METAL BINDER JETTING & METAL MATERIAL JETTING AS COMPLEMENTARY TECHNOLOGIES: A USER'S PERSPECTIVE

AZOTH INC.

January 2024

CONTENTS

ABOUT US

Azoth is a world-class, vertically integrated manufacturing company founded in 2018, and headquartered in Ann Arbor, Michigan. We specialize in manufacturing small and complex parts leveraging production-capable additive (3D) manufacturing technology. We offer over 45 different polymers and metals to ensure the right material, process and technology is used in every application.

Azoth's additive technology is a disruptive force in traditional manufacturing through its quick production lead times and **TOMO®** (Take One Make One). The TOMO process is designed to convert physical inventory to digital inventory eliminating supply chain disruptions, inventory obsolescence and saving its partners significant inventory costs and cash flow.

Not just another service bureau – **Azoth is your dedicated manufacturing partner**..

AZOTH INC.

1099 Highland Drive
Ann Arbor, Michigan 48108

Phone: 734-669-3797
Email: info@azoth3d.com

MADE IN U. S. A.

ABSTRACT

Metal Binder Jetting and Metal Material Jetting are two Additive Manufacturing techniques included under the Sinter Based Additive Manufacturing category.

In this work, Azoth, an independent part fabricator utilizing both technologies, presents how the two technologies complement each other from a capability, throughput, and operational point of view.

Azoth discusses unique insight into why customers and parts makers might choose one technology over the other. While many outsiders view the technologies as competing technologies, Azoth will explain their view of how the technologies co-exist and complement each other by addressing different markets and consumer demands.

A technical analysis of process differences and resulting benefits of each technology will be presented.

INTRODUCTION

Additive Manufacturing has revolutionized the manufacturing industry, providing a flexible and efficient way to produce complex parts with ease.

The development of additive manufacturing has led to the emergence of several diverse technologies that are being used to produce a wide range of components. Among these technologies, Metal Binder Jetting and Metal Material Jetting have recently gained interest for their promising results in the production of metal parts, especially due to their higher resolution and lower per-part cost with respect to established fusion-based Additive Manufacturing technologies, such as laser and electron beam powder bed fusion.

Metal Binder Jetting is a technology in its adolescents with many established users, with 485 systems installed worldwide as the end of 2022, although approximately a third of these are used for academia and or research purposes [1]. Outside equipment manufacturers, **Azoth was the first independent Metal Binder Jetting part fabricator in North America**.

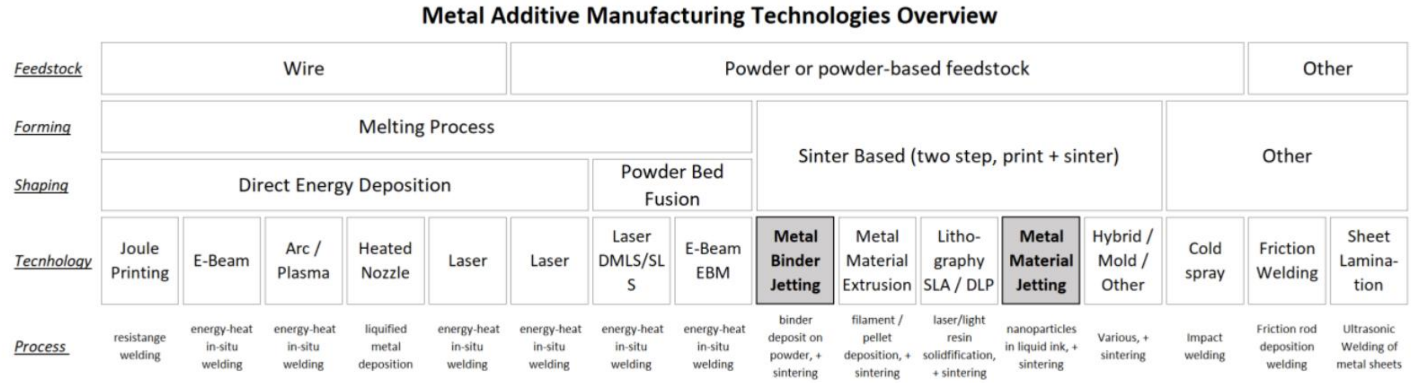
Meanwhile, Metal Material Jetting is a novel technology. A subset of the Metal Material Jetting technology used for specialized electronic printed circuit boards has been commercialized for a few years, as well as Ceramic Material Jetting, **however the only public installation of a machine for metal fabrication in the world is at Azoth**.

SINTER BASED ADDITIVE MANUFACTURING (SBAM)

Binder Jetting and Material Jetting processes are two of the seven Additive Manufacturing processes in the taxonomy defined by the ASTM F42 Standards [2]. Metal Binder Jetting and Metal Material Jetting are a specific subset of these that fit within the Metal Additive Manufacturing technologies, which also include many other technologies as summarized in the overview in Figure 1.

Considering the nature of the processes used, Metal Binder Jetting and Metal Material Jetting may better be considered within the emerging industry umbrella term, metal Sinter Based Additive Manufacturing (SBAM or M-SBAM). Diverse techniques contribute to the thriving metal sinter-based additive manufacturing field. Some are already commercialized and adopted as mainstream technologies in the industry, while others are being developed and not yet commercialized. Some that have been commercialized by machine manufacturers to date (May 2023) are Metal Binder Jetting (e.g. Markforged Digital Metal group, Desktop Metal ExOne group, Hewlett-Packard "HP", General Electric "GE", EasyMFG, B-Jetting, SinterJet, BlackGost3Dp), Metal Material Jetting (e.g. Xjet, Nanodimensions), Mold Slurry Deposition (e.g. Tritone), Hybrid Binder Jetting (e.g. 3DEO), Cold Selective Laser Sintering (e.g. Headmade Materials), Stereolithography and Digital Light Processing (e.g. Holo, Incus, Admatec, Tethon), Filament Fused Deposition Modeling (e.g. Desktop Metal, Markforged, Apium, Metallum3d, Triditive, Hage3d, Colido, Evotech, Rapidia, Xerion Berlin Laboratories, Ultimaker - BASF, Virtualfoundry), and Pellet Fused Deposition Modeling (e.g. Aim3, Dmepeire3d, Pollen). Other companies commercializing Sinter Based Additive Manufacturing are still in out of public view or precommercial, and many other sinter-based techniques or hybridization of techniques have been developed at academic level, for instance a hybrid process combining Direct Ink Write and Stereolithography [3].

What all these technologies have in common is the fact that the shaping of the products being manufactured is done via additive manufacturing, forming shape-defined powder agglomerates, that subsequently go through debind and sintering to form solid metal parts.



Metal Additive Manufacturing Technologies Overview

Feedstock	Wire					Powder or powder-based feedstock									Other	
Forming	Melting Process								Sinter Based (two step, print + sinter)					Other		
Shaping	Direct Energy Deposition						Powder Bed Fusion									
Tecnhology	Joule Printing	E-Beam	Arc / Plasma	Heated Nozzle	Laser	Laser	Laser DMLS/SLS	E-Beam EBM	**Metal Binder Jetting**	Metal Material Extrusion	Litho-graphy SLA / DLP	**Metal Material Jetting**	Hybrid / Mold / Other	Cold spray	Friction Welding	Sheet Lamina-tion
Process	resistange welding	energy-heat in-situ welding	energy-heat in-situ welding	liquified metal deposition	energy-heat in-situ welding	energy-heat in-situ welding	energy-heat in-situ welding	energy-heat in-situ welding	binder deposit on powder, + sintering	filament / pellet deposition, + sintering	laser/light resin solidification, + sintering	nanoparticles in liquid ink, + sintering	Various, + sintering	Impact welding	Friction rod deposition welding	Ultrasonic Welding of metal sheets

Figure 1 Simplified overview of Metal Additive Manufacturing Technologies categorized by feedstock.

MATERIAL AND METHODS

METAL BINDER JETTING ADDITIVE MANUFACTURING

Metal Binder Jetting Additive Manufacturing, also known as 3D printing, is a manufacturing method consisting of selectively joining powdered material together, layer by layer, to make objects from digital three-dimensional model data. The Metal Binder Jetting process is characterized by the absence of thermal energy in the shaping process. Indeed, it is a two-step process where the manufactured objects are printed and densified in separate steps. The printing step consists of high-precision inkjet printing of binder on a metal powder bed substrate. Metal powder is bonded together when the binder is jetted on the powder bed in a selective manner, corresponding to the cross-sectional shape of the objects being manufactured. In a cyclical way, the powder bed is lowered and recoated with additional loose powder on top to form the next layer, to which the binder is printed. This is done layer by layer until the whole build box is used and filled with metal powder. The printed objects are now located in three dimensions inside the build box, supported by loose metal powder. In this stage, the objects are in a "green state" (consolidated powder forms held together by binder, that have not yet been sintered for final strength). The green state objects are then cleared of the non-bonded powder surrounding them by vacuum and compressed air in a closed environment. After all of the loose powder is removed, the green state objects are placed on ceramic plates and densified in a following sintering step. In this step, the metal particles fuse together, shrinking the objects to the final size and giving them their strength, density, and material properties. After sintering, the objects can be subject to additional processes and heat treatments as per conventionally manufactured counterparts. A schematic of the Metal Binder Jetting process is shown in Figure 2.

Binder Jetting technology was initially developed at the Massachusetts Institute of Technology (MIT) and first filed for patent in 1989 by Emanuel Sachs, who developed the process using a gypsum-type powder and a glycerin/water binder deposited via thermal bubble inkjet printheads [4]. The technology was commercialized by Z Corp. and dubbed "3D printing" [5]. While initially used for prototyping in architecture and machine design, research in metal powder printing was also conducted. In 1996, the company Extrude Hone licensed the technology to start focusing on binder jetting of metals, from which in 2005 spun off the ExOne Company, now part of Desktop Metal, focusing on binder jetting infiltrated metals, sands, and later, single alloy metals. Meanwhile, Metal Binder Jetting, as it is known today, was also being developed by Swerea, a subsidiary of the Research Institutes of Sweden (RISE), and subsequently commercialized in 2003 by Fcubic, which was later incorporated in Digital Metal now Markforged.[6].

Although Metal Binder Jetting may seem a veteran technology, it was only in the last decade that it gained industry interest, with most known commercial players entering the market only in the past five years. Industry adoption is still somewhat limited to non-critical applications, and some identify a lack of research and published work regarding the properties of binder jetted parts. Because binder jetting of metallic components has its origins in metal powder technology, sintering, and prototyping, published works have mainly presented microstructure and density studies rather than characterization of properties such as mechanical, thermal, and magnetic behavior [7, 8].

Compared with other Additive Manufacturing methods, Metal Binder Jetting is developing quickly. The transition from prototype to production technology happened in short timespans in non-critical industries. Although large-scale industry adoption is only recently growing, the utility of Metal Binder Jetting technology is becoming clear. Since shape forming, or 3D printing, and sintering, are separate, Metal Binder Jetting Additive Manufacturing allows for a wide range of materials, where the process can be optimized for each material selected. Virtually, all materials that can be sintered can be processed via Metal Binder Jetting Additive Manufacturing if they are available in powder form with properties within the limits suitable for the printing process. Powder characteristics such as particle size, powder morphology, density, and flowability affect the printing process, therefore limiting the range of powders that can be processed.

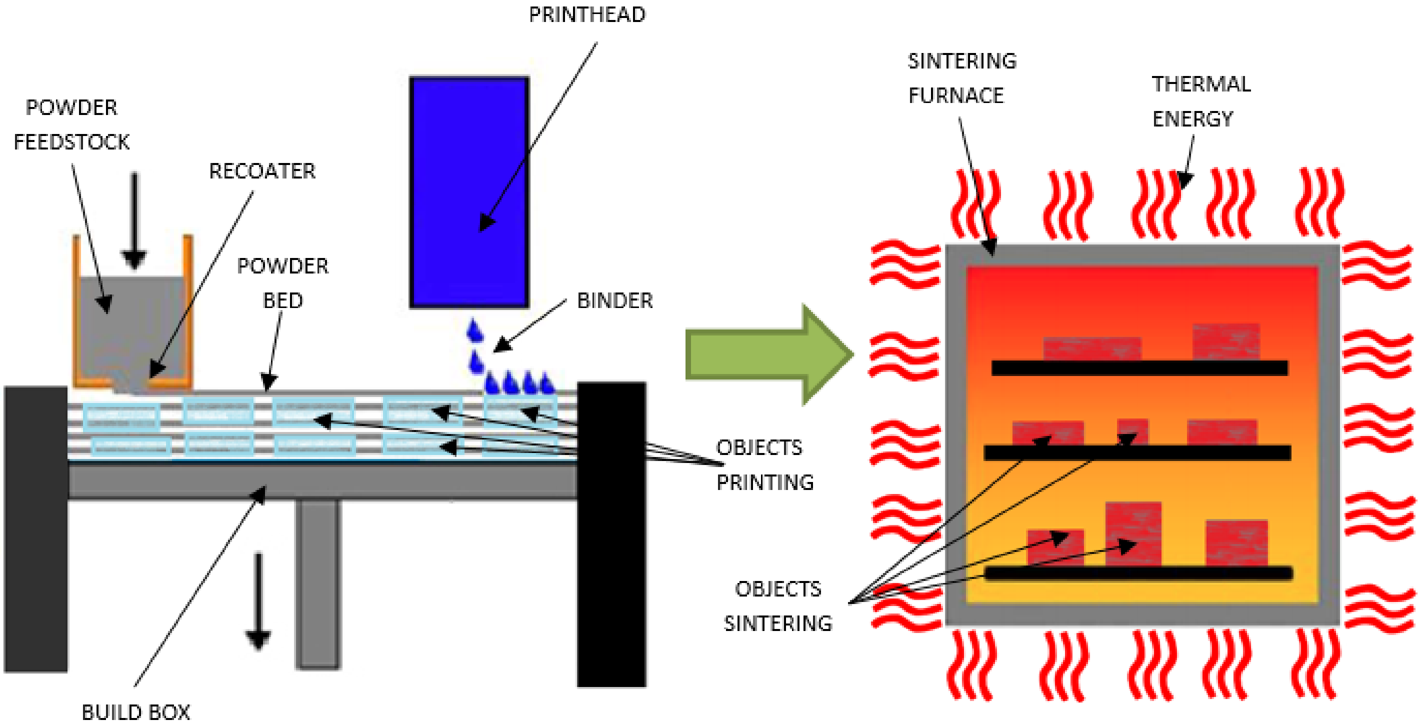


Figure 2 Schematic of Metal Binder Jetting Additive Manufacturing process, consisting of 3D printing at room temperature followed by sintering.

METAL MATERIAL JETTING ADDITIVE MANUFACTURING

Metal Material Jetting, also known as direct metal inkjet printing, or by the Xjet's trademarked name, Nanoparticle Jetting, is a novel direct inkjet printing process for selectively and successively depositing metal nanoparticles in a three-dimensional space. Specifically, Metal Material Jetting is a solution-based deposition sub-category of material jetting, where a small solid substance is contained inside of a liquid that acts as a carrier solution. This approach allows for solid particles to be used for ink jetting, while at the same time maintaining the overall fluid within the required viscosity limitations to ensure a functional process. While several parameters must be accounted for during this process, the viscosity of the printed fluid is crucial. Two of the primary challenges in using this technique are the inability to precisely control the deposition pattern of the material since it is held inside a carrier solution, and the formation of precipitates leading to nozzle clogging [9]. Although material jetting of liquid resins has been commercialized for over three decades, solid dispersion solution-based metal material jetting just gained marginal interest in commercialization in the last decade [10]. The authors consider the slow market adoption a consequence of the process complexity and physics limiting the stabilization of the process, especially the challenges resulting from the formation of precipitates leading to nozzle clogging. The challenges related to metal material jetting have first been resolved by Xjet (Revoth, Israel) and others for niche purpose-specific applications for manufacturing of devices using conductive ink suspensions, such as solar panel manufacturing [11]. However, such technology was limited to 2.5-dimensional printing and gained commercialization only in electronics prototyping and circuit board manufacturing [12]. The 3-dimensional material jetting process was first commercialized by Xjet utilizing ceramic materials, known as ceramic material jetting [13]. Metal Material Jetting has only recently become viable and commercialized by Xjet (Revoth, Israel) with the first machine installation in 2022 at Azoth (Ann Arbor, MI, United States).

Metal Material Jetting is a two-step process where the manufactured objects are printed and densified in separate steps. While printing, droplets of two liquid suspensions are jetted from separate printheads: metal nanoparticles dispersed and encased in a solvent referred as model ink, and a proprietary soluble solid dispersion referred as support ink. The printheads move transversally over the print tray and inkjet material concurrently but selectively in a fashion like multi-color inkjet paper printers. The dual-material approach allows for precise control of the jetted area perimeter, preventing the metal ink from flowing outside of the dimensional bounds via a retaining boundary formed with the support ink, which effectively creates a mini-vat around the layered section of the object being printed. Interestingly, in the support regions, both support material and build material are used, forming a network of build material separated from the part, which serves the purpose of reinforcing the structure of the support material in what is referred to as the digital support technique. When the droplets contact the hot surface, the carrier-liquid begins to evaporate leaving behind the particles, which are covered with a thin coating of bonding agent. Then, a 180C high-temperature atmosphere, produced by a mounted heating lamp containing halogen bulbs and the hot building tray (the base substrate on which the dual-material is jetted), causes the deposited liquid to evaporate and the dissolved polymer to crosslink forming a binder. Once the carrier-liquid is fully evaporated the remaining particles are able to bond to one another, leaving fine layers of metal nanoparticles agglomerated material. Finally, a roller travels over the newly printed layer in order to precisely mill at a consistent layer height. From this point the print plate indexes vertically a prescribed distance in preparation for the next layer to be printed. The process repeats layer by layer as typical fashion of most 3D printing processes [14, 15].

The printed objects are now located in three dimensions inside the build box, supported by solidified support ink. In this stage, the objects are in a green state (consolidated powder forms held together by binder, have not yet been sintered for final strength). The build plate is then removed from the printer and submerged through multiple citric acid solutions that dissolve the support material and release the green parts from the build tray. Finally, the green parts go through multiple water rinsing baths to complete the dissolution of the citric acid. The green objects are then placed on ceramic plates and densified in a following sintering step. In this step, the metal particles fuse together, shrinking the objects to the final size and giving them their strength, density, and material properties. After sintering, the objects can be subject to additional processes and heat treatments as per conventionally manufactured counterparts. A schematic of the Metal Material Jetting Process is shown in Figure 3.

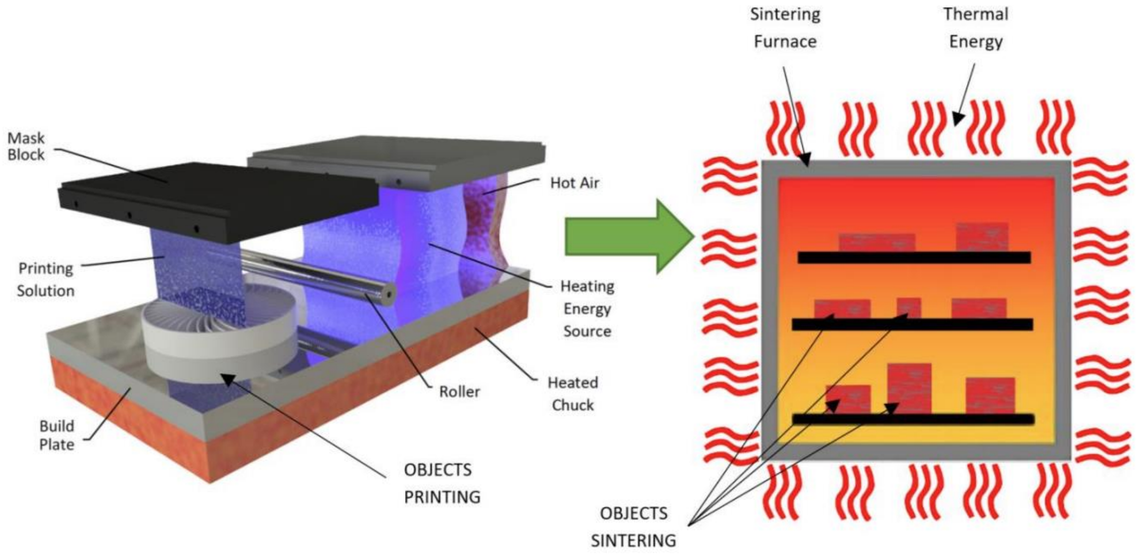


Figure 3 Schematic of Metal Material Jetting Additive Manufacturing process, consisting of 3D printing.

ANALYSIS AND RESULTS

Regarding Metal Binder Jetting, work has been conducted both at academic and commercial level in the field of process analysis and results investigation, and there has been exponential growth in the number of independent papers published in recent years. In comparison, the work around Metal Material Jetting has been limited to a small niche of individuals, mostly enclosed within the primary research and development centers at machine manufactures. To the authors' knowledge, user-based or application-based publications about the Metal Material Jetting process are yet to be released.

Rather than focusing on an individual results analysis, the intent of the authors is to explain the viewpoint of how the Metal Binder Jetting and Metal Material Jetting technologies co-exist and can complement each other by addressing different markets and consumer demands. A technical analysis of process differences, and resulting benefits, is presented in the three areas that may be considered most critical to users: materials and properties, process operations, parts capability and throughput.

MATERIALS AND PROPERTIES

The main difference between Metal Binder Jetting and Metal Material Jetting is the raw material used in the process. Metal Binder Jetting uses powder, either unimodal or multimodal, with a typical particle size distribution size D50 of ~15um, while Metal Material Jetting uses nanoparticles with a typical particle distribution size D50 of ~ 0.75um (hence the name Nanoparticle Jetting). The powder particle size is approximately 20 times smaller for Metal Material Jetting (0.75um vs 15um), as shown in the scaled representation in figure 4.

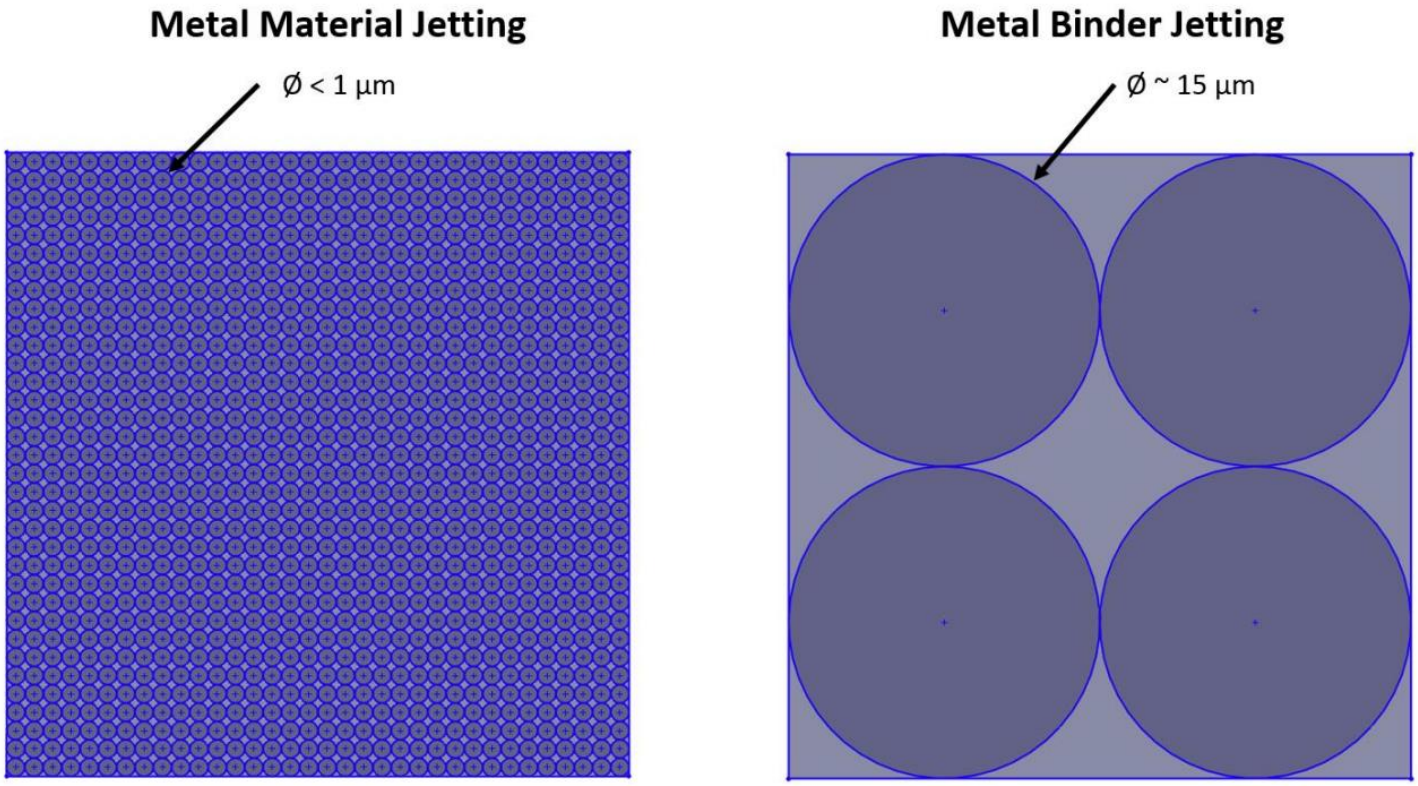
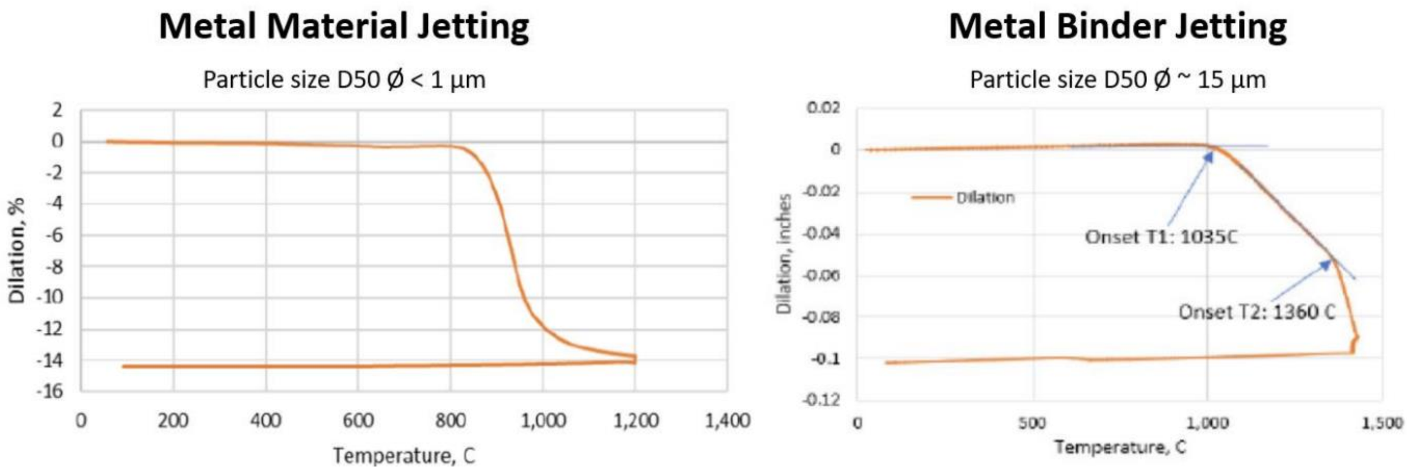


Figure 4 Scaled representation of particle size difference in volume for Metal Material Jetting (Left) and Metal Binder Jetting (Right).

The key advantage is that for the same part volume, there will be many more Metal Material Jetting particles thus exponentially increasing the total surface area. This is a key advantage for sintering, since surface energy is the main driver combined with heat [16]. In practice, this means that Metal Material Jetting materials can sinter at relatively low temperatures in order to achieve high densities, as demonstrated in the Differential Thermal Analysis conducted on Metal Material Jetting 316-L stainless steel feedstock and an equivalent Metal Binder Jetting 316-L feedstock shown in Figure 5.



Metal Material Jetting

Particle size D50 Ø < 1 µm

Metal Binder Jetting

Particle size D50 Ø ~ 15 µm

Figure 5 Dilatometry of typical Metal Material Jetting (left) and Metal Binder Jetting (right) [17].

High density with minimal distortion can be achieved thanks to the lower sintering temperature, which is likely the greatest advantage of Metal Material Jetting compared to Metal Binder Jetting and other sintering-based technologies.

However, sintering of smaller particles comes with its own challenges. The binder escape network between particles is extremely dense, making the debinding process challenging and therefore limiting the geometric capability only to thin cross sections (approximately up to 3mm), while in Metal Binder Jetting parts with much larger cross sections (above 30mm) can be processed. Work is in progress to optimize the debinding process of Metal Material Jetting components to increase thickness capabilities.

Moreover, the raw material for Metal Material Jetting is still restricted to a very limited supply chain, since nanoparticles are produced from a cut of larger powder batches and require specialized equipment. Also, the process of feedstock preparation requires creating a stable and tightly controlled ink: a dispersion with narrowly controlled amounts of binder, solvent, powder, and additives. Although the process is like paint fabrication, the exact working composition and feedstock preparation parameters have been identified only by equipment manufacturers. In comparison, Metal Binder Jetting can utilize common metal injection molding powder and many Metal Binder Jetting systems are open source. Although the relatively open-source nature of Metal Binder Jetting, machine manufacturers provide qualified materials that have a working advantage since they are tailored to their process and machine hardware. Launching new non-qualified materials is very challenging due to the tight working window of the printing process, but possible.

Finally, a major difference is in the resultant material properties after sintering. While Metal Binder Jetting is typically in line with typical material proprieties for powder metallurgy alloys, the same alloy manufactured via Metal Material Jetting offers noticeably higher strength but slightly lower elongation at break, as summarized in Table 1. To simplify the metallurgy behind this, it can be said that the Metal Material Jetting microstructure is made up of extremely small grains, thus a significant strengthening mechanism is driven by the higher amount of grain boundaries and lower amount of grain deformation since the grains are so small. Moreover, the retained porosity in Metal Material Jetting is composed of much smaller pores compared to Metal Binder Jetting, as shown in Figure 6, thus having a lesser decremental impact on material properties. This is an added beneficial characteristic of this manufacturing technology.

The range of materials commercially utilized in Metal Binder Jetting includes stainless steels, low-alloy steels, tool steels, as well as copper, nickel-based and cobalt-based superalloys, precious metals, and more. Meanwhile, Metal Material Jetting is currently limited to 316-L stainless steel. The authors expect material offerings for both technologies to expand significantly in the upcoming years.

Table 1 Comparison of typical properties mechanical properties: both materials have the same chemical composition, and properties in accordance with applicable industry standards.

Typical Material Properties of sintered 316-L	Metal Binder Jetting	Metal Material Jetting
Ultimate strength	520 Mpa	600 Mpa
Yield strength (0.2%)	175 Mpa	265 Mpa
Hardness	55 HRB	85 HRB
Elongation	50%	42%

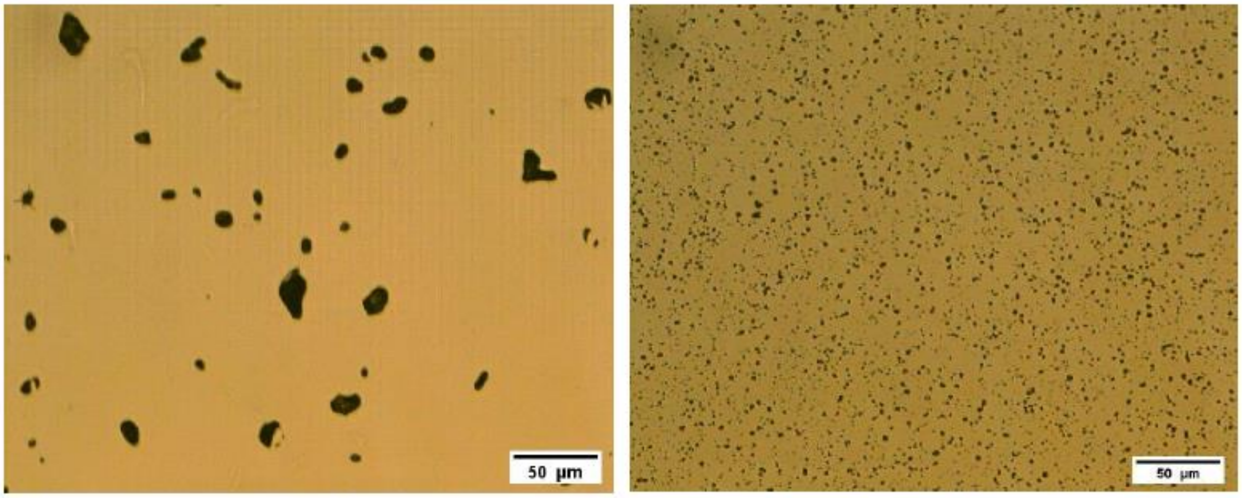


Figure 6 Comparison of unetched microstructure of Metal Binder Jetting (left) and Metal Material Jetting (right). Note pores (black areas) are smaller for Metal Material Jetting than Metal Binder Jetting, but the microstructure of Metal Material Jetting presents.

PROCESS OPERATIONS

Although Metal Binder Jetting and Metal Material Jetting are both Sinter-Based Additive Manufacturing technologies, the operational process is different and distinguished.

To start, the machine architecture is very different. Industrial Metal Binder Jetting machines are composed of two main systems, a powder delivery system, and an ink delivery system. The powder delivery system is the most critical system, of which designs vary greatly between equipment manufacturers. The powder delivery system is the subject of extensive and active research in industry, with unsettled discussions regarding what may be the prevailing design. The binder delivery and printing system is relatively less unique, as much of the hardware designs are a transfer from decades old paper printing equipment technology. Additional systems typically include a printhead washing and purging station, atmosphere control mechanisms, and an extraction system to handle airborne powder and other potential contaminants. In conclusion, the software behind the machines and the fine-tuning of each parameter is the main differentiator between different brands of additive manufacturing machines. The machines are built to handle free powder, and as such the hardware is built to resist interaction with powder. While using the machine, the operator does interact directly with metal powder, however the exposure to airborne powder is minimal.

On the other hand, Metal Material Jetting machines are complex systems formed by an array of sub-systems whose main goal is to keep the ink in circulation all the time, including through the printheads. Since the ink is a solid dispersion that would separate and sediment if let settled, it must be always kept in circulation. This means that continuous mixing, purge, and recapture systems must be employed throughout the whole system. Moreover, since the build material and support material are separate, the systems are basically duplicated twice within the machine. Secondary systems include heat generation systems, atmospheric extraction systems, a layer milling system, a printhead wiping system, printhead parking and maintenance system, a purging system, and others. A characteristic of Metal Material Jetting machines is that there is no interaction with powder, but rather interaction with an ink feedstock with handling like paint handling operations.

In terms of machine operability, the software is the main differentiation between machines together with the amount and ease of machine access granted to the user.

From an operational standpoint, the main difference between Metal Binder Jetting and Metal Material Jetting is not in printing, but in the process steps that lay in between printing and sintering, informally referred to as "decaking". In Metal Binder Jetting printed components lay inside a powder box from which they must be extracted, and all the powder in excess must be blown away from the printed part. This process, referred to as depowdering, pictured in Figure 7, is very simple but it is currently a manual and very labor consuming process. Advancements have recently been made in industry towards automated depowering, and the authors expect fully automated systems to be released in the next year [18].

In Metal Material Jetting, since parts and support material are printed from different materials, the depowering process is replaced by a step referred to as support removal, pictured in Figure 8. Support removal is a semi-automated process involving the dissolution and washout of support material via a multi-step acid-water solution and water rinse. Although the process is hands off in-theory, in practice, this process is not yet optimized. The build material dissolved from the support areas, referred to as digital support, releases and mixes with the acid-water solution. Care must be taken to prevent such material from depositing on the surface of the printed green parts while they are all immersed in the acid-water solution. Often, residuals of free-floating build material deposit on the surface of the green parts, ultimately requiring manual intervention for cleanout of the parts utilizing manual tools such as water jets and brushes. Improvements in the support removal and washout process are being investigated.

Commonly for both Metal Binder Jetting and Metal Material Jetting technologies, the following debinding and sintering steps transform powder agglomerates in the actual metal parts, fusing the particles together as the parts shrink, eliminating the voids between particles, and providing the density and material properties of the final metal object. The thermal debinding process is critical to remove the binder and provide uncontaminated chemistry to the alloy being sintered, however Metal Material Jetting requires significantly longer debind time. Moreover, the Metal Material Jetting products have significantly more total surface and have many more surface oxides shelling every particle, thus requiring longer processing in reducing atmosphere prior to final sintering to reduce the oxides.

Figure 7 "Depowdering" process of Metal Binder Jetting (a.k.a. "Decaking"). Process consists of removing excess powder manually with the assistance of compressed air.

Figure 8 "Support Removal" process of Metal Material Jetting (a.k.a. "Decaking"). Process consists of dissolving the support material by immersion of the entire build in citric acidic solution, and then manually rinsing the parts in water.

PARTS CAPABILITY AND THROUGHPUT

The given physics of the printing process drives part capability and throughput. Metal Binder Jetting runs at a typical layer height between 42um and 75um, while Metal Material Jetting runs at a typical layer height of between 7um and 12um. The build area size is comparable between typical industrial commercial Metal Binder Jetting machines and Metal Material Jetting machines. Printing speed, in terms of volumetric throughput, is very different, as shown in the calculations in Formula 1.

Equation 1 Nominal volumetric throughput calculation, where MMJ = Metal Material Jetting, MBJ = Metal Binder Jetting

$$Total\ material\ throughput = print\ area\ x\ layer\ height\ x\ print\ speed$$
$$MMJ\ to\ MBJ\ print\ area\ ratio = 1:1$$
$$MMJ\ to\ MBJ\ layer\ height\ ratio = 1:5$$
$$MMJ\ to\ MBJ\ print\ speed\ ratio = 1:1.5$$
$$MMJ\ to\ MBJ\ throughput = (1x1x1):(1x5x1.5) = 1:7.5$$

It results that Metal Binder Jetting provides 7.5 higher volumetric throughput in terms of total printed material. However, total printed material is not the only metric that matters and should be considered in relation to the parts that are printed.

In terms of capability "you can print anything, but you cannot sinter everything": limitations are imposed by both Metal Binder Jetting and Metal Material Jetting systems. As today, the Metal Binder Jetting is best suited for parts under 75 mm in the longest direction and cross sections of less than 25mm. In comparison, Metal Material Jetting is best suited for parts with less than 20mm height and cross section of less than 3 mm. A comparison of typical key characteristics is shown in Table 2. Both technologies can print complex shapes, but they may struggle with long enclosed channels, and part designs must be evaluated individually. Generally, Metal Material Jetting is capable of smaller parts with smaller features and higher accuracy, and can provide smoother surfaces, as shown in Figure 9.

Machine specifications alone, for example print resolution, measured as the quantity of single jets per area unit commonly as dots-per-inch (DPI), although important are not highly relevant comparative measurements of the results output of the technologies [19]. Ultimately, the final parts quality and capability are driven by the individual machine hardware-software combination and by the individual user capability of tuning in process parameters for optimal results. A comparison of

Table 2 Typical key characteristics of Metal Binder Jetting and Metal Material Jetting.

Design Specification metric	Metal Binder Jetting	Metal Material Jetting
Component size, typical minimum (mm)	3	1
Component size, typical maximum (mm)	75	20
Unsupported feature thickness to size ratio	1:5	1:10
Minimum feature size (mm)	0.200	0.075
Layer height (um)	42-75	7-12
Tolerance at best	+/-0.75%	+/-0.50%
Tolerance typical	+/-1.5%	+/- 0.75%
Surface roughness (µm)	6	3

Figure 9 Typical feature resolution comparison between Metal Binder Jetting (left) and Metal Material Jetting (right).

DISCUSSION

In evaluating the benefits of Metal Material Jetting and Metal Binder Jetting technologies, both offer distinct advantages depending on the specific application and desired outcomes.

A key characteristic of Metal Material Jetting is that it has the lowest sintering temperature and produces high-density parts with minimal distortion, making it an ideal choice for intricate designs and complex geometries. Additionally, the use of ink-type feedstock material and soluble support simplifies the labor involved in the printing process, since there is no requirement of handling powder nor manual depowering. This technology also allows for the thinnest layers, which contributes to refined detail, fine feature resolution, and smooth surfaces in the final product. Some example applications are shown in Figure 10.

On the other hand, Metal Binder Jetting technology offers significant advantages in terms of speed and process throughput, making it an excellent choice for low and medium scale production. The existing powder supply from metal injection molding also offers a wide variety of materials to work with, increasing the versatility of the technology. Moreover, Metal Binder Jetting is a well-established technology with a large market offering, making it a trusted and reliable choice for many applications, some of which are shown in Figure 11.

Looking at the future, at academic level hybrid approaches between Metal Material Jetting and Metal Binder Jetting have been explored but aren't yet commercialized. [20]. To date, it could be argued that both Metal Binder Jetting and Metal Material jetting are still "2.5D printing" technologies since the material properties are equal between all printed layers across the whole part. True 3D printing, with material changing across the part, has been explored in both technologies, for example with material with varying controlled porosity across the part. [21]. Metal Material Jetting has a theoretical advantage, as different printheads could be used alternatively in varying rations to create an alloy of varying composition while printing. The outlook would be towards potential space applications, electronics, and tooling. For example, a tungsten-carbide-cobalt mill could be produced with gradually changing elemental concertation to purposely control hardness, ductility, and toughness selectively changing across the part.

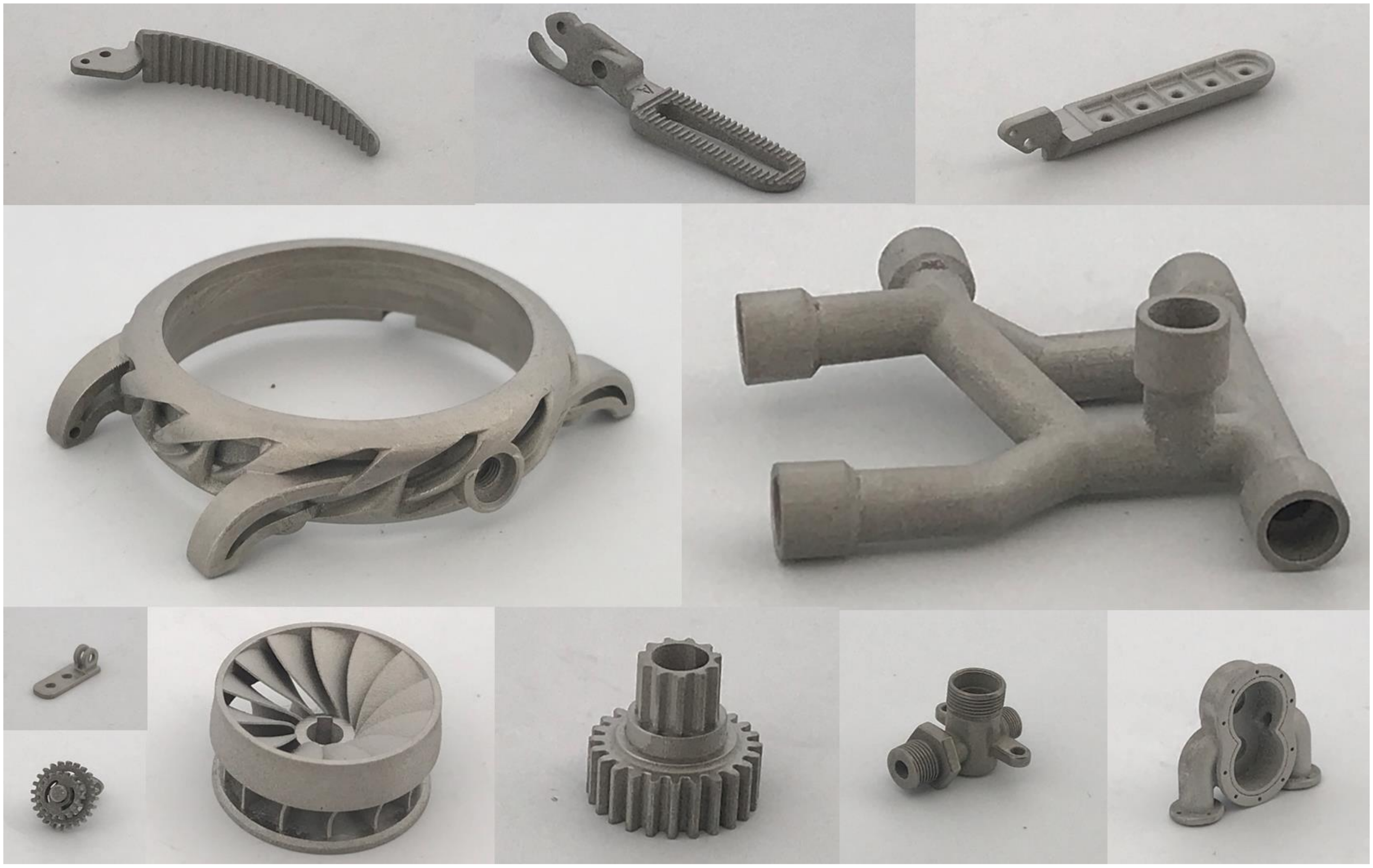


Figure 10 Metal Material Jetting example applications.

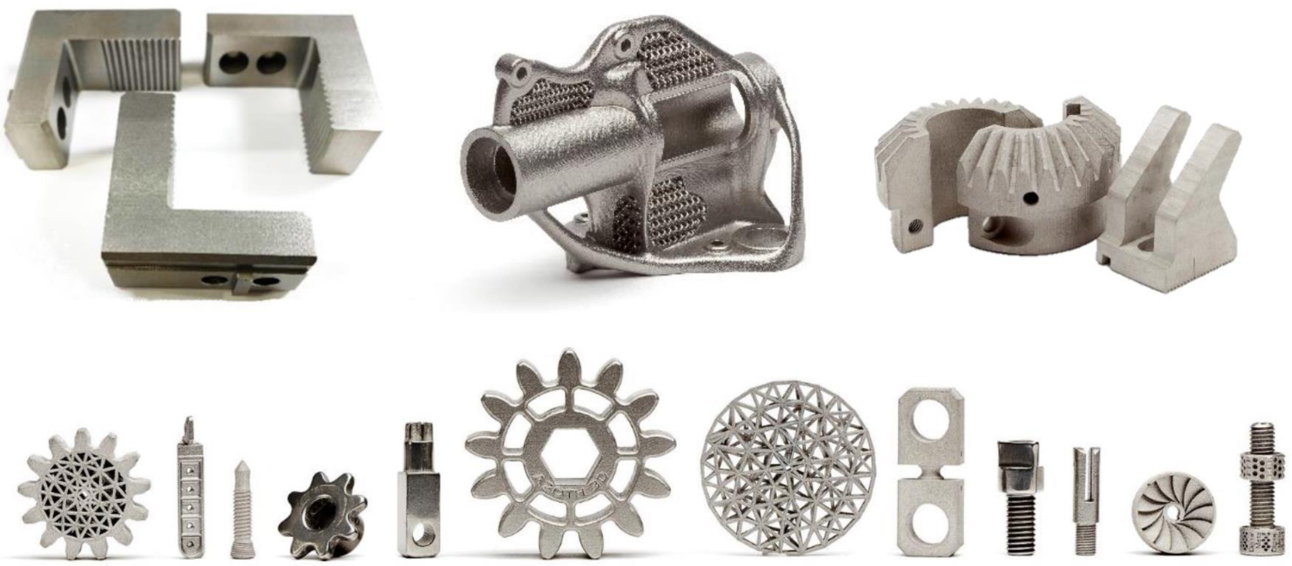


Figure 11 Metal Binder Jetting example parts applications.

CONCLUSION

Both Metal Binder Jetting and Metal Material Jetting offer a range of benefits and fit different applications and needs. They are complementary technologies, and the choice between them mainly depends on the specific requirements of the user application. Metal Material Jetting, with its fine details and smooth surfaces capabilities, is ideal for smaller and more intricate parts. Metal Binder Jetting, with its high-speed printing and existing powder supply, is well-suited for production products.

As such, continued research and development in these technologies will be instrumental in expanding their potential applications and unlocking new possibilities for metal additive manufacturing.

From a user perspective, Metal Binder Jetting and Metal Material Jetting technologies fit different applications and needs, they are complementary technologies.

ACKNOWLEDGMENTS

The authors acknowledge Fredrik Berg Lissel and his team at Digital Metal - Markforged (Höganäs, Sweden) for the continuous collaborative work, specifically in Metal Binder Jetting.

The authors acknowledge Jonah Myerberg and his team at Desktop Metal (Burlington, MA, United States) for the continuous collaborative work, specifically in Metal Binder Jetting.

The authors acknowledge Ron Fermon and his team at Xjet (Rehovot, Israel) for the continuous collaborative work, specifically in Metal Material Jetting.

The authors acknowledge Bryan Sherman and his team at DSH Technologies - Elnik (Cedar Grove, New Jersey, United States) for the continuous collaborative work, specifically in debinding and sintering.

The authors acknowledge their respective company - Azoth Inc - for enabling this work.

REFERENCES

1 Matthias Schmidt-Lehr, Bastian Barthel "AMPOWER Report 2023", AM Power, 2023.

2 American Society for Testing and Materials Committee F42, "ASTM F2792 – 12a. Standard Terminology for Additive Manufacturing Technologies", ASTM International, West Conshohocken, PA, 2012

3 D. A. Rau, M. Forgiarini, C. B. Williams, Christopher "Hybridizing Direct Ink Write and mask-projection Vat Photopolymerization to enable additive manufacturing of high viscosity photopolymer resins", Additive Manufacturing Vol. 42-2021, ISSN 2214-8604, Elsevier, 2021

4 M. Sachs, J. S. Haggert, M.J. Cima, P. A. Williams, "Three-Dimensional Printing Techniques", US Patent No. 5,204,055 A; 1989.

5 I. Gibson, D. Rosen, B. Stucker. "Additive manufacturing technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing". 2nd ed. ISBN : 978-1-4939-2112-6, New York, Springer; 2015

6 Urban Harryson, " Method and apparatus for producing free-form products", US Patent No. 20030133822A1 ; 2022

7 Amir Mostafaei, Amy M. Elliott, John E. Barnes, Fangzhou Li, Wenda Tan, Corson L. Cramer, Peeyush Nandwana, Markus Chmielus, "Binder jet 3D printing - Process parameters, materials, properties, modeling, and challenges", Progress in Materials Science, Vol. 119-2021, 100707, ISSN 0079-6425; 2021

8 E. M. Sachs, et al. "Three-Dimensional Printing: The Physics and Implications of Additive Manufacturing." Cirp Annals - manufacturing Technology 42, 1993

9 B.J. Gans, de, E. Tekin - Kazancioglu, W. Meyer, U.S. Schubert "Ink-jet printing polymers and polymer libraries using micropipettes", Macromolecular Rapid Communications Vol 25-1, Wiley Online Library, 2004

10 Hanan Gothait, "Apparatus and method for three dimensional model printing", US Patent No. 6259962B1, 1999

11 Eliahu M. Kritchman, Ofir Baharav, Michael Dovrat, Lior Lavid, Hanan Gothait "Solar Cell Electrically Conductive Structure and Method", Patent Application Number: 14/404,455 , Xjet Ltd, 2013

12 Sharon Fima, Hila Elimelech "Double-sided and multilayered printed circuit board fabrication using inkjet printing", Patent No 11039541, Nano Dimension Technologies, LTD 2015