AMPOWER INSIGHTS

Metal Binder Jetting Implementation

A strategic guideline to implement Metal Binder Jetting

INSIGHTS GAINED:

- How does the Binder Jetting process chain look like and what materials are available?
- What applications should I consider when identifying business cases for Binder Jetting?
- What are the challenges during Binder Jetting implementation and how to master them?

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SCHNEIDER ELECTRIC FILTER ELEMENTS IN SERIAL PRODUCTION AT GKN ADDITIVE, COURTESY GKN ADDITIVE

DRILL BIT NOZZLE IN OIL AND GAS INDUSTRY. CEMENTED CARBIDE H12N
COURTESY OF SANDVIK ADDITIVE MANUFACTURING

Insights gained

How does the Binder Jetting process chain look like and what materials are available?

What applications should I consider when identifying business cases for Binder Jetting?

What are the challenges during Binder Jetting implementation and how to master them?

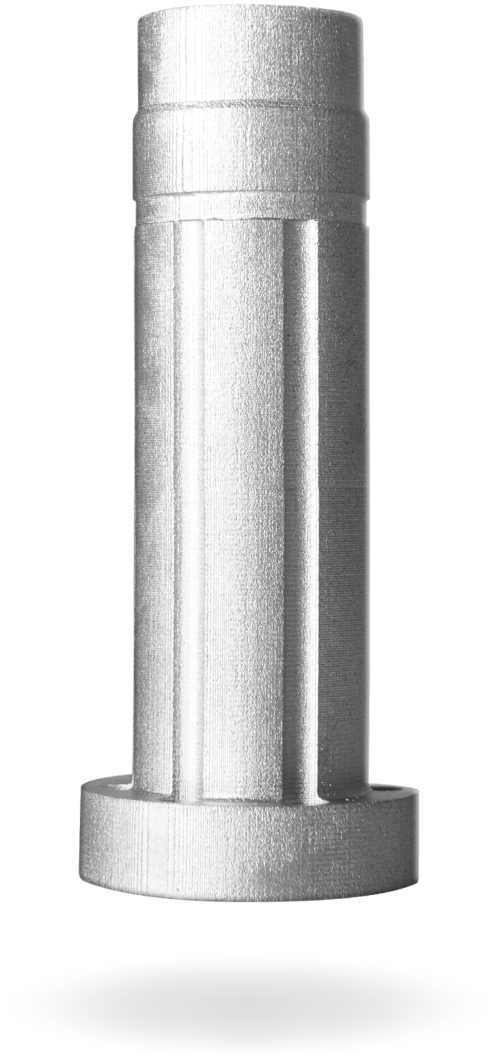
Management summary

Metal Binder Jetting can achieve high material properties, outperforming casting and metal injection molding. From an economical perspective, BJT can reduce the TCO by 50% compared to the established Powder Bed Fusion. Paired with a wide range of available and potential materials that already extends beyond the most common stainless steel, BJT has the potential to establish itself for small to medium sized components for serial parts in the range of 1,000-50,000 parts per year.

The technology, however, still lacks the maturity of other metal AM processes and standards are not yet available. To fully leverage the potential, customers have to go through an extended implementation and qualification process in order to establish process stability and repeatable part properties. Besides the actual printing process parameters, also powder characteristics, depowdering strategies and sintering parameter have to be considered.

Presently, successful industrial applications predominantly utilize stainless steel and achieve cost advantages over other Additive Manufacturing (AM) and conventional processes. Additionally, difficult to weld or non-weldable materials can be processed with BJT, an advantage compared to other AM processes such as widespread Powder Bed Fusion.

AMPOWER outlines a strategic approach for the successful implementation of Binder Jetting, evaluating the entire process chain, including its advantages, challenges, and available materials. Emphasizing the identification of business cases, the analysis covers the cost structure of the process, along with the characteristics and best practices of industrial applications. The insights pinpoint potential implementation challenges and provide a comprehensive strategy to overcome them.



TOOLING INSERT. M2 TOOL STEEL
COURTESY OF INDO-MIM INC.

About AMPOWER

AMPOWER is the leading strategy consultancy and thought leader in the field of industrial Additive Manufacturing. The company advises investors, start-ups as well as suppliers and users of 3D printing technology in strategic decisions, due diligence investigations and provides unique access to market intelligence.

On operational level, AMPOWER supports the introduction of Additive Manufacturing through targeted training programs, support in qualification of internal and external machine capacity and technology benchmark studies. The company was founded in 2017 and is based in Hamburg, Germany, operating worldwide.

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Introduction

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Metal Binder Jetting on the brink of industrialization

While initially Binder Jetting was mainly used for prototype production, it slowly evolves into a manufacturing technology for functional end parts. However, for a long time, the technology did not live up to the exaggerated expectations.

Metal Binder Jetting is based on Binder Jetting Technology (BJT) or short Binder Jetting developed at the MIT in the late 1980s. Shortly after, Z CORPORATION was the first to commercialized the BJT principle to produce full-color prototypes from gypsum for architecture models and design prototypes. A decade later first machines using metal feedstock were introduced to the market. In 2005 EXONE started using Binder Jetting to print stainless steel components. However, due to its large powder particles the stainless steel body could only be pre sintered to a porous part and needed to be infiltrated with bronze to increase the overall density. As the technology advanced, it was possible to process finer metal powder, which enabled sintering to full density.

In todays Metal BJT systems finer powder and advanced machine and process development allow the production of highly dense parts comparing to conventional Powder Metallurgy (PM) and Metal Injection Molding (MIM) processes.

In 2012, DIGITAL METAL entered the competition with EXONE as supplier of industrial Metal Binder Jetting systems. Following the patent expiration and general AM hype in the mid 2010s, DESKTOP METAL announced its entry into the market and further fueled the excitement. Bold claims to make metal 3D printing 100 times faster were made, creating a significant media buzz. At the end of the 2010s more companies such as HEWLETT PACKARD and GE entered the market with their own Metal BJT systems. Although the increased competition pushes the technology development and industrialization of the process chain, the technology still struggles to fully live up to the heightened expectations so far.

AMPOWER Maturity Index: Metal AM 2024

To evaluate different AM technologies AMPOWER has developed a model to describe their maturity based on two indices. The Industrialization Index and the Technology Maturity Index describe and compare the adoption rate and its capabilities of each AM technology in an industrial environment. Both indices are crucial for evaluating the overall status of a technology.

Metal Binder Jetting continuously moved forward in the Maturity Index over the last couple of years. The Technology Maturity improved due to continuous innovation and development in machine technology, partially triggered by increased competition between machine suppliers. Focus on reliable machine technology increased due to demanding requirements from first users. The Industrialization Index rose as the installed base at MIM and PM part manufacturing suppliers grew, and first serial production parts in specific applications emerged.

1988
Binder Jetting
Prototype (MIT)

1993
Binder Jetting
patent filed (MIT)

1998
EXTRUDE HONE
introduces first metal printer

2005
EXONE is founded
out of EXTRUDE HONE

2012
DIGITAL METAL
is founded

2015
DESKTOP METAL
is founded

2016
EXONE launches first
fine metal powder System

2017
DIGITAL METAL
launches first System

2018
DESKTOP METAL
launches first system

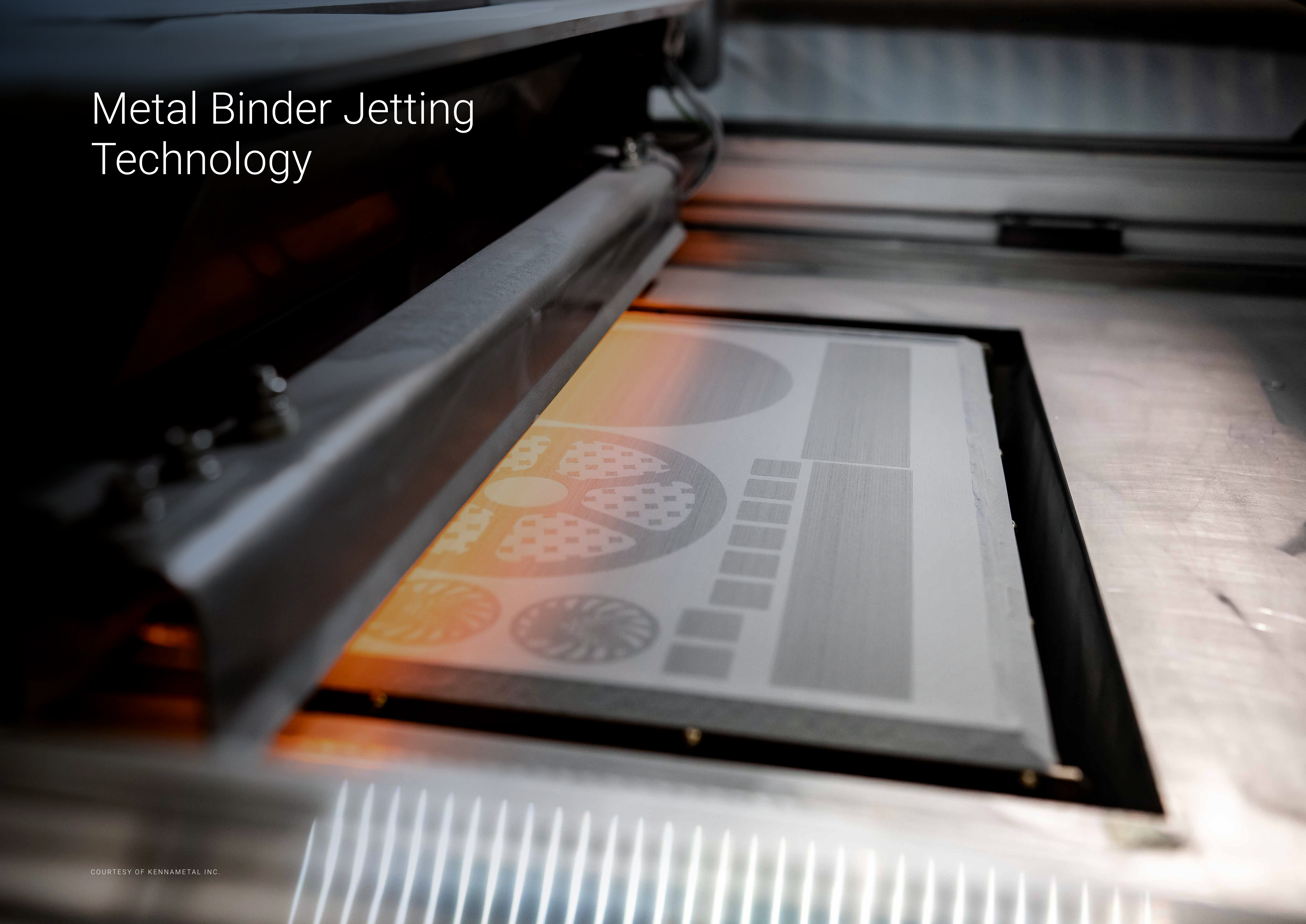
2019
HP launches first
printing system

2019
GE ADDITIVE
launches first system

2021
DESKTOP METAL
acquires EXONE

2022
MARKFORGED acquires
DIGITAL METAL

Metal Binder Jetting Technology



COURTESY OF KENNAMETAL INC.

Printing the 3D part geometry

Printing

The Metal Binder Jetting process begins with the application of metal powder onto a build platform, serving as the foundation for the printing process. The metal powder is dispensed through a hopper or feed bed. Typically, fine metal powders with a moderate flowability are used. A roller is used to evenly spread and compact the powder. Achieving a dense and uniform powder layer is crucial for final part density and distortion.

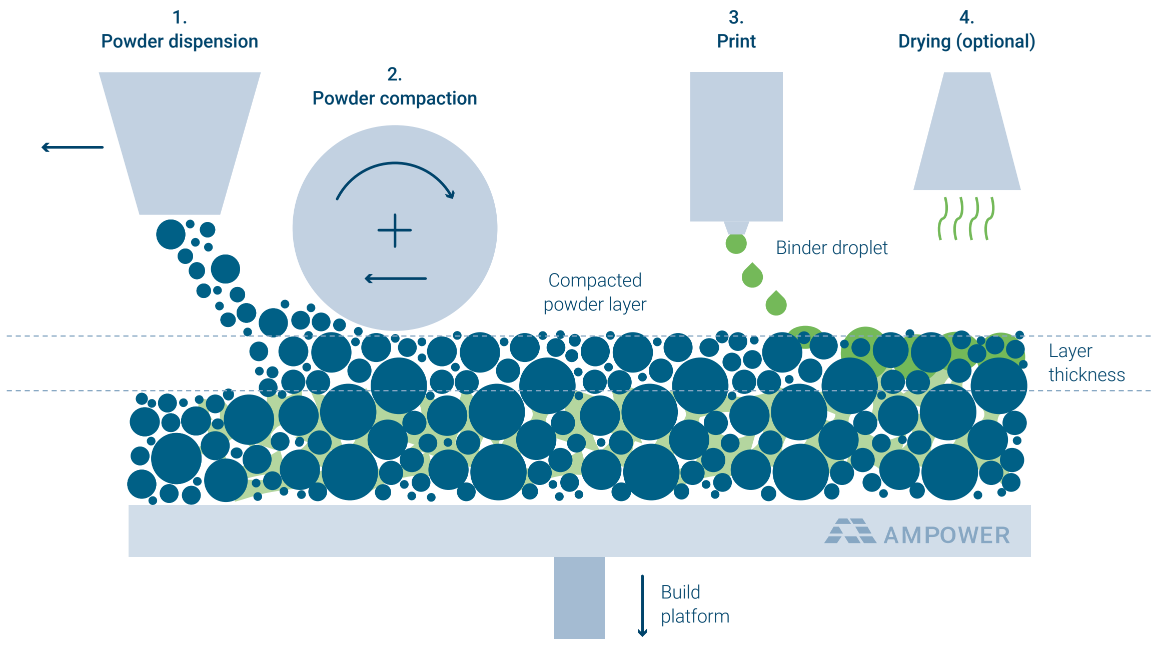
In the next step the binding agent is selectively applied to the powder bed through the use of a thermal or piezoelectric inkjet print head. The print head generates binder droplets that penetrate the surface of the powder bed. These droplets wet the powder particles and are absorbed into the powder bed through capillary forces. An optional drying process can be executed after each binder application by using a heat lamp. During this step, a portion of the binder's solvent is evaporated, and the powder particles are bound together. The powder application and printing process steps are repeated until the desired part geometry is completely built.

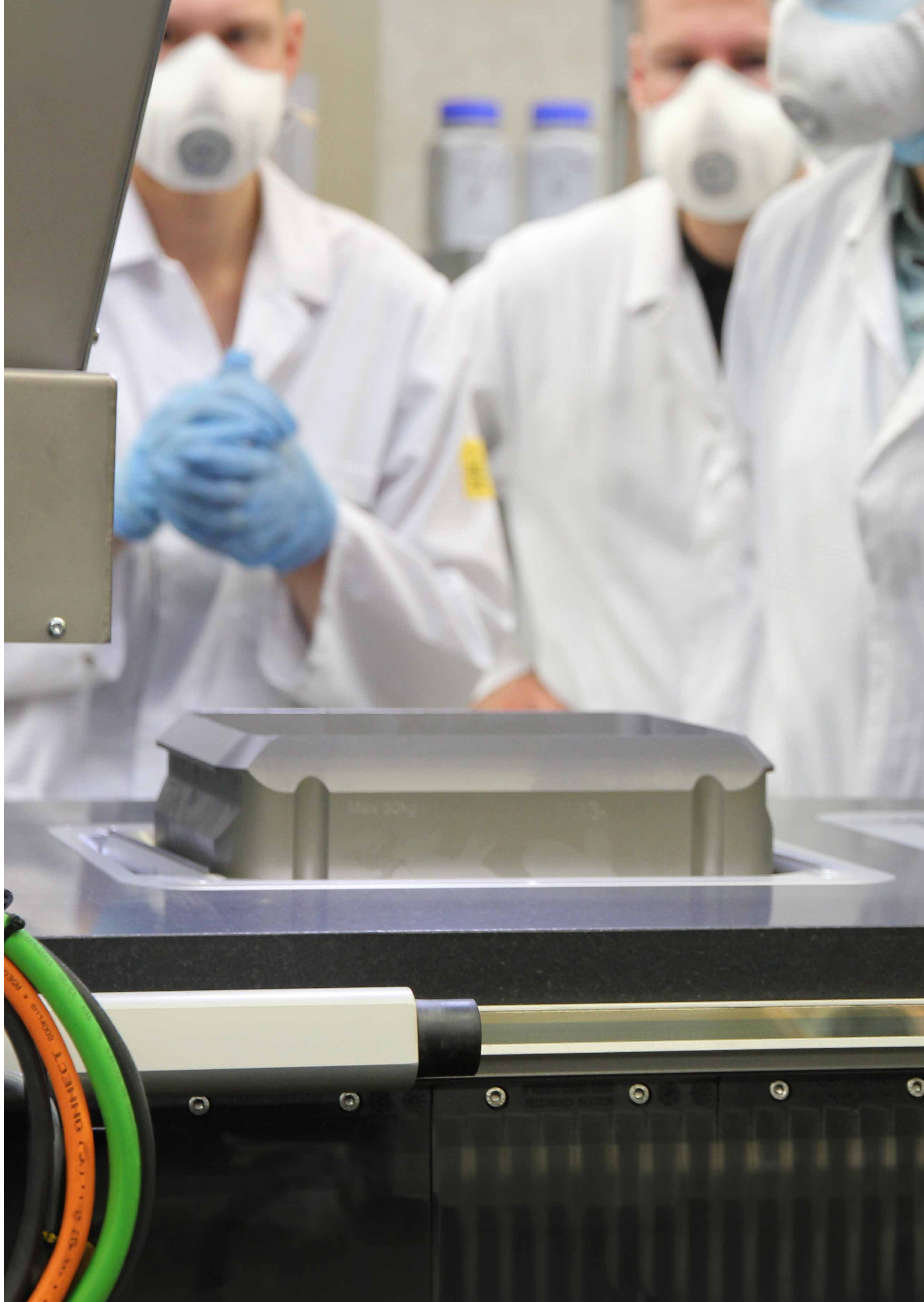
Curing

Once printing is finished, the binder must be cured or cross-linked to ensure the structural integrity and stability of the printed green part. For this purpose, the entire powder bed is heated in an oven to temperatures of up to 200°C to activate the chemical reaction of the binder or to completely evaporate the solvent. The atmosphere used depends on the material but is typically air.

Depowdering

After the binder is cured, the printed green parts are removed from the powder bed and cleaned of residual powder. Excess, unbonded powder is carefully removed using compressed air, brushes, or vibration. Proper depowdering is crucial as any remaining powder becomes part of the component during sintering, affecting the final geometry.

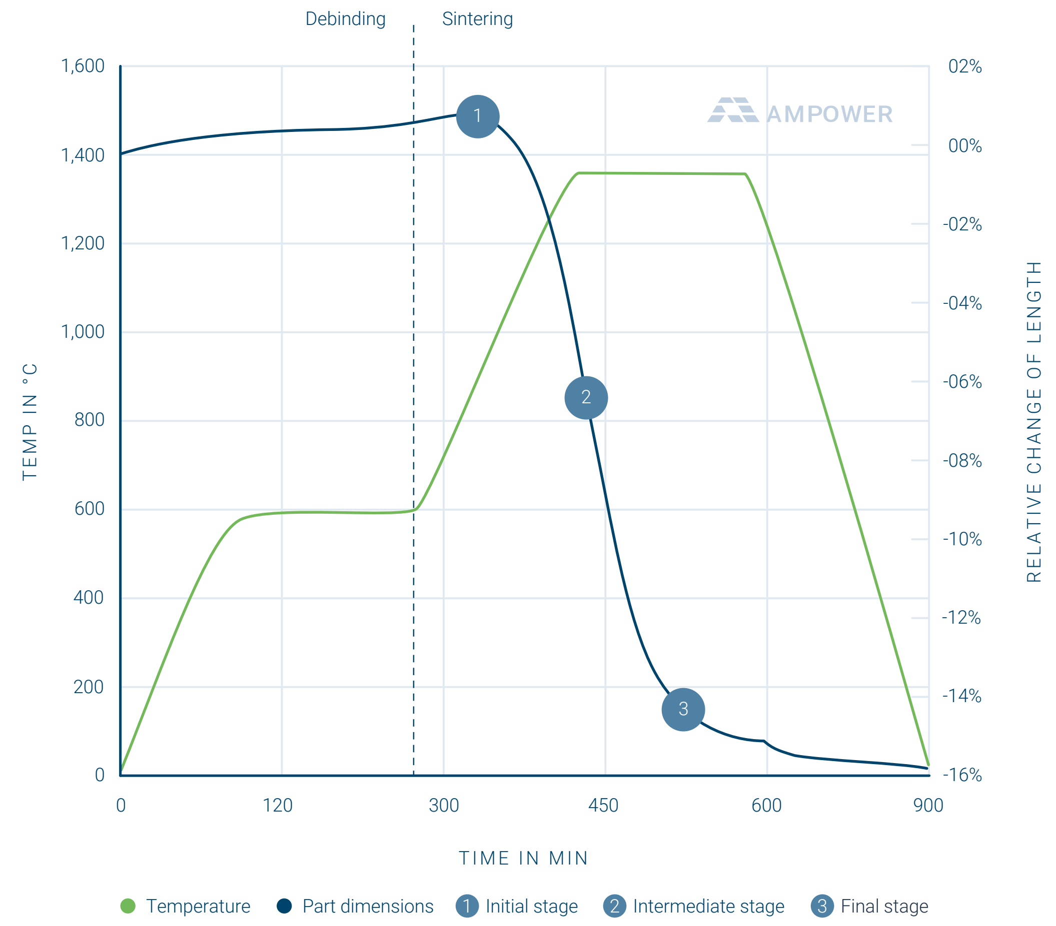


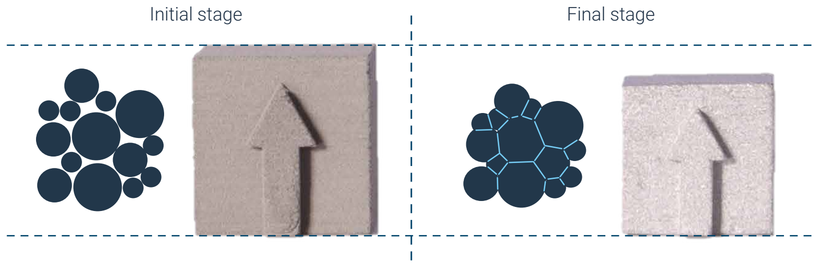


Creating fully dense metal parts

Sintering is a well-known process and industrially established in many conventional powder metallurgical processes. The main challenge in Metal Binder Jetting is a reliable production of green parts with consistent properties to achieve the highest end part quality.

Part shrinkage during sintering





Debinding

To achieve consistent part properties, it is essential to remove the binder from the green parts without leaving any residue. Metal BJT green parts possess an open porosity, enabling a thermal debinding after unpacking. The debinding process is ultimately based on thermal decomposition of the binder system.

Debinding temperature and atmosphere are important parameter of this step. Sudden or uneven temperature changes can lead to cracks and distortions in the green parts. The environment in which thermal debinding occurs also plays a crucial role. The choice of the debinding atmosphere affects the overall debinding kinetics and the potential for oxidation of metal powders.

Subsequent to binder removal, the part enters what is known as its "brown state". In this state, the part contains only a minimal amount of secondary binder, which makes it extremely fragile. To circumvent handling the parts during this fragile phase, the debinding process is frequently conducted in a combined oven process with the final sintering.

Sintering

The sintering transforms the brown part into a dense metal part. During the process, the powder body shrinks to final dimension and achieves the desired material properties. In solid-state sintering, densification occurs by diffusion processes below the melting temperature.

The process can be divided into three stages. In the initial stage, contact formation and contact growth of adjacent powder particles occurs, with contact points between powder particles increasing to form contact areas, resulting in the formation of material bridges. These so-called sinter necks are mainly formed by surface diffusion and lead to a slimming of the particles.

During the intermediate stage, the sinter necks grow as the particle centers approach each other due to volume diffusion. The contact areas between the particles continue to grow, changing their shape to the extent that they are no longer recognizable as individual powder particles, and a polycrystalline body is formed. An interconnected pore network is formed, which becomes denser with increasing duration and temperature.

The final stage begins with the transition from open to closed porosity, when the pore network separates into individual pores. This process usually occurs between 5% to 10% residual porosity. The pore size decreases until the part is densified to its final density. Depending on the alloy, the process yields a final porosity between 0% to 3%.

A denser packing of the powder particles in the printing process and consequently the green part leads to an increase of contact points, which promotes the densification process. Furthermore, less pore volume needs to be filled up, resulting in lower shrinkage. In addition to the density of the green parts, its particle structure is also important for the densification behavior. More homogeneous green parts lead to better dimensional stability and higher densification during sintering.

What impacts the process?

Powder

In sinter-based AM processes, powders with particle sizes between 5 and 25 µm are used. The high specific surface area of these fine powders increases the sintering activity and therefore improve the sintering behavior. Typically, spherical powders are used, as they have good flow and packing properties. However, very fine powders tend to flow more poorly than, powders used in laser (20-63 µm) or electron beam (63-106 µm) PBF. Hence the need for a roller in the application mechanism.

Binder

The used binder should result in a high green part strength. This is achieved both by good adhesion between the powder particles and by the cohesive strength of the binder itself. In addition, it is important that the binder decomposes thermally without leaving residues. It must be ensured that the binder can be reliably processed by the print head. To this end, criteria for viscosity, surface tension and rheological properties must be met to enable optimum droplet formation.

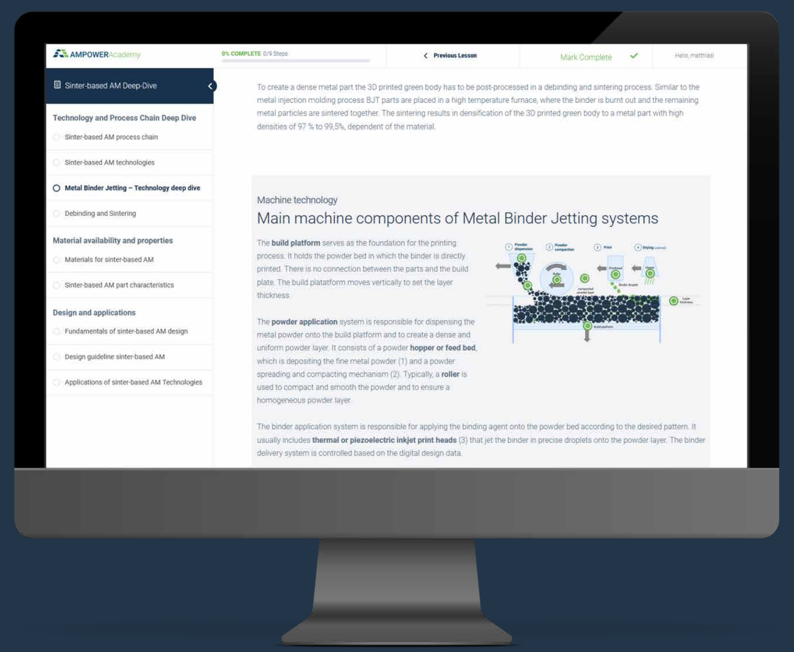
Debinding and Sintering Atmosphere

A suitable atmosphere plays a decisive role in the debinding and sintering processes. It serves not only for the heat transfer, but also to protect the material from undesirable reactions such as oxidation, to remove by-products from desirable reactions, or to selectively remove certain elements. The optimal atmosphere is material-dependent and requires careful selection based on the material and desired part properties.

In debinding, the atmosphere is used to support the thermal decomposition of the binder and to remove the debinding products. Depending on the material, debinding is usually carried out in argon or nitrogen, but oxygen-containing atmospheres can also be used to improve binder decomposition. Then, a reducing atmosphere is required in the subsequent sintering. Debinding is often carried out under atmospheric pressure, however, partial pressure can improve the debinding behavior.

Throughout the sintering process, the atmosphere is even more important. Stainless steels, like 316L, typically undergo sintering in a high-purity hydrogen atmosphere. This serves the purpose of cleansing particle surfaces and minimizing carbon content. However, for materials containing carbon, such as low-alloy steels and tool steels, nitrogen is the preferred sintering atmosphere. The same holds true for aluminum. In contrast, sensitive materials like titanium or nickel-based alloys demand inert atmospheres such as argon or vacuum during sintering, as hydrogen and nitrogen may trigger undesirable reactions. When using argon, it should be noted that it is not soluble in the metal lattice. Consequently, this can lead to increased porosity within the part.

Sinter-based AM and Binder Jetting E-Learning



To create a dense metal part the 3D printed green body has to be post-processed in a debinding and sintering process. Similar to the metal injection molding process BJT parts are placed in a high temperature furnace, where the binder is burnt out and the remaining metal particles are sintered together. The sintering results in densification of the 3D printed green body to a metal part with high densities of 97 % to 99,5%, dependent of the material.

Main machine components of Metal Binder Jetting systems

The **build platform** serves as the foundation for the printing process. It holds the powder bed in which the binder is directly printed. There is no connection between the parts and the build plate. The build platatform moves vertically to set the layer thickness.

The **powder application** system is responsible for dispensing the metal powder onto the build platform and to create a dense and uniform powder layer. It consists of a powder **hopper or feed bed**, which is depositing the fine metal powder (1) and a powder spreading and compacting mechanism (2). Typically, a **roller** is used to compact and smooth the powder and to ensure a homogeneous powder layer.

The binder application system is responsible for applying the binding agent onto the powder bed according to the desired pattern. It usually includes **thermal or piezoelectric inkjet print heads** (3) that jet the binder in precise droplets onto the powder layer. The binder delivery system is controlled based on the digital design data.

This course will provide a deep dive into both Binder Jetting and Material Extrusion technologies and is specifically targeted toward engineers, designers and other professionals that want to understand if their applications are suitable for these technologies.

The three main areas that will be covered are
- Technology and process chain deep dive
- Overview of available materials and properties
- Design guidelines and application examples

Training available at
https://additive-manufacturing-training.com/courses/sinter-based-am/

Material availability

In principle, any powder material that can be sintered could be processed by Metal Binder Jetting. However, technical and economical part requirements favor certain materials. Additionally, lengthy process qualification focus on materials from known and established sinter applications.

Beyond commonly used metals like stainless steels, nickel and titanium alloys, BJT excels in processing materials that are challenging or impossible to weld. Notably, it accommodates high-carbon tool steels, hard metals, and cemented carbides. Despite the broad potential for material processing, only a limited number of alloys are fully qualified and readily available from multiple sources yet.

Stainless steels 316L and 17-4 PH are the most common used and widely available materials in BJT. In a hydrogen atmosphere they can be reliably sintered to over 99.5% density. These materials are readily accessible from service suppliers with short lead times. Other stainless alloys, including 304L, 420, and a nickel-free austenitic stainless steel, are also available.

The most common BJT tool steels are M2, D2 and H13 alloy. Alloys with a high carbon content are particularly interesting for Binder Jetting since they show a good sinterability and are difficult to process with other AM technologies.

Low-alloy steels include the alloys 4340, 4140 and 8620. Additionally, a dual-phase steel similar to DP600 is also available. Low alloy steels typically exceed 95% density when sintered and require post heat treatment to enhance their mechanical properties.

Among the most widely used nickel-based superalloys in Binder Jetting are the alloys IN 625 and 718, which are qualified and available from several sources. In addition, the alloy Mar-M247 has also been commercially processed.

Ti-6Al-4V is the only titanium alloy that has been qualified by several sources and from which parts are currently available. Achieving the requirements of Grade 5 is a challenge due to the reactivity of the titanium powder.

For copper alloys, pure copper is available from multiple sources. The electrical conductivity is specified at 90% IACS. In addition, CuCr1Z and bronze can also be processed.

Sintering Aluminum is still challenging due to its strong tendency of oxidation. By adding alloying elements, such as magnesium, the sinterability can be increased. In particular, alloys such as 6061 and AlSi3Mg2 are currently under development.

Binder Jetting also extends its focus to materials like cobalt chrome, precious metals, and cemented carbides. The continuous exploration and development of these materials further enhance the versatility of Metal Binder Jetting.

Material	Processable	Data sheet available	Multiple sources	Short Term Availability*
Tool Steels				
316L	✓	✓	✓	✓
420	✓	✓	✓	
17-4 PH	✓	✓	✓	✓
Nickel Free Austenitic	✓	✓	✓	
304L	✓	✓		
Tool Steels				
D2	✓	✓	✓	✓
M2	✓	✓	✓	✓
H13	✓	✓	✓	✓
S7	✓	✓		
440C	✓	✓		
Low alloy steels				
4140	✓	✓	✓	✓
DP600	✓	✓		
4340	✓			
8620	✓			
Nickel alloys				
IN 625	✓	✓	✓	✓
IN 718	✓	✓	✓	✓
Mar-M247	✓	✓		✓
Hastelloy	✓			
Haynes 230	✓			
René 108	✓			
Copper alloys				
Copper	✓	✓	✓	✓
CuCr1Z	✓	✓		
Bronze	✓			
Other				
Ti-6Al-4V	✓	✓	✓	✓
Cemented carbides	✓	✓	✓	✓
Cobalt Chrome	✓	✓	✓	
Sterling Silver 925	✓	✓		
Gold	✓			
Aluminium 6061	✓			

*DELIVERY OF ONE-TIME SAMPLE PARTS/PROTOTYPES.

Mechanical Properties

In BJT the printed green part experiences a debinding and sintering process that is crucial for microstructural development. The chosen conditions contribute to the chemical composition, pore structure and grain size of the part, influencing its microstructure and consequently its mechanical properties. Homogeneity of the resulting microstructure is a key factor in achieving uniform and consistent material performance. Overall, the mechanical properties of BJT material are comparable to those of MIM, as they share similar feedstock and sintering processes.

In Metal BJT a slow cooling after sintering takes place in a state of equilibrium, requiring a subsequent heat treatment for most materials in order to achieve the desired material properties.

This contrasts L-PBF with its rapid solidification during the manufacturing process. The L-PBF process leads to a fine-grained structure which often only requires a precipitation hardening or annealing process to reach the desired end-properties. L-PBF microstructure is also characterized by little to no porosity. Consequently, mechanical properties of L-PBF are usually higher compared to BJT.

Standards

There are currently no standards for Binder Jetting itself. However, as BJT and MIM share the same sintering process, MIM standards are often applied. The most widely used standards include "MPIF Standard 35 - MIM" of the Metal Powder Industries Federation (MPIF) and "ISO 22068 - Sintered-metal injection-moulded materials - Specifications" an international standard by the International Organization for Standardization (ISO). The standards provide a comprehensive set of mechanical and physical property data for metal sintered materials.

The existing MIM standards cover a broad range of commonly utilized materials, often providing both minimum and typical values. These standards predominantly cover the materials used in MIM specific applications. As BJT delves into novel applications involving new materials, there might be instances where MIM standards may be lacking, for example particularly for tool steels, and other PM standards need to be considered.

Comparing 17-4 PH Stainless Steel properties

17-4 PH is a precipitation-hardening stainless steel alloy known for its excellent combination of corrosion resistance, high strength and toughness. This alloy can easily be processed by Metal BJT, MIM and L-PBF. Additionally, to the part production a decisive step in achieving its final mechanical properties is the heat treatment. Among the noteworthy heat treatments for 17-4 PH is the H900 condition. In this state, the alloy undergoes a solution heat treatment, followed by rapid cooling and aging at a temperature of 900 °F (482 °C). This process results in a significant increase in hardness and strength while maintaining a desirable level of toughness. On the next page, the influence of the different manufacturing technologies on the mechanical properties of 17-4 PH in "as process" and "H900" condition are illustrated.

Tensile properties

	Wrought			MIM			BJT			L-PBF		
	UTS [MPa]	A [%]	Source	UTS [MPa]	A [%]	Source	UTS [MPa]	A [%]	Source	UTS [MPa]	A [%] Source	Source
316L	485	40	ASTM A276	520	50	MPIF 35	530	58	Data sheet	615	45	Data sheet
17-4 PH (Heat treated, H900)	1310	10	ASTM A564	1190	6	MPIF 35	1255	5		1375	14	
H13 (Heat treated)	1400-2000[1]	9-15[1]	Data sheet	N/A	N/A		1200-1520[1]	2-10[1]		1400-1900[1]	2-10[1]	
4140 (Heat treated)	930-1800[1]	8-22[1]		1650	5	MPIF 35	1740	4		N/A	N/A	
IN625 (As sintered)	760	30	AMS 5666	N/A	N/A		710	54		975	40	
IN718 (Heat treated)	1241	12	AMS 5662	1241	6	AMS 5917[2]	1300	14		1430	15	
Ti64	895	10	ASTM B348	800	3	ISO 22068	870	13		1050	15	

[1] DEPENDING ON HEAT TREATMENT; [2] HOT ISOSTATIC PRESSED

Hardness

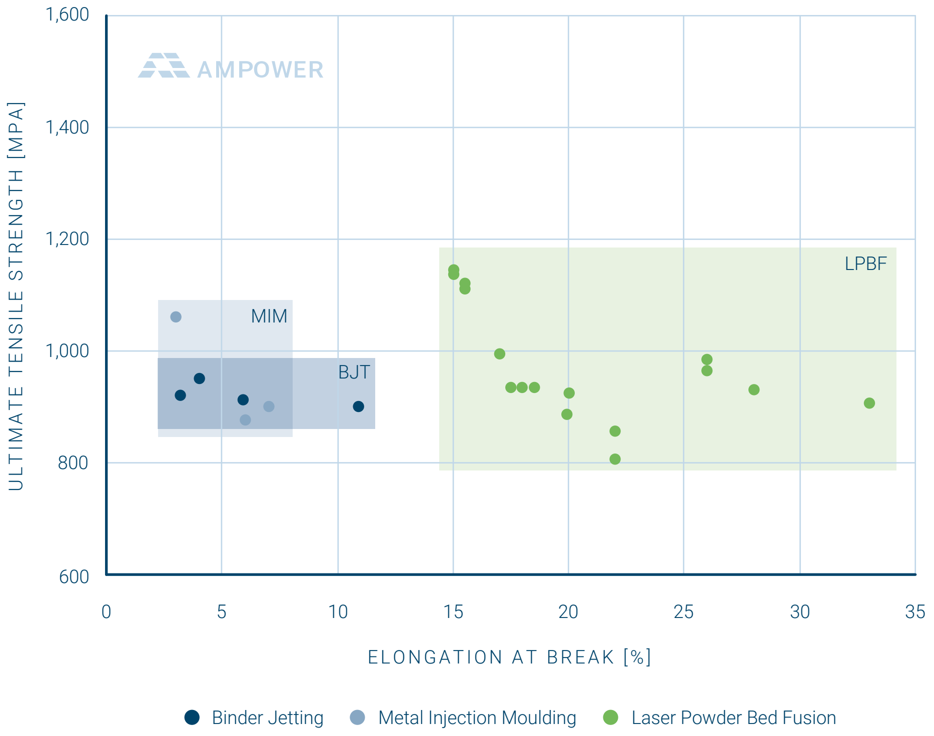
	Wrought		MIM		BJT		L-PBF	
	Hardness [HRC]	Source	Hardness [HRC]	Source	Hardness [HRC]	Source	Hardness [HRC]	Source
D2 (Heat Treated)	62	ASTM A681	N/A		63	Datasheet	N/A	
M2 (Heat Treated)	65	ASTM A600	N/A		61		N/A	
H13 (Heat Treated)	28-55[1]	Datasheet	N/A		44-52[1]		48-54	Datasheet

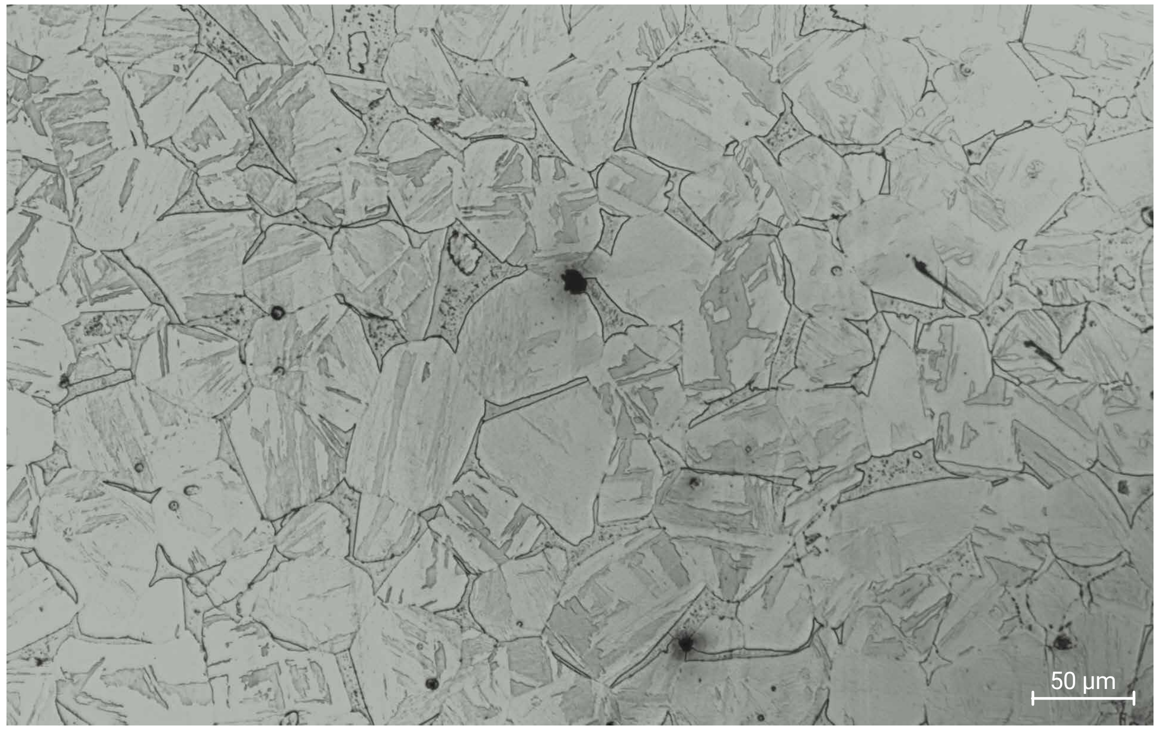
[1] DEPENDING ON HEAT TREATMENT; [2] HOT ISOSTATIC PRESSED

The tables provides a comprehensive comparison of mechanical properties sourced from standards for bar material and MIM parts as well as typical average values sourced from public data sheets for BJT and L-PFB.

The mechanical properties of low-alloy steels like 4140 and tool steels like H13 are largely determined by the postprocess heat treatment. Depending on the tempering temperature, the properties can be set in a wide range optimized to the application.

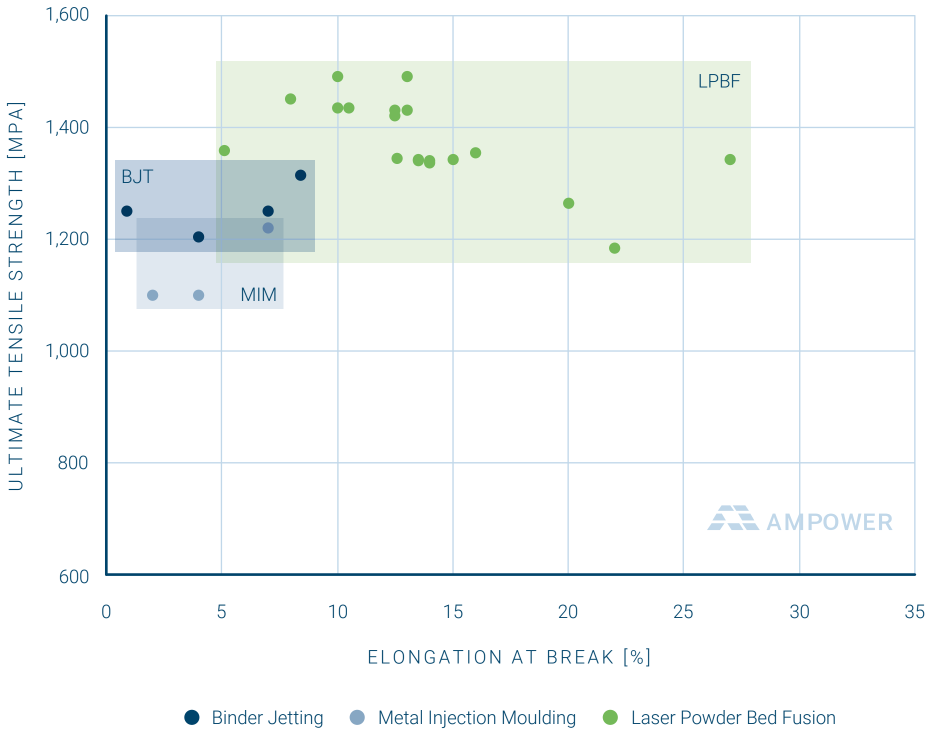
17-4 PH as processed





BJT: 99,8 %

17-4 PH heat treated H900



BJT: 99,8 %

Benefits and challenges of Binder Jetting

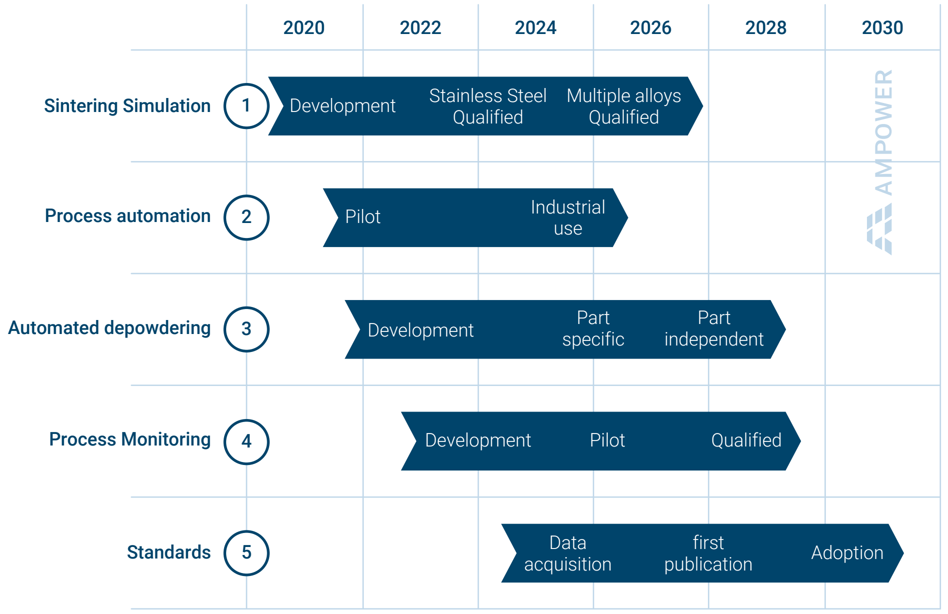
⊕

- **High productivity**
  Binder Jetting is fast resulting in high production rates compared to other AM technologies. It can produce large volumes of parts cost-effectively.
- **High part complexity & surface quality**
  The lack of need for support structures allows design freedom and high surface quality when it comes to overhangs and internal channels.
- **Wide material variety**
  The complete process chain is compatible with a wide range of materials.
- **Reduced post-processing**
  BJT parts typically have a higher surface quality and require less post-processing compared to other AM technologies, reducing time and costs associated with finishing.

⊖

- **Distortion risks in sintering process**
  Friction of parts on the sintering substrate during shrinkage can lead to distortion in the sintering process, especially for large parts.
- **Low degree of process automation**
  BJT printers have little automization and the handling of the fine powder as well as the de-powdering of the green parts is largely done manually.
- **Low system maturity**
  Most system manufacturers sell their first printer generation. No established process monitoring is available and investigation on repeatability and robustness are ongoing.
- **Little publicly available knowledge**
  Only little public research is available and a lack of specific standards exists.

Outlook on upcoming developments



① Predicting and compensating the shrinkage during sintering and therefore enabling fast development cycles or even first-time-right, is considered as one of the major challenges for BJT industrialization. SIMUFACT was among the first companies to develop a sinter simulation, joined by DESKTOP METAL who brought it first to commercial maturity.

② Automatization of the process chain and capsuling is a key to widespread industrial use, especially for harmful fine metal powders. GE ADDITIVE's Series 3 will be the first system with a closed loop consumables handling.

③ Automated de-powdering of parts will significantly decrease manual labor and allow for the processing of large quantities of parts rivaling conventional PM processes. So far MARKFORGED and HP offer semi-automated solutions. However, due to the fragile green parts and overall process complexity full atomization will still need more time.

④ While process monitoring is essential for some industries documentation requirements, it can also contribute to increased cost efficiency when detecting flaws early in the process chain. HP's Metal Jet and DESKTOP METAL's P50 are already equipped with basic monitoring systems, but developments to full functionality are expected to continue for at least 5 more years.

⑤ The agreement on common standards is important for widespread industrial use. Characteristic values are currently being gathered for the creation of preliminary standards. It usually takes several years before standards are widely established.

Applications

BINDER JETTING IMPELLER PROTOTYPES WITH 25 AND 20 CM DIAMETER.
COURTESY OF GE ADDITIVE

The cost structure of Binder Jetting

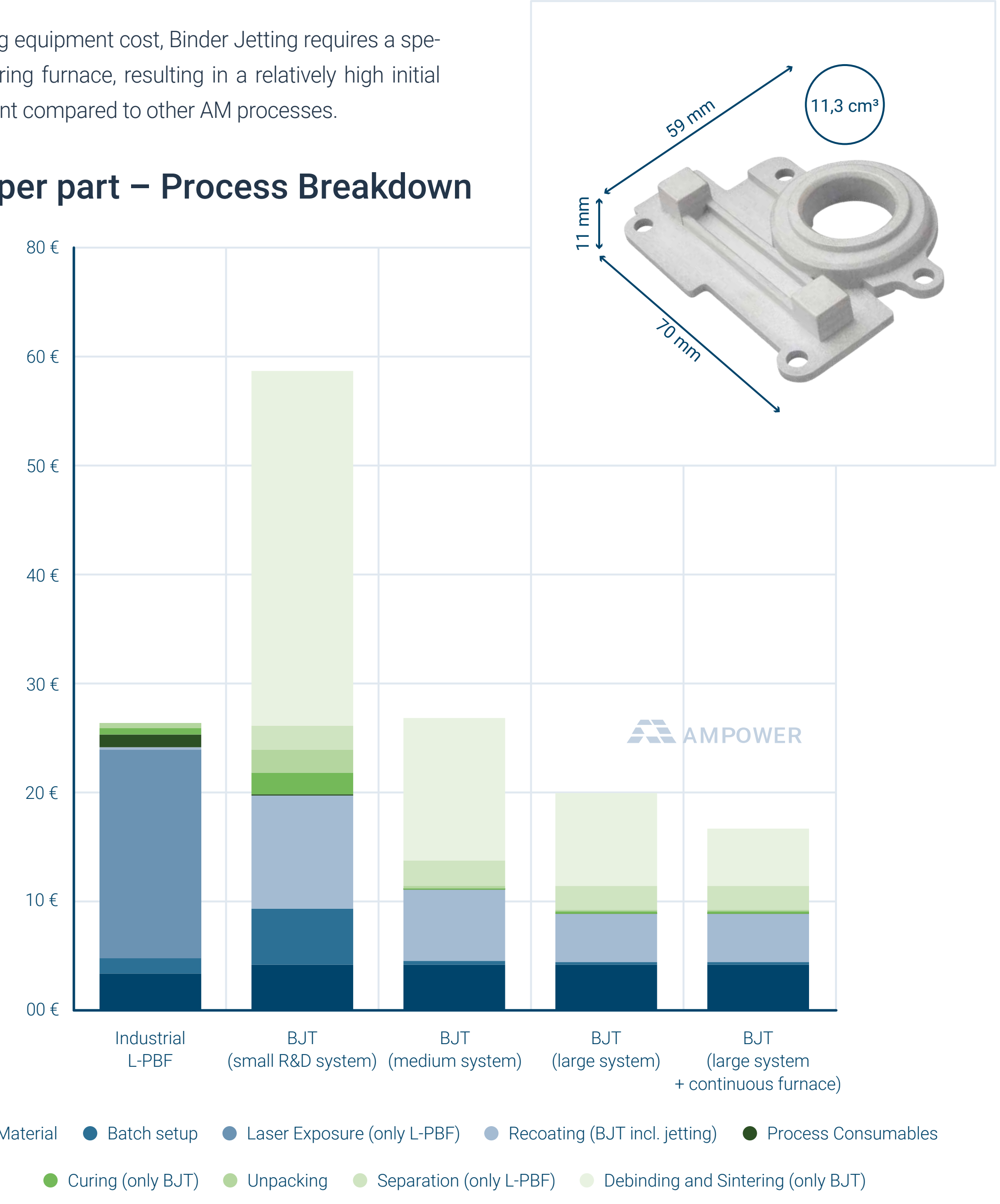
Typically, Binder Jetting requires a higher initial investment compared to other AM processes and therefore the process must achieve cost efficiency through high utilization and scaling.

Considering direct production or as-printed cost, the cost of additively manufactured parts are significantly dependent on the equipment investment and feedstock price. The share of cost of these factors are predominantly influenced by the part's geometry. The part volume determining the material consumption and the part size influencing machine utilization and print time.

Regarding equipment cost, Binder Jetting requires a special sintering furnace, resulting in a relatively high initial investment compared to other AM processes.

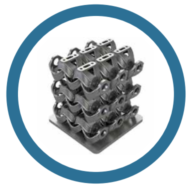
The following cost calculation provides a basic comparison between L-PBF and different BJT system sizes. Not in the scope of the calculation are advanced post processing (machining, surface treatment), ongoing quality assurance, company overheads, initial qualification investment as well as application design and optimization.

Cost per part – Process Breakdown



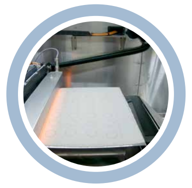
Material

Gas atomized powder with particle sizes between 5 and 30 µm is typically used in BJT. The fine powder has a high sintering activity, which is required for the densification of the parts. The powder cost are typically lower than for L-PBF powder of the identical alloy.



Batch setup

The setup time of a batch is similar in L-PBF and BJT. Only if complex support structures for L-PBF are needed, it takes additional efforts. Additionally, in BJT the setup time can typically be allocated to more parts in the build chamber. The batch setup is important for maximum utilization of the build box. A dense nesting is possible as parts are printed directly into the powder bed, omitting the need for support structures. In industrial applications, this "nesting density" is typically in the range of 5-20 %. Costs are minimized with higher utilization.



Recoating/Printing

The system price and the printing speed essentially determine the costs of the printing process. BJT printers are characterized by very high speeds. The print head typically covers the entire width of the powder bed and therefore the binder can be applied in a fast single pass movement. In combination with the machine investments, the hourly rate per part of the printing process is typically significantly lower in BJT to compared L-PBF.

Curing

Curing is carried out in comparatively simple and inexpensive ovens. The larger the build box and the higher the build job, the longer the process takes to ensure the powder bed is completely heated through. For small build boxes curing is done in 4 hours, while for large build boxes curing can exceed 24 hours.

Unpacking

De-powdering of the green parts is manly manual labor. While partially automated solutions are available, the removal of excessive powder from the delicate parts requires cost-intensive manual work. In the future, higher green part strength is needed for fully automated solutions.

Debinding and Sintering

The debinding and sintering process is commonly integrated into a combined treatment cycle. Costs associated with this process heavily rely on the scaling and utilization of the furnace. Continuous furnaces, offering higher throughput along with cost and sustainability advantages, outperform batch furnaces. Realizing these cost benefits necessitates full utilization of continuous furnaces, requiring a production capacity of at least three highly productive printers.

IMAGES COURTESY OF DESKTOP METAL, ELNIK SYSTEMS, FRAUNHOFER IFAM AND NABERTHERM

Identifying business cases

Evaluating business cases for BJT require consideration of different technological and economical factors. Based on AMPOWERs experience and cost model the Economic Feasibility Guide evaluates BJT compared to L-PBF based on simple part characteristics.

Materials

Currently business cases in Binder Jetting are realized in stainless steels, due to the well developed and dependable processing. Additionally, BJT is making significant headway with materials that can not be processed with other AM technologies, such as high carbon tool steels and cemented carbides. BJT combines the freedom of design of AM with the processability of conventional PM technologies for these alloy groups and therefore can compete favorably with traditional manufacturing methods. In comparison to conventional technologies, BJT stands out by streamlining the production process. This not only reduces overall production costs but also shortens lead times.

Design

The sintering process significantly influences the design freedom of BJT parts. Shrinkage during sintering makes applications with flat sintering surfaces more suitable. Additionally, the materials experience reduced strength during sintering, necessitating consideration of gravitational forces, which limits overhangs and features with high aspect ratios. In comparison to components produced through Laser Powder Bed Fusion (L-PBF), BJT parts typically exhibit a slightly bulkier and less delicate structure.

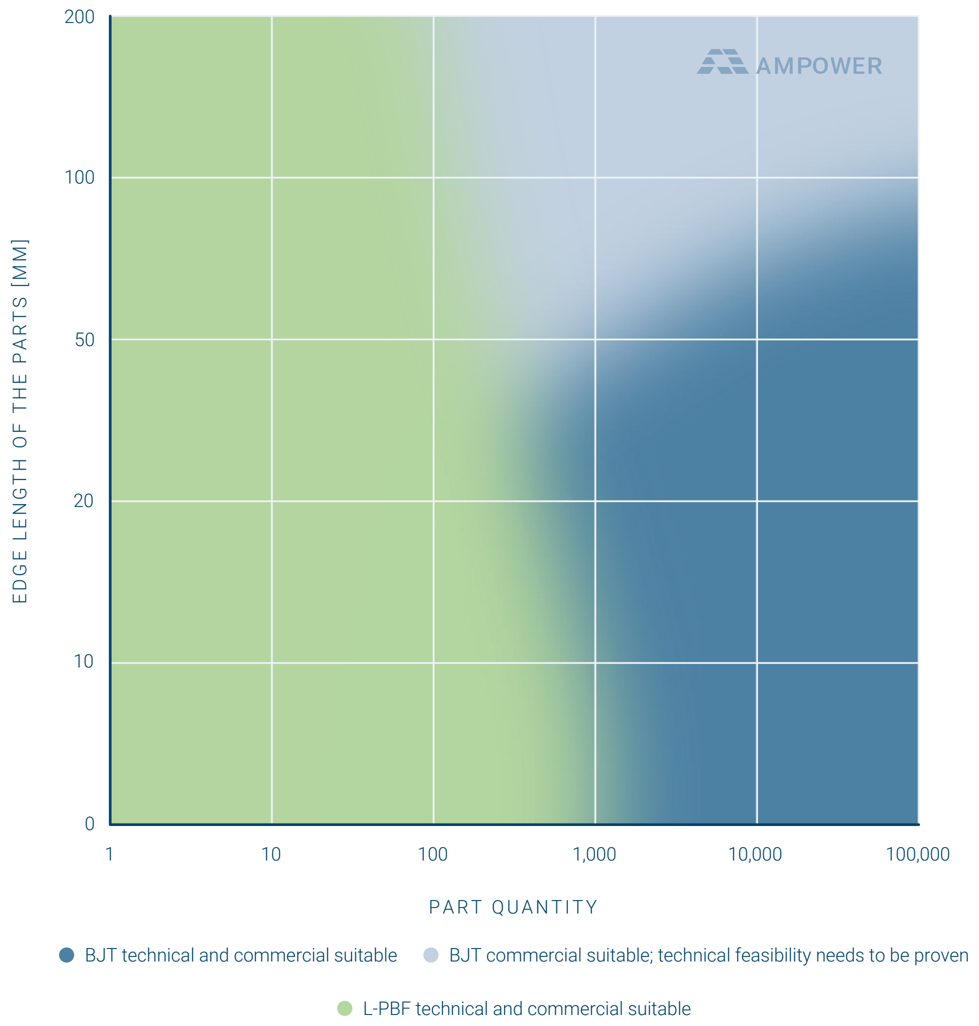
Part size

Increasing the part size leads to higher absolute shrinkage and weight of the parts, making them more prone to distortion. While in the past "fist size" has served as a rough upper limit, nowadays sintering simulations and stronger green part strength are enabling larger parts. Shrinkage and distortion can be predicted and largely compensated by the use of simulation. However, with larger parts, the iteration loops prior to series production typically increase.

Part quantity

In most cases, the economic feasibility of manufacturing applications using BJT becomes advantageous for larger part quantities. This is primarily attributed to the higher utilization requirement in BJT. Additionally, BJT typically involves several iteration loops to correctly compensate for shrinkage and distortion during sintering. However, with advancing simulation capabilities it is expected that the need for multiple iterations of part design will decrease significantly, and "first-time-right" might become feasible.

Economic Feasibility Guide



AMPOWER has provided extensive support to numerous companies on their journey to uncover potential Additive Manufacturing applications and subsequently overhaul their conventional manufacturing processes. These applications span across a multitude of categories, showcasing a diverse array of part sizes and their corresponding part volume, respectively part volume per bounding box.

For the Economic Feasibility Guide a series of standardized sample parts were generated based on this experience. The sample parts effectively embody the characteristics of a typical AM part. As the part size increases, the part volume share in the bounding box decreases. The economic feasibility was evaluated with AMPOWERs Cost Calculation Tool. The calculation assumes a fully utilized process chain and does not take into account any iteration loops during production start-up.

Industrial Metal BJT applications

Today, different industrial applications for BJT exist. While some are fully qualified and in daily use others still explore the possibilities of the technology regarding design freedom and material choice.

Fluid matter exchanger

Printed out of 316L via binder jetting, the fluid matter exchanger is designed with complex internal channels that facilitate critical function for the end application. Incorporating small internal channels, internal filters, and complex features this part could not be manufactured with any other technology.

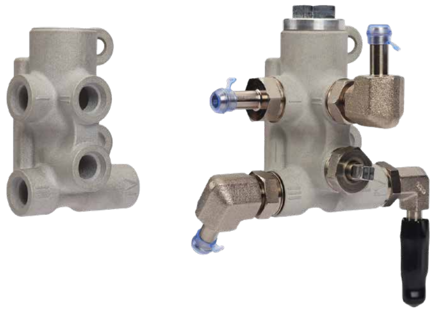
Material: Stainless Steel 316L

COURTESY OF AZOTH

Tractor Fuel Valve

The thermal diverter valve was engineered to effectively regulate fuel temperatures of John Deere tractors without affecting engine performance in cold environments. After redesigning for BJT, the part is smaller and uses less material than a conventionally manufactured valve, saving up to 50% in costs. The part performance increased due to smoother and more efficient internal channels that enhance fuel flow.

Material: Stainless Steel 316L



COURTESY OF JOHN DEERE

Press Punch

The punch is used for pressing green parts in in a Press & Sinter process. BJT enables the production of a near-net-shape tool which is finished by eroding to the final contour. A subsequent HIP process, as well as plasma nitriding and PVD coating are possible. The BJT process route reduces the tool manufacturing process steps omitting the need for machining of the tough and hard material with 61 HRC.

Material: Tool Steel M2

PRESS PUNCH IN ERODED AND SINTERED CONDITION
COURTESY OF GKN ADDITIVE

Wire Drawing Nib

Wires are produced by drawing a thick wire through numerous drawing dies, the active part of which are nibs that gradually reduce the cross-section of the wire. Efficient nib cooling increases the drawing speed, resulting in increased productivity. Only BJT enables the integration of cooling channels near the hot drawing zone for nibs from cemented carbides. The material used is one of the hardest grades of cemented carbide available with 1600 HV.

Material: Cemented Carbides, H10F

COURTESY OF SANDVIK ADDITIVE MANUFACTURING

Heat Sink

The heat sink has been designed using ToffeeAM's topology-optimizing software and printed in an aluminum alloy. The goal is to significantly enhance the efficiency of thermal diffusion compared to traditional heat sink designs. It also offers a lightweight solution compared to copper alloy heat sinks.

Material: Aluminium alloy

COURTESY OF RICOH

Implementing Binder Jetting

INSTALLED CONTINUOUS SINTER FURNACE.
COURTESY OF CREMER THERMOPROZESSANLAGEN

Challenges along the implementation journey

Implementing a new manufacturing technology is a complex change process within an organization, which requires a strategic approach. Especially when customer products are involved, the number of stakeholders increasing, and quality and economical aspects can prove to become critical showstoppers.

Technology awareness of Additive Manufacturing is often the first phase of an implementation journey. One of the most critical decision factors to move beyond awareness and enter the Application phase, however, is the question of maturity. While most potential AM users are highly aware of the maturity of metal L-PBF technologies, users are still uncertain about the maturity level of BJT. Currently, only few companies surpassed the first stage and moved towards the application phase, where they are often met with increased uncertainty about BJT specific design limitations due to the required sintering process step.

Once, potential applications are identified, users are screening for potential suppliers to support with first test components. Currently, only few supplier, typically experienced in conventional sinter technologies, are capable of delivering Binder Jetting parts, at high and consistent quality. Users often have difficulties to locate suitable supplier and often end up with a direct contact to the machine OEM. This makes it challenging for SMEs to gain access to the latest state of the art Binder Jetting technology, since the OEMs currently prefer to work with larger potential customers.

Only few BJT users currently are in the phase of qualifying a binder jetting component on an industrial manufacturing level, where specifications are developed regarding design, material and process boundaries. The main challenge is still the lack of standards and best practices that users can refer to.

Awareness

- What is possible
- Where is the added value
- Where is the technology maturity
- Which materials are available
- Who can help
- Who is doing it already

Application

- What parts should I look for
- How do I re-design the part
- What software do I need
- Who can help me with the re-design
- How do I make sure, the part is printable
- How much does the part cost

Testing

- Where can I do test prints
- Can I achieve cost advantages
- Do I achieve the required material properties
- Do we have a significant added value
- Can I "sell" this technology internally
- Can we sell this to our customers
- How does the process chain look like

Qualifying

- How do I ensure consistent and proven part quality
- Which defects can occur during the process chain
- How do I measure the defects
- How du I measure the quality along the process chain
- How do I create specifications for
    - Design
    - Material
    - Process

Supply chain

- Where is my supply chain in terms of
    - System technology
    - Feedstock
    - Software
    - Service supplier
- Do I manufacture internally or externally
- How do I qualify my supply chain

Scaling

- How can I communicate
- How do I spread knowledge
- How can I develop internal guidelines and technology acceptance

Strategic BJT implementation guideline

Metal Binder Jetting is in the transition from an R&D to an industrial manufacturing technology. Organizations have to make well educated decisions if and when they should consider Binder Jetting for their applications. This guideline gives a first indication into a potential strategic outline for a Binder Jetting technology implementation.

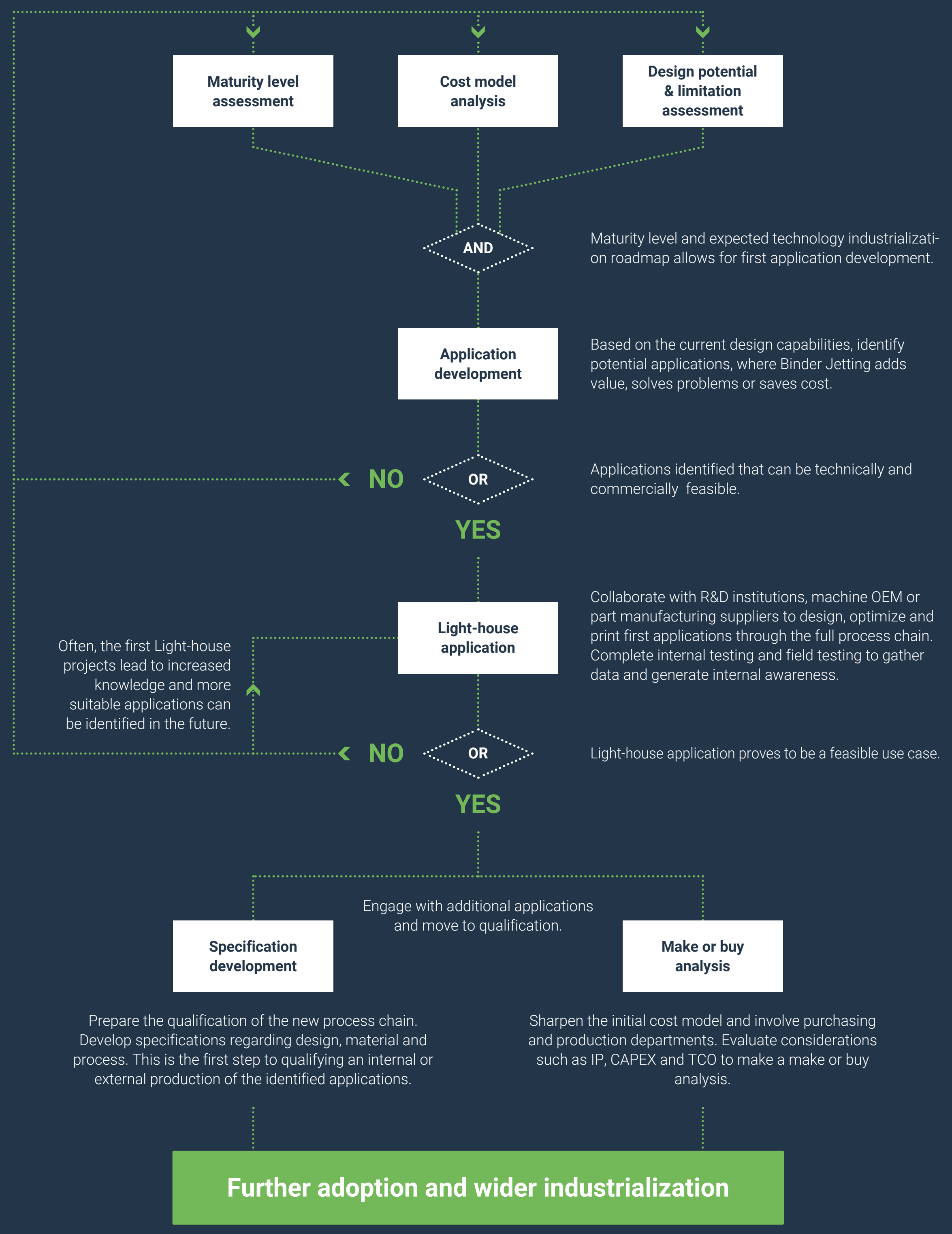
Today nearly every manufacturing organization is aware of Additive Manufacturing and utilizing the most common AM technologies to some degree. Regarding Metal Binder Jetting, companies are often still unaware of the its maturity and capabilities or in an early evaluation phase.

In this awareness and evaluation phase, three aspects have to be considered before a first application screening can be initiated. Companies have to build an understanding of the maturity of Metal Binder Jetting as well as define a required maturity level that is needed to move to the next phase. Secondly, a preliminary cost model needs to be developed in order to help identifying economical viable components in the next step. Thirdly, engineers need to gain an understanding of design the potential and limitations. As the technology is still in a highly innovative phase, all three aspects need to be closely monitored and regularly updated. When certain thresholds are met, the next phase of application development can be initiated. As a result of this phase, there are either first identified potential applications, or knowledge that the technology needs to improve further to be suitable. Especially cost models and design limitations might chance in the future with further technology developments. For example, the use of lower cost powder, automated depowdering and continuous furnaces might significantly lower cost per part in the future.

With so-called "light-house applications", the first part testing phase is initiated. Aim of those projects is a real-life feasibility test. Additionally, it often serves as a marketing vehicle within the company to initiate further funding for the implementation. Light-house applications do not need to be the optimum Binder Jetting part. Often the know-how increases dramatically after completion of such projects, which leads to further adaptations in the process and more suitable applications.

If one or more of those light-house applications prove to be feasible use cases, multiple actions are initiated which require additional funding for the AM team. While specifications need to be developed in preparation of a production qualification, a make or buy analysis must be conducted in parallel. Here not only the TCO is to be considered but also IP rights and the high initial CAPEX needed to implement a Metal BJT process chain. Naturally, further applications should be developed to generate an application funnel.

Identify the technology capabilities, limitations and the current maturity level. Based on the company profile, applications and regulatory limitations, the maturity level has to be determined (similar to NASA TRL Level) and assessed in regular intervals



Maturity level and expected technology industrialization roadmap allows for first application development.

Based on the current design capabilities, identify potential applications, where Binder Jetting adds value, solves problems or saves cost.

Applications identified that can be technically and commercially feasible.

Collaborate with R&D institutions, machine OEM or part manufacturing suppliers to design, optimize and print first applications through the full process chain. Complete internal testing and field testing to gather data and generate internal awareness.

Often, the first Light-house projects lead to increased knowledge and more suitable applications can be identified in the future.

Light-house application proves to be a feasible use case.

Engage with additional applications and move to qualification.

Prepare the qualification of the new process chain. Develop specifications regarding design, material and process. This is the first step to qualifying an internal or external production of the identified applications.

Sharpen the initial cost model and involve purchasing and production departments. Evaluate considerations such as IP, CAPEX and TCO to make a make or buy analysis.

Specification development, qualification and process validation

Qualified equipment and validated processes are a prerequisite for production in regulated environments. Specifications describe the part, material and process. The development of these specifications is the initial step in the implementation of a new manufacturing technology.

Part specification

The part specification or product requirement contains all the functional requirements for a specific part. Typically, it includes a technical drawing featuring dimensions, tolerances, and surface quality details. Additionally, the specification outlines the designated material and establishes a standard for its essential properties or defines the criteria required for part acceptance. The severity and the extent of the criteria are tied to the safety criticality of the part. The classification is based on the operating conditions and the consequences of a potential failure during operation.

Material and process specification

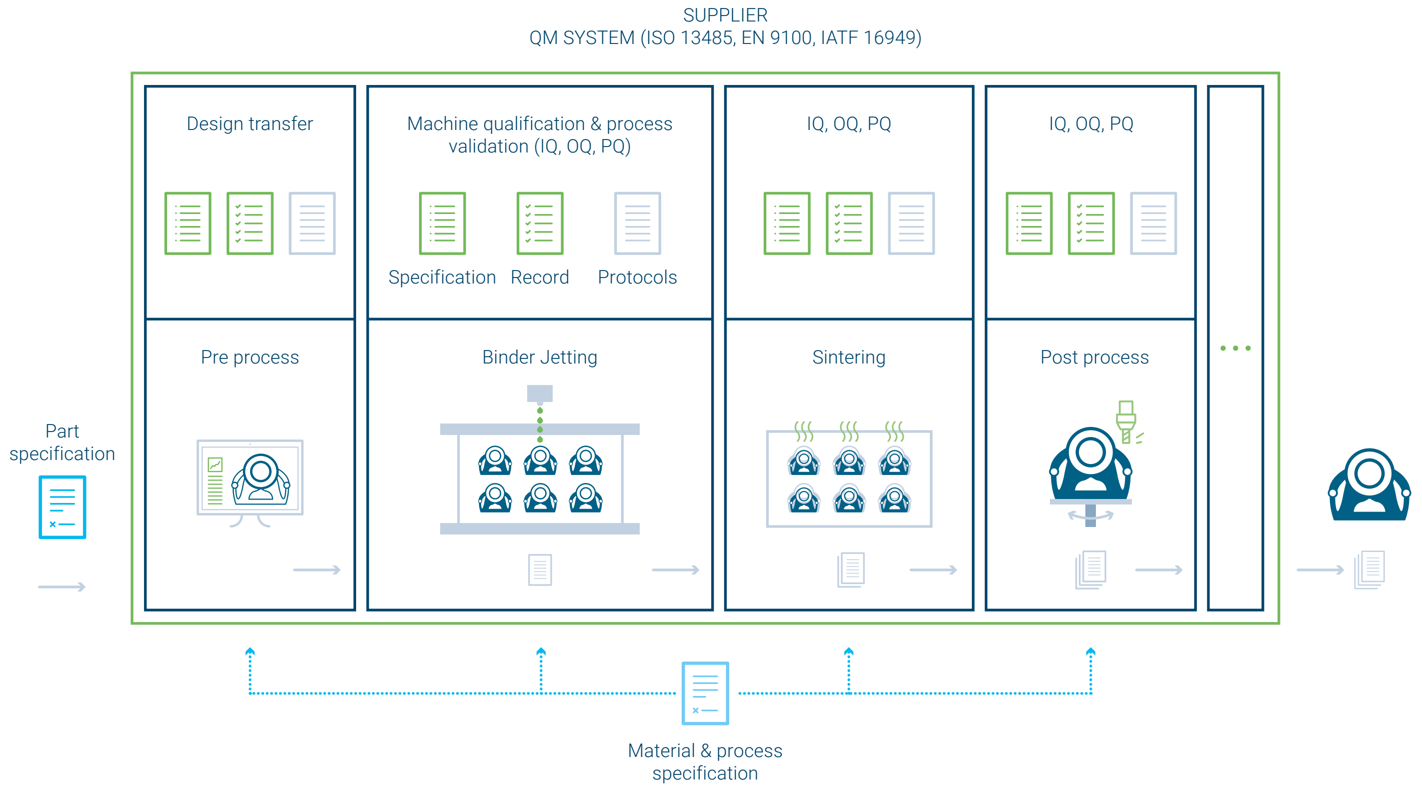
The material and process specifications outline how a part should be manufactured. It includes a description of all feedstock materials, process strategies, machine technologies, quality assurance measures, inspection intervals, non-destructive testing, and personnel requirements necessary for production. Additionally, it establishes the quality criteria, testing methodology and performance standards of the process.

Material and process specifications are crucial for ensuring the quality of the part. Developing a specification involves gathering relevant information and data and creating a document detailing the considered process. It is essential to ensure that the document is comprehensive, considering the complete process chain. Once the process specification is developed, it should be tested and validated to ensure it meets the quality criteria and performance standards.

Process validation

Process validation is a documented evidence-based process that demonstrates that a particular process consistently produces a product meeting its predetermined specifications and quality attributes.

If a process yields a result that cannot be directly verified, such as the measurement of the length of a part, process validation is required to ensure operation within acceptable boundaries. An example is the verification of mechanical properties after a melting process. Direct verification would involve destructive testing of each part to ensure its mechanical integrity. By understanding, defining, and controlling significant process parameters, the process is kept within acceptable ranges. During process validation, the limits of a successful process are determined to define acceptable process windows.



Qualified production

The defined specifications have to be fulfilled by the supplier to receive production approval, regardless whether it is an in-house production facility or an external supplier.

The machine qualification is a series of inspections and tests to verify that equipment meets requirements. This includes procedures and documentation for the acceptance tests (at factory or on site) as well as installation, operation and maintenance of the machine. The requirements typically derive from industrial standards, manufacturer and customer specifications. The method of Installation, Operational and Performance Qualification (IQ, OQ, PQ) used in medical industry has been proven to be well adaptable to AM systems.

Furthermore, a detailed specification and documentation of each process step ensures reproducible execution. Continuous and gapless reporting guarantees full traceability of all critical process parameters and the material flow.

User voices

"Kennametal has been able to utilize Binder Jetting Technology for both internal and external solutions using our in-house developed and manufactured WC-Co grades for high wear applications. The value proposition for BJT includes but is not limited to: manufacturability of complex solutions not capable via conventional manufacturing methods, product performance improvement through DfAM, tooling cost reduction, JIT inventory, lead time reduction, and more. There is also potential ESG benefits compared to conventional methods of manufacturing, adding to the list of pros for BJT."

JERRY DOMINGUEZ

BUSINESS DEVELOPMENT MANAGER, ADDITIVE MANUFACTURING, KENNAMETAL INC.

"Azoth specializes in sinter-based additive manufacturing utilizing technologies like binder jetting to mass produce small complex metal parts. Our innovative technology disrupts the production manufacturing of small complex parts in a way that allows for mass customizations and product configurations unattainable by conventional manufacturing.
We provide seamless transitions from prototype to production parts that allow customers faster product development and market entry at scale.

RONNIE SHERRER

APPLICATIONS ENGINEER, AZOTH

"Working with hard materials such as cemented carbides, there are only a few additive manufacturing technologies with which we can truly master these. Binder jetting is one of the sinter-based additive manufacturing technologies which unleashes their full potential, breaking free from design restrictions. With such freedom, we can redesign wear-resistant, cemented carbide nozzles and nibs with increased performance. This generates true customer value at a reasonable cost."

MIKAEL SCHUISKY

HEAD OF ADDITIVE MANUFACTURING SERVICES, SANDVIK ADDITIVE MANUFACTURING

"Metal 3D Printing technologies have revolutionized the manufacturing industry with the use of less material, labor, and energy yet more effective than conventional manufacturing technologies. As Indo-MIM is deploying the additive manufacturing techniques like Metal Binder Jetting at a scale and fully integrate it in our system, it can revolutionize the flow of products in the supply chains. We can manufacture highly complex, precision, and innovative designs instantly without any prerequisite tool or mold, but with greater efficiency and lead time. Customers would love JIT (just in time) manufacturing and we would eventually work to accomplish their goal."

JAG HOLLA

SR. VP-MARKETING, INDO-MIM INC.

"At GKN Additive, Metal Binder Jetting (MBJ) enables a transformative era in manufacturing by seamlessly integrating innovative part design with our established expertise in powder metallurgy, sintering and large-scale production.
By allowing the cost-effective serial fabrication of highly complex solutions with internal functional structures, MBJ complements GKNs core production technologies (press & sinter, MIM, Laser Powder Bed Fusion). We revealed significant innovation potential in media distribution components (nozzles, manifolds, distributors) and high-performance tools, enhancing the competitiveness of automotive and industrial customers."

DR. PATRICK KÖHNEN

BUSINESS DEVELOPMENT & TECHNOLOGY MANAGER AM, GKN ADDITIVE

Binder Jetting adoption strategy – AMPOWER's implementation roadmap

1. Awareness Workshop

- Binder Jetting technology principles including debinding and sintering
- Available Materials and their characteristics
- Design restrictions and guidelines as well as successful design examples
- The fundamentals of BJT cost structure
- Typical project timeline 2-4 weeks

Results

- Awareness of technology potential, limitations and best practices
- Capability to identify potential lighthouse applications

2. Lighthouse Application Project

- Structured methodology and guideline that enables part selection
- Design and test print of 1-3 applications
- Proof of commercial feasibility
- Proof of technical feasibility
- Basis for further technology implementation decision
- Typical project timeline 8-12 weeks

Results

- 1-3 Binder Jetting applications with commercial and technical feasibility report

3. Implementation support

- Make or buy analysis
- Specification creation for design, material and process
- Quality determination along the process chain
- Establishment of manufacturing with consistent and proven part quality
- Qualification of the supply chain
- Typical project timeline 6-24 months

Results

- Qualified internal or external manufacturing capacity

AMPOWER CONSULTING SERVICES

Trusted industry advisors

As trusted industry advisors, we specialize in guiding companies through complex business landscapes. Our consultancy services cover everything from Mergers and Acquisitions to Go-To-Market Strategy, ensuring your success.

Our Consultancy Services:

- Mergers and Acquisitions
- Technical Due Diligence
- Business Expansion
- Go-To-Market Strategy
- Market Intelligence
- Operational Excellence

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AMPOWER REPORT

Access to the most reliable AM market data

Shortly, after its first release in 2019, the AMPOWER Report became the reference for the Additive Manufacturing industry. It provides a detailed view on the AM market and state of the AM technologies. The AMPOWER Report shows the current market and forecasts the developments expected in the next 5 years.

Features & Benefits

- Based on primary research data from over 300 personal interviews
- Over 100 figures and graphs of AM market data
- Application database with over 150 industrial applications
- System supplier data based on personal interviews representing over 90 % of the globally installed base
- Online report with all data and figures directly accessible
- Global system, service and powder supplier database with more than 2,400 entries
- Metal AM machine database with system properties
- PDF report available

Read the full report today:
additive-manufacturing-report.com

About the authors

Bastian Barthel

LEAD SINTER-BASED ADDITIVE MANUFACTURING

Bastian has been a highly skilled professional in the field of additive manufacturing, specializing in binder jetting and powder metallurgy. Since 2016, he has effectively managed projects, with a strong focus on material and process development. With his Background in production technology and management he was further involved in various management and consulting projects. Bastian joined the AMPOWER Team in 2023, where he leads the metal and ceramic sinter-based Additive Manufacturing activities.

Matthias Schmidt-Lehr

MANAGING PARTNER AT AMPOWER

Matthias successfully led multiple projects in Additive Manufacturing with focus on business case and strategic development for AM users as well as system and material supplier. With a history in management consulting, he has a wide experience in business development, strategy development and communication. At AMPOWER he led multiple projects concerning DED, BJT and Metal Material Extrusion as well as a wide range of polymer AM technologies.

Dr.-Ing. Eric Wycisk

MANAGING PARTNER AT AMPOWER

Since 2008 Eric successfully supports OEMs from aerospace, medical and automotive to identify Additive Manufacturing applications and implement production capacities in their regulated environments. With a background in topology optimization, titanium alloys and fatigue he is focused on achieving the maximum part performance with the right AM technology. As Managing Partner at AMPOWER, Eric focuses on technology evaluation and benchmarking, AM material and part properties as well as sustainability.

Dr.-Ing. Maximilian Munsch

MANAGING PARTNER AT AMPOWER

Maximilian is a professional user of Additive Manufacturing since 2007. After finishing his dissertation on reduction of residual stresses in metal Additive Manufacturing in 2012, he acquired extensive hands-on experience with different Powder Bed Fusion processes in regulated industry before co-founding AMPOWER in 2017. As Managing Partner at AMPOWER, Max focuses on data analysis, market intelligence and due diligence investigations.

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