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Metal Binder Jetting: Taking metal Additive Manufacturing into high volume production

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1. Sinter-Based Additive Manufacturing

Sinter-Based Additive Manufacturing (SBAM) has witnessed significant growth in the recent years in terms of technologies and applications. SBAM encompasses a family of AM processes based on binder jetting, material extrusion, jetting and vat polymerization (explained in more detail later). All of these routes utilise a final solid-state sintering step to 3D-print metal and ceramic components. In SBAM a sacrificial binder is typically used to join the metal or ceramic powders, forming partially consolidated 'green parts' that are subsequently processed (thermally or chemically) to remove the binder (debind) and densified using conventional sintering in a furnace. The underlying principle behind SBAM technologies is that, unlike traditional 'beam-based' AM, the 3D-printing (shape-forming) step is decoupled from the densification (sintering) step, leading to a multi-step process [1]. This decoupling enables a fully solid-state process route that has a number of key advantages:

- Overcomes the technical challenges associated with powder bed fusion processes that involve melting materials within the build process, such as the need for support structures or heat sinks to manage residual stresses.
- Unlike traditional processes, it does not limit the range of materials to weldable alloys.
- It allows materials with high melting point such as ceramics and refractory metals, to be processed.
- The decoupling of shape-forming and densification increases the throughput of both stages and, hence, enables an increase in overall process yield, especially for small components.
- By avoiding the need for thermal management during part forming step allows the build process to operate at room temperature, making it relatively scalable and allowing for large build volumes to be achieved in recently released systems.

These advantages have attracted increasing interest from industry and resulted in the adoption of SBAM technologies across multiple sectors, such as automotive, medical, aerospace, electronics and jewellery. Technological developments in SBAM have seen rapid increases in recent years, and currently there are 4 specific methods of SBAM, as shown in Figure 1.

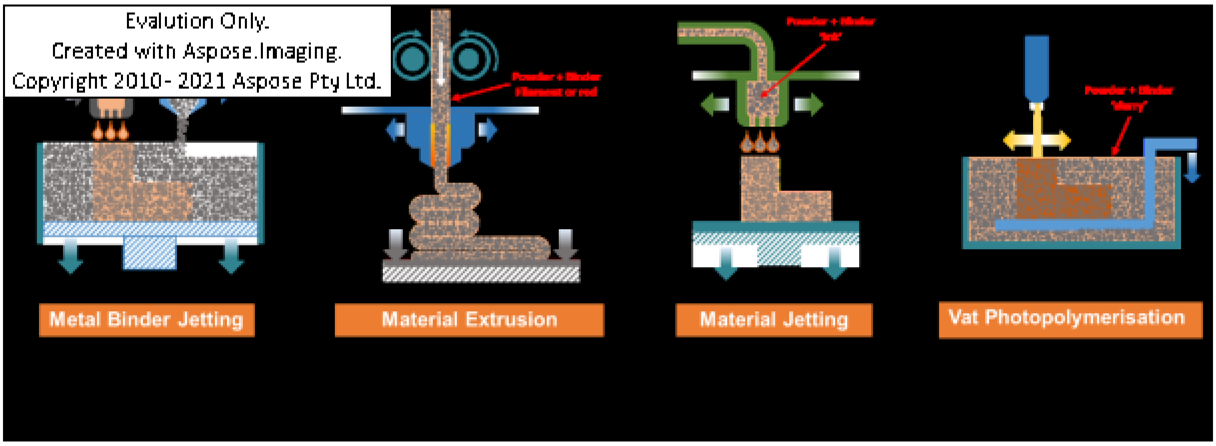

Figure 1: An overview of the main types of sinter-based AM technologies

2. Metal Binder Jetting

Amongst the SBAM processes shown in Figure 1, metal-binder jetting (MBJ) has been one of the fastest growing and earliest to be adopted by industry. In MBJ, metal powder and a binder "ink" are sequentially layered to form a 'green part' which then goes through a debinding step before being and sintered to almost full density (>98%). Figure 2 shows a schematic diagram of the process.

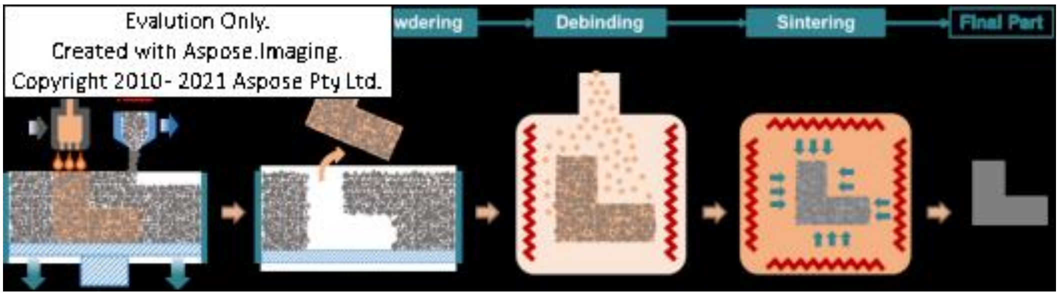

Figure 2: An illustration of the metal-binder jetting (MBJ) process

The process starts with a CAD (Computer Aided Design) file of the part, which is sliced into layers and converted into a printable file format. A layer of metal powder is then deposited and spread over the area of the build box using an applicator. The binder is then selectively deposited on the powder layer following information received from the sliced CAD file, similar in a way to conventional ink-jet printing. The process continues with sequential depositing of powders and binder layers until the print is complete, upon which the bonded 'green' parts are removed from the build box and the surrounding loose powder is recycled. The green parts are then subjected to thermal debinding to extract the binder material forming partially-consolidated 'brown parts', which are subsequently sintered close to full density with the part shrinking to compensate for the space previously occupied by the binder. This shrinking must be considered at the design stage – much like the shrinkage that occurs in the injection moulding of polymers.

3. Advantages and Limitations of MBJ

In addition to the general advantages of SBAM processes discussed earlier, MBJ has the following specific characteristics, which has contributed to its accelerated adoption by industry:

- The powder-bed nature of the process eliminates the need for support structures during printing, which allows for utilising the full build box via part 'nesting' and, hence, increase process throughput.
- The fine particle sizes of powders typically used in binder jetting enables good feature definition, high dimensional accuracy, and excellent surface finish properties.

As shown in Figure 3 produced by AMPower [2], these advantages have placed MBJ in a competitive position compared to other AM technologies and as a credible potential alternative to other traditional processes, such as casting.

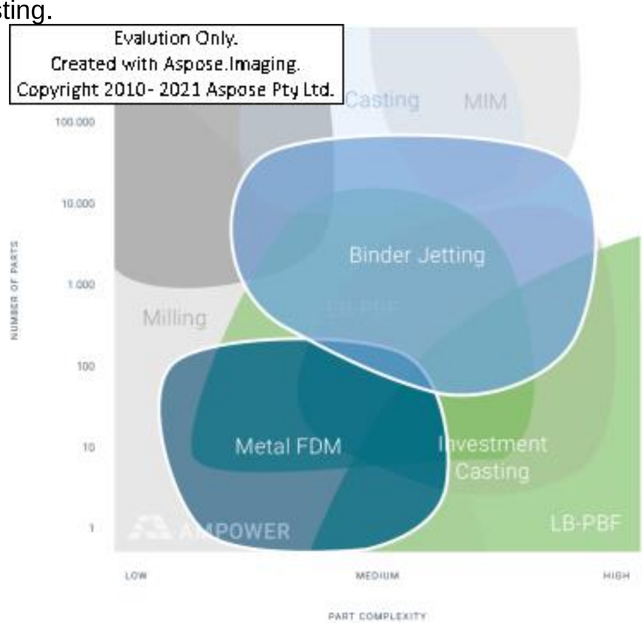

Figure 3: Technology impact in terms of production volume and part complexity (Image source: AMPower [2])

On the other hand, MBJ has a number of limitations, such as:

- The decoupling of printing and densification results in a multi-stage process (printing, drying, debinding and sintering), which is typically longer and more laborious than conventional AM and requires careful control of every stage.
- Sintered parts typically have a level of porosity, which for some applications would require post processing, e.g. HIP (Hot Isostatic Pressing) , to reach full density.
- Like all sinter-based technologies, design options for MBJ are limited by factors related to sintering challenges, such as non-uniform shrinkage and deformation of unsupported features. This in turn puts limitations on part design, such as overall size and wall thickness.
- The use of relatively fine powders in MBJ poses technical challenges (e.g. layer deposition), health and safety challenges (e.g. handling and storage) and cost challenges.

4. Recent Developments in MBJ

In order to overcome challenges that hamper the industrial adoption of MBJ, developments have focused on three primary areas: widening material options, enhancing part quality and increasing process throughput.

With regards to materials, a range of alloys have been successfully printed using MBJ in industry and academia, such as stainless steel 316L [3,4], stainless steel 420 [5,6], copper [7,8,9], Inconel 625 [10,11], Inconel 718 [12,13], titanium [14], Invar36 [15] and shape memory alloys [16]. Beyond metals, binder-jetting has also been used to 3D-print ceramics, polymers and biomaterials [17]. Machine producers keep certifying new materials for their specific systems, and recently more 'open' systems have been made commercially available, which would accelerate the development of new materials.

With regards to enhancing part quality, developments have focused on enabling consistent and defect-free parts. This includes improving powder properties (e.g., size distribution, flowability and wettability), improving binder properties (e.g., saturation) and controlling key process variable (KPV's), such as layer thickness, orientation, and droplet generation [18]. In addition to reducing defects and improving process fidelity, these improvements have also led to parts with higher dimensional accuracy and surface finish. Benchmarking studies have shown that MBJ could produce parts with linear features down to 150µm and surface finish down to 10µm (S_a) [19], making it suitable for applications that require high accuracy and excellent surface properties.

The third area of technical development is increasing process throughput. As discussed earlier, SBAM technologies are inherently suited for batch production due to the decoupling of printing and densification. However, relatively slow printing speeds and limited build volumes have been a significant limitation on process throughput and, hence, the full potential of productionising has not been exploited. Recent developments have focused on increasing process throughput by increasing build volume and build rate. Table 1 lists examples of some MBJ systems and their capacities.

Provider	System	Build Volume	Maximum Build Rate [cm^3/hr]	Minimum Layer Thickness [µm]	Ref
Desktop Metal	P-50	490x380x260 mm (48 Lt)	12,000	30	[20]
Desktop Metal	X160 Pro	800x500x400 mm (160 Lt)	3,120	30	[21]
Digital Metal	DMP/PRO	250×217×186 mm (10 Lt)	1,000	35	[22]
GE Additive	Series 3	500x500x500 mm (125 Lt)	n/a	n/a	[23]
HP	HP Metal Jet	400x320x200 mm (25 Lt)	n/a	50	[24]

Table 1: Examples of MBJ systems and their specifications

Across all the areas of development, modelling and simulation have been key enablers to overcome process challenges. This includes simulating aspects of both the printing (including binder droplet impact and penetration [25,26]) and sintering process (including shrinkage and deformation [27,28]).

Automation is another development area that is gaining increasing priority due to the laborious nature of the process. Digital Metal, for example, has worked on an automated system for de-powdering MBJ build boxes, which is currently a bottleneck in the process [29].

5. Market Trends and Commercial Uptake

The rapid developments in MBJ have brought the technology closer to commercialisation. Figure 4 shows the 2020 Maturity Matrix of Additive Manufacturing developed by AMPower, where MBJ was forecast to reach industrialisation in less than 2 years [30].

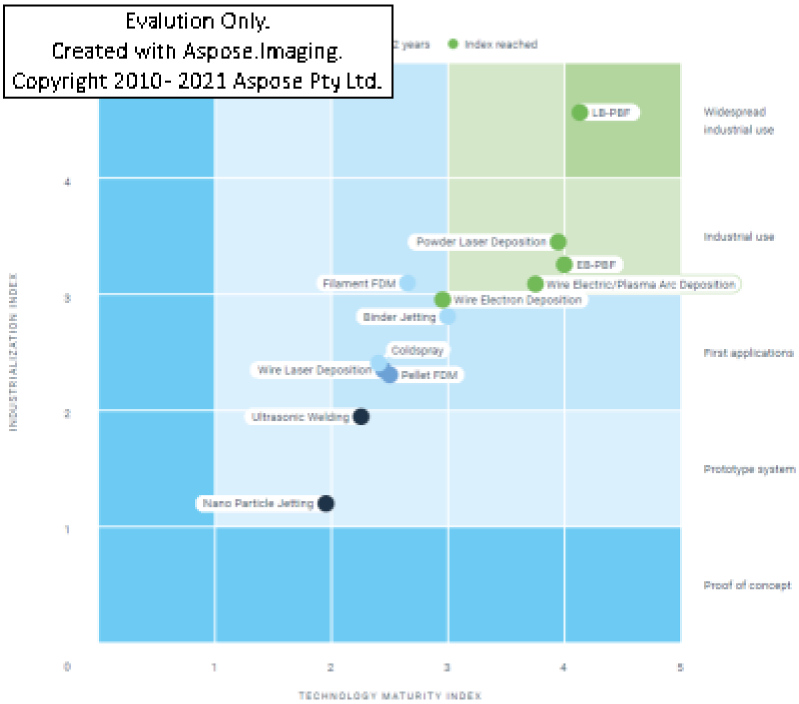

Figure 4: Maturity Index 2020 for Additive Manufacturing (Image source: AMPower [30])

In terms of market penetration, like many emerging technologies MBJ has had a relatively slow start, where at the end of 2020 the number of installed MBJ machines was 275 (compared to 10,600 beam-based systems) according to AMPower. In 2020, MBJ accounted for 3% of metal AM machines in terms of sales revenues (equivalent to ~€27Mil.). Despite this relatively small market share, AMPower forecasts that sales revenues will reach 8% of the total metal AM machines market by 2025 (equivalent to ~€225Mil.) at a CAGR of 53.1% (over double the 20% CAGR forecast for beam-based technologies) [23].

In terms of MBJ companies, there are not many manufacturers out there, and their numbers have recently decreased due to acquisitions. The key players in this market with fully commercial systems are currently Desktop Metal (based in USA and has recently acquired ExOne and MetaAdditive) and Markforged (based in USA and has recently acquired Digital Metal from Höganäs). Other key players with systems that are not commercially available yet include HP, GE Additive and Ricoh.

The commercial uptake of MBJ has notably increased in recent years, with partnerships between technology developers and industrial end-users accelerating adoption across several sectors. For example, in 2019, Cummins Inc. announced a partnership with GE Additive to develop MBJ for production [31] and in 2021, they announced finalising their first production part, the lance tip adapter, which is a critical emissions component in Cummins engines (Figure 5).

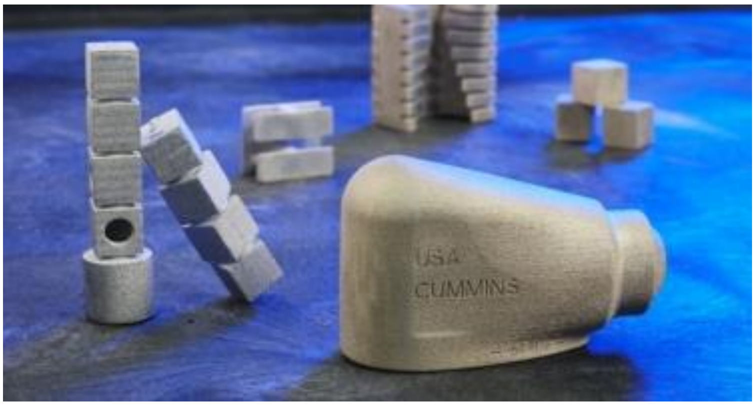

Figure 5: An image of the lance tip adapter developed by MBJ using the GE Additive System (Image source: Cummins [32]).

In 2021, Volkswagen, in collaboration with HP and Siemens, announced that it will integrate MBJ into vehicle production [33] for making automotive components (Figure 6).

Figure 6: An example of an automotive component produced by MBJ (Image source: HP [34]).

The growth is also driven by the traditional metal-injection moulding (MIM) industry, where MIM producers have seen an opportunity in MBJ for making small batches or prototypes to avoid tooling cost and lead time. For example, in 2019, Indo-MIM, one of the world largest producers of MIM parts for aerospace, automotive and other industries, has entered a partnership with Desktop Metal to integrate MBJ into production [35].

It is expected that MBJ will quickly find more applications in a range of sectors, such as medical parts like bone implants and scaffolds [36-38], fuel cells [7], aerospace components [37], energy and automotive [38].

6. The Role of Awareness and Training in Accelerating Adoption of MBJ

A key challenge to the wider industrial adoption of MBJ is that each stage of the process needs to be optimised in order for the final part to be successful. Unlike conventional AM processes, the printing stage of MBJ is not the most technically challenging aspect of the process. It is rather the downstream processes, especially sintering, that dictates the final quality of the part. It has been noted that knowledge in sintering technologies, both theoretical and practical, is not widely available and is not easily learned [23]. This is primarily because of the complexity of the process and the number of variables that need to be optimised to achieve successful sintering. Although the principles of sintering are relatively available in public domain, the practical aspects that are typically gained via years of experience are not as widely accessible. This relatively lack of knowledge extends to other relevant aspects of the process such as design rules for sintering, achievable surface properties, quality assessment, standards, etc.

These challenges were taken into consideration when the SAM training programme for MBJ was put together. The training was jointly organised and delivered by the MTC and Politecnico di Milano between 28th and 30th of March, 2022. It was aimed at delivering a comprehensive programme that combined both theoretical and practical aspects of MBJ. The programme also included subjects that were designed for both engineers and operators. Topics covered included an overview of the MBJ process, material selection and characterisation, key process variables, design rules for MBJ, sintering theory and practices and industrialisation of MBJ. Attendees gained a broad knowledge of MBJ technology, hardware and process capability, as well as more detailed understanding of the effect of processing parameters, advanced sintering principles, and when to use the process and the benefits its brings.

The training, which was attended by ~30 participants, was followed by an assessment, which was prepared by Istituto Italiano Saldatura, the Italian ANB (Authorised Nominate Body), and performed on site at Politecnico di Milano, with support from the UK's National Centre for Additive Manufacturing at the MTC in Coventry, UK.

The participants were asked to assess the pilot course and provide feedback on the learning experience. As shown in Figure 7, the majority of participants were satisfied or highly satisfied with the content, especially for knowledge and skills acquired [39].

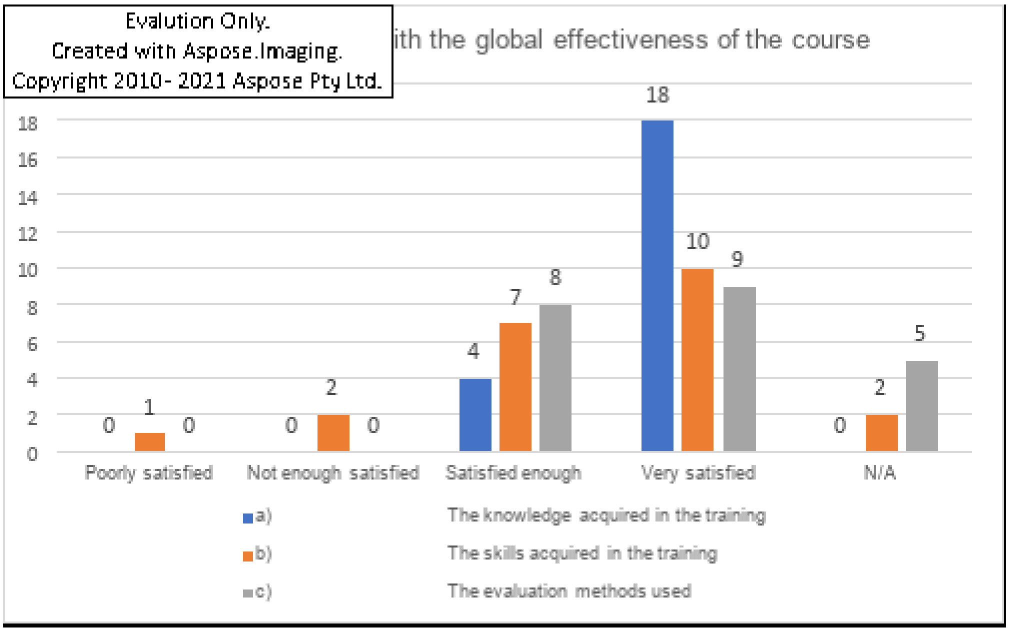

Figure 7: Assessment results for the pilot MBJ training

In their written feedback, the participants highlighted a number of positive aspects about the course, such as:

- The comprehensive content and coverage of different aspects of MBJ
- The expertise and knowledge of the trainers.
- The clear and well-organised structure and delivery.
- The combination of theoretical and practical aspects of the process
- The practical angles of the courses, such as process applications and industrialisation.

The participants also highlighted potential areas of improvement. Such as:

- The need for hands-on aspects, which was missing in the on-line delivery.
- The content was relatively dense compared to the duration of the course, which makes it challenging to comprehend all the delivered content.
- More focus is required on successful applications and case studies.

7. Conclusions

Metal binder jetting is the fastest growing SBAM technology today and the closest to commercialisation. The rapid adoption of the technology by industry is driven by the batch-production capabilities of the process combined with design freedom, high dimensional accuracy, and good surface finish. A key challenge that hampers faster uptake by industry is lack of awareness and knowledge about the process in general and about the downstream stages in particular. Therefore, developing dedicated training on MBJ is a key enabler for faster industrialisation, until now this training was not available. The SAM MBJ training is aimed at bridging this gap by creating a Europe-wide comprehensive theoretical and practical training offering. As mentioned, this was piloted in March 2022 and has been favourably received by participants. The next stage would be to follow up with the participant, in order to assess the impact of training on their current activities, as well as to take their feedback onboard in the next iterations of the training and make the course available as a regular offering to the wider industrial community in Europe, through its integration in the International Metal AM Coordinator Qualification or as separated training within the IAMQS.

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