with a material-specific profile to burn away remaining binder and solidify metal powder.

Considerations

Metal FFF carries several design and operation considerations that should be considered when using the machine. First, metal FFF is not optimized for solid parts — typically, the machines print parts with closed cell infill. Solid parts can be printed, but increased solid part thickness exponentially impacts debinding time. Some metal FFF solutions forgo a solvent based debind and perform the entire debinding process in the sintering furnace. However, this approach adds time to the sintering process and limits the variety of parts that can be manufactured. Metal FFF typically creates near net shape parts that do not hit precision machining tolerances. Parts can be post-processed to hit tight tolerances if needed.

Differentiators

Metal FFF provides an array of benefits and advantages.

- + **Metal FFF 3D Printers are affordable**, requiring significantly lower investment to own and operate than other metal printers.
- + **Bound powder filament is relatively safe** — machines can be used effectively with minimal training and PPE.
- + **Machines have high first part yield** by using a bulk sintering process which introduces fewer internal stresses than selective sintering.
- + **Metal FFF offers wide material availability** with even broader future state compatibility; for example, the capability of printing pure exotic metals and alloys formulated for specific material properties are all candidates for this process, so long as they can be powderized.

Current Outlook

Metal FFF is rapidly maturing as machines become more capable and reliable. With new features continually expanding the application base, metal FFF is a manufacturing-ready technology that many industries are tapping into now.

Long Term View

As metal FFF continues to mature, more materials and capabilities will continue to diversify the applications the technology can be used for. Metal FFF printers will become a regular fixture in manufacturing facilities due to its affordability, accessibility, and versatility of manufacturing complex metal parts.



Powder Bed Fusion

Powder bed fusion is the most mature type of metal 3D printing and is the incumbent technology.

How Powder Bed Fusion Works

A laser mounted on a gantry traces the path of a given layer, precisely fusing the metal powder together.

1. A powder distribution system pushes a new layer of loose powder over the forming part.
2. The laser fuses the next layer, and the process repeats.
3. After printing, parts are depowdered and post processed as needed.

Considerations

While the technology has been around for 20+ years, powder bed fusion solutions remain expensive; for example, machines typically cost at least \$500K+ to acquire and install. Powder bed fusion requires a skilled operator to run, significant isolated space on a manufacturing floor, and expensive PPE/facilities modifications.

The powder bed fusion process is repeatable, but can be difficult to dial in — for more complex parts, many iterations are needed to get a successful and accurate print. The process yields internal stresses in parts, which can in turn lead to cracking and deformation. However, once design and printing parameters are dialed in, high-quality parts can be repeatedly printed.

Differentiators

Powder bed fusion can make parts that neither of the other two processes highlighted here can make; including ultra complex geometries, large parts, and large fully dense parts. Powder bed fusion is a mature technology, with massive material selection and several industry players offering a wide selection of machines.



Current Outlook

Powder bed fusion remains the market leader in the metal 3D printing industry. There are a small number of leading industry players with advanced capabilities, and a class of new entrants attempting to fulfill a specific niche or offer a more cost competitive solution. Industries known for ultra-specialized, high-performance applications have led the way in adopting powder bed fusion, including aerospace, automotive, and medical.

Long Term View

It is expected that broader adoption will drive even more innovative applications of powder bed fusion technology. As more industries start to leverage powder bed fusion, more distinct applications will emerge. Increased competition will help drive more accessible machines.

Binder Jetting

Binder jetting uses specialized liquid polymer binders to form parts by adhering loose metal powder together. This process creates lightly bound parts that can be sintered in batches. Binder jetting, which is an emerging technology, has great potential and is a developing technology to watch.

How it Works

Binder jetting uses a two-step process, featuring loose powder and post-print sintering.

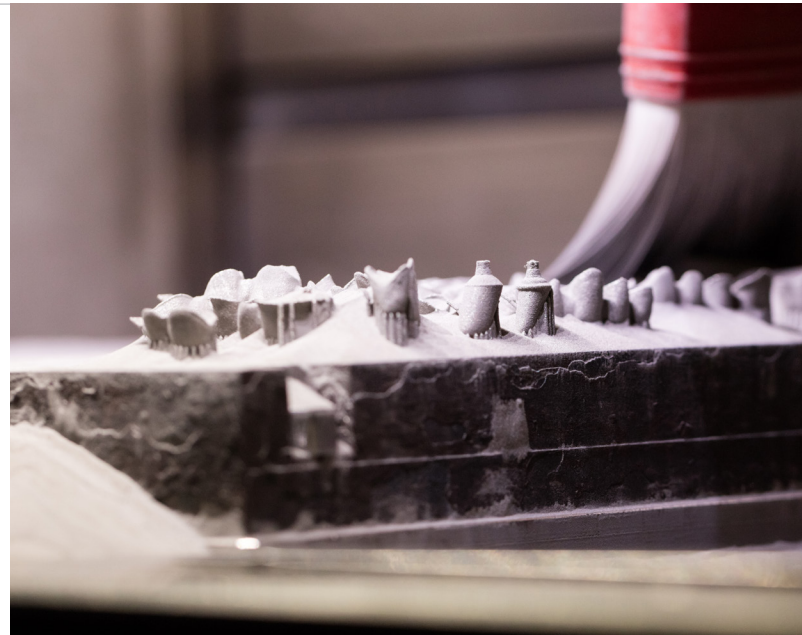
- + During the printing process, an inkjet-style print head precisely deposits a specialized binder on a bed of metal powder. After each layer is printed, the machine deposits more powder on top in a similar manner to powder bed fusion, repeating the print and spread process until parts are built.
- + The fragile parts are first carefully depowdered and then sintered, burning away the binder and fusing them together into fully metallic parts.

Considerations

While binder jetting machines can be cheaper than powder bed fusion machines, they still use loose powder and carry the same safety and handling concerns. In terms of pricing, minimum acquisition cost is at least \$300K and can go beyond \$2M.

Binder jetting carries a lot of promise, but there are several key considerations:

- 1. Part porosity/mechanical properties:** Parts coming out of the process need to have reliable and repeatable mechanical properties, which has not yet been proven on a broad scale.
- 2. Part size and design constraints:** Much is still unknown about the size and complexity of parts that binder jetting machines can effectively produce.



- 3. Durability of green parts:** After printing, parts are extremely fragile — it's unknown how that will affect throughput and part constraints.
- 4. Repeatability:** There is still a question whether these machines can repeatedly produce accurate parts.

Differentiators

Despite the considerations and unknowns, there are some advantages to adopting binder jetting technology. The printing process is extremely fast and can fabricate many parts simultaneously. As a result of these advantages, it's the most likely candidate for mass production in metal 3D printing. The process lends itself well to complex parts and intricate features because the inkjet heads that dispense binder are extremely precise.

Current Outlook

Binder jetting is still a developing technology with only a few manufacturers in the space. While these binder jetting manufactures are making significant investments in the technology, there are a small paucity of actual users in industry.

Long Term View

Some industry analysts predict that binder jetting might be the future of mass production when printing in metal. However, these projections depend on whether manufacturers find answers to the key technical questions facing the process. We will see some significant development in the next 3–5 years.



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.

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