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A REVIEW OF METALLIC BINDER JETTING PROCESSES WITH THERMAL INKJET HEADS

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Abstract. *Due to its versatility, Binder Jetting (BJT) has allowed for obtaining complex components using binders to agglomerate material particles spread in a bed. It can manufacture several materials, including metals, which demand a subsequent sintering phase. BJT operates with in-liquid or in-bed binding agents. Generally, systems that work with in-liquid binders have piezoelectric inkjet heads that handle fluids with higher viscosity and surface tension. In turn, thermal inkjet heads are cheaper but have limitations to jet more viscous fluids. This paper contributes to the literature by presenting an integrative review of studies that used BJT with thermal heads to manufacture metallic parts. The literature indicates a trend towards adopting piezoelectric BJT processes as they eliminate an extra step for feedstock preparation. However, jetting water-based solutions and solvents is faster and easier than binder solutions. Also, in-bed binders allow users to control both porosity and mechanical properties. For metal powders, results showed that not all demand an in-bed binder to be printed, such as the Inconel® and some copper composites. Standard in-bed binders include polyvinyl alcohol (PVA) and organic compounds like dextrin, maltodextrin, sugar, sucrose, and cornstarch. Water-based compounds with humectants and polymeric surfactants are jetted to activate the binders. Finally, the research demonstrates the importance of studying metallurgy to understand the role of the powder properties, the formulations, and the different approaches when designing a new BJT process.*

Keywords: *Binder Jetting, thermal inkjet heads, in-bed binders, metallic parts, metal-binder powder mixes, metal-binder systems*

1. INTRODUCTION

Additive Manufacturing (AM), commonly known as 3D printing, is a well-known group of manufacturing techniques within mechanical engineering. It emerged in the mid-1980s and has garnered significant attention (Dini et al., 2020). AM provides many benefits as a manufacturing process. One of the most prominent is the unparalleled design freedom, which allows the creation of parts with geometric complexities that cannot be obtained using subtractive manufacturing processes. It has been extensively used worldwide in many sectors, mainly in prototyping, tooling, and, more recently, end-use production (Bhatia & Sehgal, 2021; Rasiya et al., 2020). AM consists of adding material to a platform, building it up layer by layer until the 3D model is completed. This material deposition can be accomplished through diverse methods, categorized by ISO/ASTM 52900:2021 as material extrusion, vat polymerization, material jetting, binder jetting, powder bed fusion, directed energy deposition, and sheet lamination (Mehrpouya et al., 2021; Pagac et al., 2021). The literature shows that AM can process a wide range of materials. Specifically about metals, some of the techniques proved to manufacture complex parts with excellent dimensional accuracy (Barba et al., 2020; Gonzalez-Gutierrez et al., 2018).

In particular, the Binder Jetting (BJT) AM technique has gained significant attention for its application in printing metallic materials. A thin layer of powdered material is spread evenly across the building platform, also called tray. This powder acts as the base material for the object to be printed. A print head moves across the powder bed, depositing a binder material onto the specific areas corresponding to the cross-section of the printed object. The binder acts as an adhesive, bonding the powder particles in the desired shape. After the binder is applied, the build platform lowers by a precise distance, and a new layer of powder is spread over the previously printed layer. The binder is then used again, adhering the new layer to the prior one. This process is repeated until the entire object is constructed (Hong et al., 2016; Mostafaei et al., 2021).

For metallic materials, the process creates green parts, which have reduced mechanical resistance, provided solely by the binding agent. The metallurgical union and the final strength of the piece are only achieved after the post-processing stages, which will burn the polymeric binder and lead to a phenomenon of coalescence between the metallic particles from the application of a controlled heating cycle (Suwanpreecha & Manonukul, 2022; Thompson et al., 2019).

Notably, the primary advantage of utilizing BJT is the ability to achieve low levels of residual stresses in the final part, as demonstrated in various studies. Additionally, this method offers several other benefits, such as reduced operating and equipment costs owing to the utilization of low-energy sources, the capability to print without the need for support structures, and the elimination of controlled environments during the printing process (Dini et al., 2020; Fayazfar et al., 2018; Salehi et al., 2019; Volpato et al., 2017).

With that and knowing that the choice of binder in the BJT process can significantly impact the printing process's overall success (Utela et al., 2008), the present paper aims to review what researchers are studying about metallic BJT technology employing thermal inkjet heads to understand the use of in-bed binders, the powder properties, formulations, and the different techniques used for mixing.

2. METHODOLOGY

This article was structured based on an integrative literature review. Four guiding questions were elaborated based on the objectives of the research to discuss the results found. The studies analyzed were obtained from different databases, including Google Scholar, Science Direct, Scopus, Portal Periódicos Capes, and Electronic Library Online (SciELO), prioritizing the most cited articles. The keywords used in the search were “Additive Manufacturing, Binder Jetting, metallic powder, metal, solid binder, in-bed binder, thermal inkjet heads”, and some combinations of them.

In total, 49 relevant papers were found through the keywords used. Among them 7 are reviews, 26 have used equipment with piezoelectric inkjet heads, and 16 have used equipment with thermal inkjet heads. These were published between 2010 and 2022. After selecting the articles, four guiding questions were elaborated, as presented in Table 1.

Table 1. Guiding questions.

1	What materials researchers are using to manufacture metallic parts with BJT?
2	What are the main properties that must be evaluated before making a metal-binder powder mix?
3	What are the most common in-bed binders that researchers are using?
4	What are the different techniques researchers employ to create metal-binder powder mixtures?

3. DISCUSSIONS

The research has shown that there is possibly no limitation regarding metallic materials that BJT technologies can process. Researchers have been employing BJT to manufacture parts of a wide range of metals, including iron, stainless steels (SS) like 17-4 PH, 316L, and 420, nickel-chromium superalloys, pure copper, brass, bronze, zirconium, zinc, gold, aluminum, and pure titanium (Bhatia & Sehgal, 2021; Lecis et al., 2021; Meenashisundaram, Xu, et al., 2020; Rishmawi et al., 2018; Ziaee & Crane, 2019). Especially regarding equipment with thermal inkjets heads, as shown in Table 2, the range of materials is also broad, going through Inconel®, 17-4PH, iron, titanium, copper, and its alloys.

Table 2. Summary of papers analyzed.

Authorship	Material	Equipment	In-bed binder	Liquid binder	In-bed binder mix strategy	RD
Wiria et al. (2010)	Ti PS 44 µm	Z Corp. 310 Plus	PVA PS 75 µm	–	Tumbling mixer	–
Basalah et al. (2012)	Ti PS 45-150 µm	Z Corp. 310 Plus LT 100 to 175 µm	PVA 3.0 & 5.0 wt% PS < 63 µm	ZB 58	Jar mill at 128 rpm for 4h	57.0 to 69.0%
El-Hajje et al. (2014)	Ti PS 45 µm	Z Corp. 310 Plus LT 100 µm	PVA 5.0 & 10.0% PS 75 µm	–	Dry ball milled at 50 rpm for 24h, vacuum dried & sieved < 180 µm	–
Carreño-Morelli et al. (2016)	17-4PH (granule) PS D90 22 µm	Proprietary Table-Top Machine 10 pL LT 50 to 200 µm	Organic binder	Solvent	-	95%
Enrique et al. (2018)	Inconel® 625 PS D50 24 µm	Z Corp. 310/510 Plus LT 70 µm BSC 100% BSS 200%	–	ZB 60	–	–
Rishmawi et al. (2018)	Iron WA PS 45 µm	Z Corp. 310 Plus LT 75, 100 & 125 µm BSC & BSS 200 to 300%	PVA 1.0 wt% PS < 63 µm	ZB 60	Rotary tumbler for 30 min	64.0 to 91.0%

Authorship	Material	Equipment	In-bed binder	Liquid binder	In-bed binder mix strategy	RD
Maleksaeedi et al. (2018)	Ti + granule PS 45 & 15 µm	Z Corp. 310 Plus	PVA 7.5 wt% PS 80 µm	–	Granule or Hybrid Modified Binder: Ti + PVA (1:1 vol%) mixed with a planetary ball milling at 200 rpm for 3h, vacuum dried & sieved < 80 µm	70.0 to 83.0%
Wheat et al. (2018)	Ti PA PS 0-45, 45-106 µm	Z Corp. 310 Plus LT 150 µm BSC 200% BSS 100%	PVA 3.0 wt% PS < 63 µm	ZB 60	Jar mill at 128 rpm for 4h	59.7%
Barui et al. (2019)	$TiAl_4V_4$ PS 10 to 20 µm	Z Corp. 510 Plus LT 100 µm BSC & BSS 100 to 150%	Ammonium persulfate 4.0 wt%	Aqueous solution of acrylamide (78:22 wt%) + TEMED (1-2 vol%)	Dry ball mill for 30 min with WC balls	99.7%
Enrique et al. (2019)	Inconel® 625 PS D50 24 µm	Z Corp. 310/510 Plus LT 70 µm BSC 100% BSS 200%	–	ZB 60	–	92.8 ± 0.8%
Carreño-Morelli et al. (2020)	TiH_2 (granule) PS 11, 20, 34 µm	Proprietary Table-Top Machine LT 50 & 100 µm	Organic binder	Solvent	Wet blending of TiH_2 + polymeric binder + solvent, then drying, milling & sieving	–
Enrique et al. (2020)	Inconel® 625 with & w/o MMC PS D50 24 µm	Z Corp. 310/510 Plus LT 70 µm BSC 100% BSS 200%	–	ZB 60	–	–
Meenashisundaram, Wang, et al. (2020)	Ti + Mg PS D90 45 µm	Z Corp. 310 Plus LT 100 µm BSC & BSS 100%	PVA 7.5 wt% PS D90 80	Isopropyl Alcohol + Deionized H_2O (1:1 vol%)	Dry mixing in a tumbler mixer at 200 rpm for 2h	57.7 to 84.6%
Yadav et al. (2020)	$TiAl_4V_4$ GA PS 45-105 µm	Z Corp. 310 Plus LT 150 µm BSC & BSS 100%	Dextrin	H_2O + Glycerol (70:10 mass%)	Ti-4Al-4V + (Dextrin + Deionized H_2O - 90:10 vol%), ball milled in tumbling mixer for 24 h, freeze-dried, milled for 24h & sieved < 160 µm	82.0%
Wheat et al. (2020)	Ti PS 0-45 + 106-145 µm	Z Corp. 310 Plus LT 150 µm	PVA 3.0 wt%	ZB 60	Jar mill at 128 rpm for 4h	65.7 to 82.9%
Li et al. (2021)	Cu + diamond PS 16, 30, 53 (Cu) / 31, 59, 59 (diamond) µm	CومeTrue T10, MicroJet Technology LT 120 µm	–	8% Diethylene Glycol + 2% TERGITOL 15S7	–	–

Notes:
The symbol "-" stands for information not mentioned in the paper.
Materials: PVA - Polyvinyl Alcohol; MMC - Ceramic-reinforced Metal Matrix Composites; TEMED - N; N; N′; N′-tetramethylethane-1;2-diamine; ZB 58 & 60 - commercial liquid binders.
Parameters: RD - Relative Density; LT - Layer Thickness; BSC - Binder Saturation Core; BSS - Binder Saturation Surface; WA - Water Atomized; GA - Gas Atomized; PA - Plasma Atomized; MMC - Ceramic-Reinforced Metal Matrix Composites; WC - Tungsten Carbide; wt% - Percentage by Weight; vol% - Percentage by Volume.

BJT processes can use liquid or solid binding agents (Mao et al., 2021). In the first approach, the binding agent is diluted in a binder solution (in-liquid binder), which is directly dispensed onto pure metal powder by the print head to form the part. In this case, particle bonding occurs through the evaporation of the vehicle that carries the binding agent. In the second approach, a solid polymeric compound (in-powder or in-bed binder) is mixed directly with the metal powder, and it is activated by dispensing a lower viscosity aqueous solution compared to the previous binder through the print head. Once again, particle bonding occurs after evaporation of the vehicles in the binder (Mao et al., 2021; Meenashisundaram, Xu, et al., 2020; Wheat et al., 2018; Ziaee & Crane, 2019, p. 784).

The approaches differ and require different process treatments, especially regarding the type of printhead to be used. The viscosity and surface tension of the fluids created are key factors, and these will define the most suitable type of printhead for each case, which can be thermal or piezoelectric (Mostafaei et al., 2021). The former, found in standard 2D inkjet printers, works on the fluid vaporization principle using electrical resistance. The fluid phase change generates a volumetric expansion that projects microdroplets, generally measured in pL (picoliters), of binder onto the powder substrate. These heads are easily found in the market and are considered low-cost items (approx. $50). Piezoelectric heads, on the other hand, are built with crystals capable of deforming themselves by handing an electric current. They are more precise, robust, and can conduct more viscous fluids. However, they are usually more expensive components (approx. $1,500) (Mostafaei et al., 2021).

Most commercial printers work by jetting binders directly onto pure metal powders (Maleksaeedi et al., 2018). Also, the literature indicates a trend towards adopting BJT processes that operate with liquid binders and piezoelectric print heads. Among the reasons, the facility of jetting binder solutions directly on pure powders is greater, as this eliminates the step of preparing the metal powder (Mao et al., 2021). However, there are also particular concerns when working with binder solutions, such as the need to be kept in the liquid phase to avoid clogging the heads (Utela et al., 2008).

Despite this increasing growth of piezoelectric systems, some recent studies still explore thermal heads to take advantage of more affordable technologies and control mechanical properties to meet different requirements. Solid binders have also been explored, particularly in generating porous materials in engineering and healthcare applications (Basalah et al., 2012; Chua et al., 2021; Meenashisundaram, Wang, et al., 2020; Meenashisundaram, Xu, et al., 2020; Miyanaji et al., 2020; Tshephe et al., 2022; Wheat et al., 2018). Moreover, jetting simpler substances such as solvents and water is much faster and easier than binder solutions and does not require sophisticated hardware (Maleksaeedi et al., 2018, p. 1).

As drawback, manufacturing parts directly with metal-binder systems as feedstock can generate parts with lower strength since the polymeric network naturally tends to have less continuity than parts produced with jetted binder solutions. Inhomogeneity on material spreading can also arise from powder segregation phenomena in these systems (Maleksaeedi et al., 2018). It also requires an additional step for powder formulation any time a new material is selected (Utela et al., 2008).

Surprisingly, some papers demonstrated that not all metallic BJT processes demand an extra in-bed binder to compound the AM feedstock. Some experiments with Inconel® were conducted using just commercial liquid binders from formerly Z-Corporation Co. (Enrique et al., 2018, 2019, 2020). ZB 60, like other similar liquid binders of the same brand (ZB 54, 56, 58, 63), is a water-based solution (85-98%) with a humectant (glycerol), a proprietary polymeric surfactant, and a solvent (2-pyrrolidone) (Enrique et al., 2020; Olivier et al., 2014; Rishmawi et al., 2018; Wheat et al., 2020).

Another research with metallic material without using an in-bed binder was performed to manufacture copper-diamond parts. In the study pure copper powder was ball milled with copper-coated diamond powder (10 & 50 vol%) and then jetted with an aqueous solution with diethylene glycol (8%) and a nonionic surfactant TERGITOL® 15S7 (2%) (Li et al., 2021).

An interesting BJT approach uses granules of a specific material as feedstock (Figure 1). The granules are small conglomerates composed of metallic powder and an organic binder that will be softened by the liquid binder during printing. The granules are processed before the AM process. Among some advantages, the strategy can overcome some spreadability limitations with very irregularly shaped particles (1), improve resolution by the possibility to create smaller droplets (approx. 10 pL) due to low viscosity liquid binders (2), and improve sintered density due to the use of fine powders to create the granules (metal injection molding particles range size) (3). Some materials such as 316L, TiH_2 (Figure 2) and 17-4PH (Figure 3 and Figure 4) were already tested (Carreño-Morelli et al., 2016, 2020).

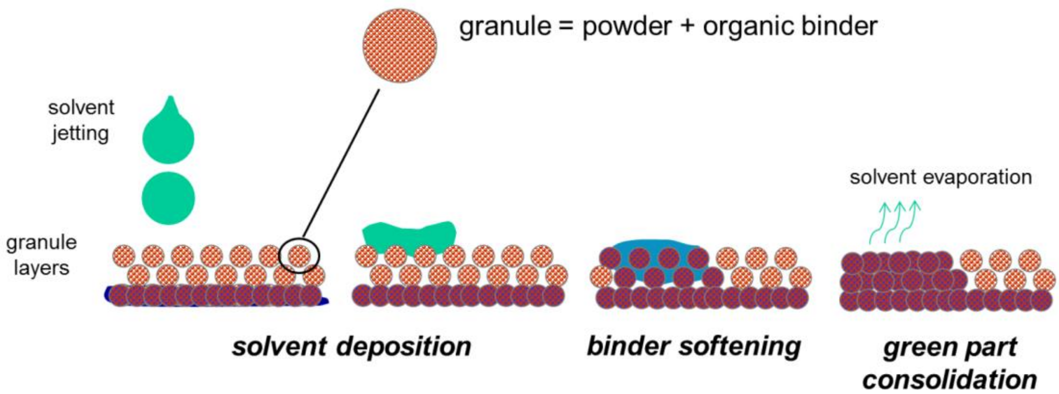

Figure 1. BJT with feedstock as granules. Source: Carreño-Morelli et al. (2020, p. 2)

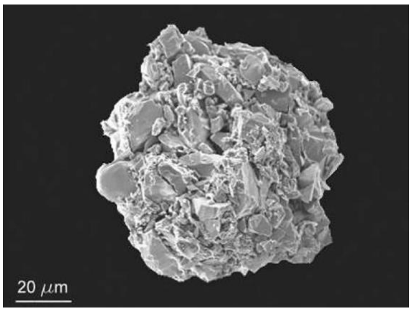

Figure 2. Granule of TiH_2. Source: Carreño-Morelli et al. (2020, p. 2)

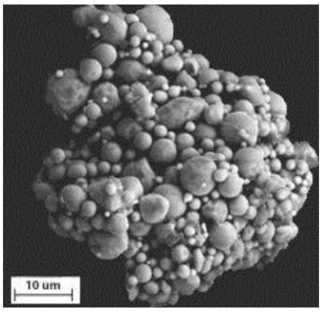

Figure 3. Granule of 17-4PH. Source: Carreño-Morelli et al., (2016, p. 2)

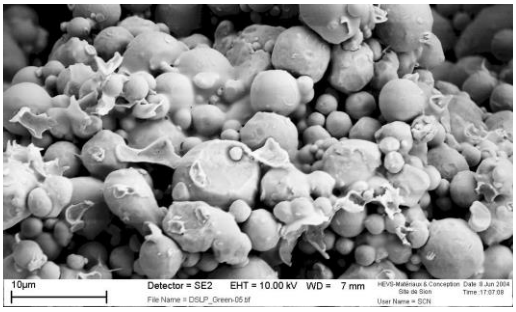

Figure 4. Green 17-4PH part showing particles bonded by polymeric bridges. Source: Carreño-Morelli et al., (2016, p. 2)

A very similar strategy was used, also with titanium, to mitigate feed powder segregation in the printing bed. Instead of granules, the authors called it a “hybrid binder (Figure 5). The hybrid binder is like a granule synthesized with equal volumes of fine powder of titanium (15 µm) and PVA. The mixture was processed at 200 rpm for 3 hours using planetary milling with a ball-to-powder volumetric ratio of 3:1. After vacuum drying and sieving, the binder was mixed with pure titanium coarser powder (45 µm), resulting in a concentration of 7.5wt% of PVA. The approach proved to be a good way to increase bed packing. Embedding metallic particles with PVA (Figure 6) has reduced the density difference between polymer and metal, decreasing the powder segregation phenomena during printing (Maleksaeedi et al., 2018).

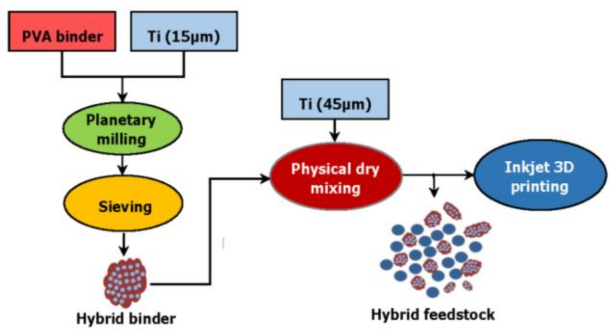

Figure 5. Preparation of “hybrid binder”. Source: Maleksaeedi et al. (2018, p. 3)

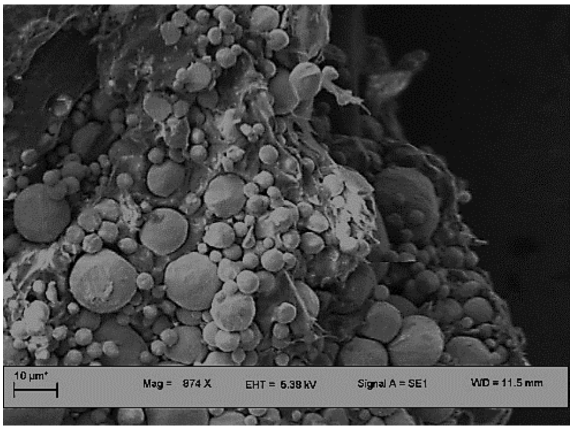

Figure 6. Hybrid binder: PVA impregnated with fine titanium powder. Source: Maleksaeedi et al. (2018, p. 3)

One important process parameter that should be analyzed in BJT processes and especially in granules printing case is the layer thickness. According to Bai et al. (2017, p. 5) and Basalah et al. (2012, p. 3) the layers must have a thickness greater than the size of the largest particle. The authors recommended using layer thickness (LT) three times greater than the largest particle for better packing densities and smoother finishing (Bai et al., 2017). The LT adopted in the selected papers vary in some standard values such as 50, 70, 100, 120, and 150 µm.

According to Utela et al. (2008), in-bed binders, should be highly soluble in the jetted liquid and present low viscosity after wetting to enhance pore filling and guarantee layer and particle interconnection. In addition, metal-binder systems should have low hygroscopicity, to prevent unwanted activation of the binder with air humidity, and high bonding force to ensure green part strength. The in-bed binder can be layer-spread (if particles are in a range of 10 to 40 µm) or integrated with the base material (Utela et al., 2008).

The literature shows that common in-bed binders include dextrin, maltodextrin, cornstarch, sugar, sucrose, some polyvinyl derivates, and some acids derivates, like ammonium persulfate (Barui et al., 2019; Maleksaeedi et al., 2018; Utela et al., 2008). Specifically on the selected papers, 8 have used PVA, 1 dextrin, 1 ammonium persulfate, and 2 only declared using an organic binder (see Table 2). The quantities of PVA, for example, vary between 1 and 10 wt%, with the higher values being employed in studies focusing on the creation of porous parts.

Among the mixing techniques, mechanical mixing is one of the most employed. It can be conducted in dry or wet ways. On both, a measured quantity of binder is added to the metallic powder to be mixed in equipment such as rotary tumblers or jar mills. The process can be conducted with or without internal rotating elements like SS, zirconia, or tungsten carbide balls. Time and velocity vary case by case. However, an optimal blend must consider the relation between gravitational and centrifugal forces to ensure a correct mixture. An optimal velocity corresponds to 76% of the critical rotation rate, which occurs when both mentioned forces get equal (Basalah et al., 2012, p. 2).

Regarding powders, it is known that some properties directly influence processability and quality of BJT parts. Flowability is a prerequisite for a good layer formation, as it influences spreadability, but it is insufficient to guarantee successful printings (Mirzababaei & Pasebani, 2019; Ziaee & Crane, 2019, p. 782). Also, powder morphology and particle size distribution (PSD) are essential features to control final density, while powder size affects the reactivity of the binder with the powder, the wettability, the resolution, and the roughness. However, contrary to what some may think, smaller particles will not always contribute to good BJT results. In fact, for fine powders, the smaller the particle size, the worse the flowability property (Dini et al., 2020). This correlation occurs due to the surface area and particle volume ratio. Under high ratios, the van der Waals forces start to be significant compared to the particles' weight force increasing then the interparticle friction and compromising flow and powder packaging capacity (Dini et al., 2020; Mirzababaei & Pasebani, 2019, p. 7).

Wettability, in turn, interferes with the printing resolution as it determines how the liquid binder will be absorbed and distributed through the powder bed. The mechanism that rules the arrival and the impact of the droplets is very complex. Poor wetting can lead to particle rearrangement, while excessive wetting can be detrimental to reproducing smaller part features (Dini et al., 2020, p. 2-3).

The powder manufacturing process also influences the feedstock properties. The morphology is distinct when particles are produced by water and gas atomization processes primarily due to the cooling rate the metal experiences. Water-based processes tend to remove heat at higher rates generating particles with more irregular shapes (Figure 7) than gas-based, which generate more spherical shapes (Figure 8). Spherical powders generally result in higher packing densities and are easier to spread (Rishmawi et al., 2018).

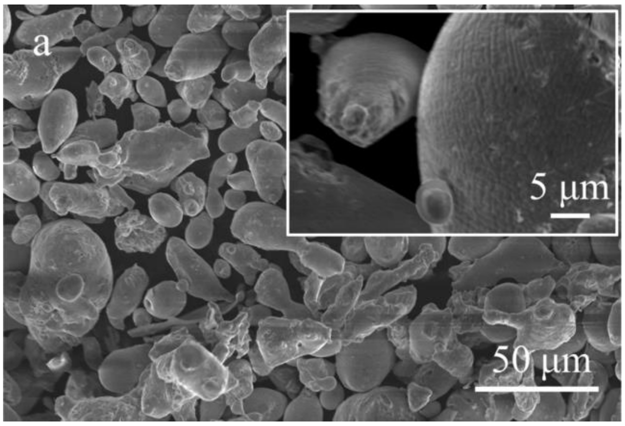

Figure 7. Nickel-based alloy 625 water atomized powder. Source: Mostafaei et al. (2018, p. 183)

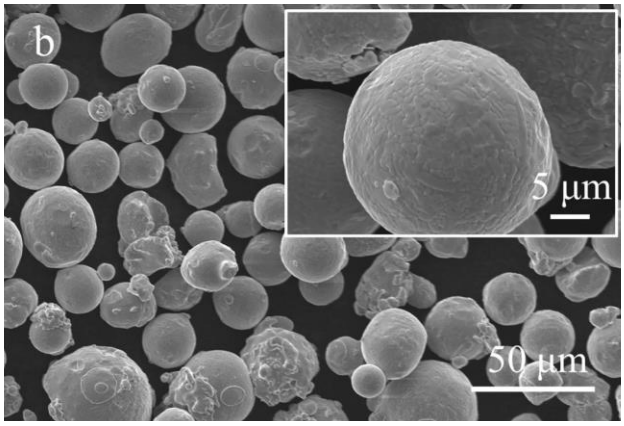

Figure 8. Nickel-based alloy 625 gas atomized powder. Source: Mostafaei et al. (2018, p. 183)

Regarding the liquid jetted, some concerns should be addressed when designing a BJT process. An ideal liquid binder is the one that is printable (1), have low viscosity to allow the nozzle streams individual droplets and break off quickly (2), and have good powder penetration and interaction (3) (Ziaee & Crane, 2019, p. 784). The viscosity measures the resistance experienced by the adjacent layers of a flowing fluid (Barui et al., 2019, p. 10).

Most piezoelectric inkjet heads manufacturers specify maximum fluid viscosities of 20 mPa.s (1 mPa.s = 10^{-3} Pa.s = 1 cPs - centipoise) (Derby & Reis, 2003, p. 817), but printers can handle up to 100 mPa.s. Another important property of the fluid that must be controlled is the surface tension. These printheads work well with surfaces tensions between 35 and 72 mN/m (1 mN/m = 10^{-3} N/m = 1 dyn/cm) (Utela et al., 2008, p. 100). In turn, thermal heads such as HP10 C4800a, used in printers like Z-Corporation 310/510 Plus, were projected to work with viscosities of 1.35 mPa.s and surface tensions up to 45 mN/m (Shakor et al., 2017, p. 399). Fluids with low viscosity and high surface tension tend to easily penetrate the powder bed (Meenashisundaram, Wang, et al., 2020, p. 11). Table 3 shows the viscosity and surface tension values for some substances to comparison.

Table 3. Viscosity and surface tension of different substances

Substance	**Viscosity** [mPa.s]	**Surface tension** [mN/m]	**Source**
Water	1	72	Utela et al. (2008)
Alcohol	1.07	21.82	Mao et al. (2021)
Phenolic resin	103	40.50	
Glycol	21.13	47.27	

It is worth mentioning that surface tension is the most accessible property to change in a fluid by simply mixing it with a fluid with a different value. The viscosity, on the other hand, is affected by factors like pH, solids loading, polymer loading, and polymer length (Utela et al., 2008, p. 100).

As mentioned, some studies were conducted with commercial liquid binders, but some researchers are synthesizing their own fluids. After mixing TiAl4V4 (10-20 µm) with ammonium persulfate (4wt%) as an initiator via dry WC ball milling for 30 min, (Barui et al., 2019) selectively jetted an aqueous solution of acrylamide (22wt%) and N, N, N′, N′-tetramethylethane-1,2-diamine (TEMED - 1-2vol%). The liquid resulted in a viscosity of 1.8 mPa.s and 56 mN/m of surface tension. The low viscosity value reiterates that fluid is non-adhesive until the interaction with the in-bed placed initiator.

3.1 Summary of results

Table 4 summarizes the answers to the guiding questions elaborated.

Table 4. Summary of answers to the guiding questions.

1	What materials researchers are using to manufacture metallic parts with BJT?
	The research has shown no restrictions concerning the materials that BJT technology can process. While ceramics were among the first materials to be processed by BJT, today, there is a wide range of metallic materials that can be employed, such as pure iron, stainless steel (14-4PH, 316, 316L, 420, 625, 718), brass, copper, bronze, gold, platinum, Inconel® and other nickel-based alloys, zirconium, zinc, aluminum, magnesium, titanium, and further combinations with other composites like tungsten-carbides, diamond particles, and copper oxide. Special composites/alloys are also already manufactured by BJT, such as CoCrFeNiMn, Ti-Al_4-V_4, and ceramic-reinforced metal matrix composites.
2	What are the main properties that must be evaluated before making a metal-binder powder mix?
	When designing a new BJT process, users can divide the analysis into four groups to understand the impact of some items like the feature designing (1), material properties (2), hardware capabilities (3), and process parameters (4) (Dini et al., 2020, p. 2). Regarding material properties, flowability and wettability are among the essential characteristics that must be evaluated when creating metal-binder systems. The former dictates the success of powder packing, while the second is essential to guarantee a correct interparticle connection. Fine powders have worse flowability when compared to coarse ones due to the van der Waals force prominence over gravitational forces. Insufficient wettability can lead particles to rearrange themselves in the bed. In contrast, excessive wettability can be detrimental to manufacturing small features. The jetted liquid binder should also have its properties analyzed in detail to ensure correct interaction with the powder. There are mainly two options for creating Drop-on-Demand (DoD): with piezoelectric and thermal inkjet heads. The thermal ones are generally more sensible and more restricted when dealing with fluids than piezoelectric ones. Usually, thermal heads work with fluids with lower viscosity and surface tension.
3	What are the most common in-bed binders that researchers are using?
	Among the studies found, researchers have been using some organic binders such as Polyvinyl Alcohol (PVA), which is a synthetic polymer derived from vinyl acetate monomers. Dextrin, maltodextrin, sugar, sucrose, cornstarch are also organic binders employed in BJT. Other less common alternatives, such as the Ammonium Persulfate $(NH_4)_2S_2O_8$ acid, can be used in-bed powders as an adhesive-initiator for the liquid that will be selectively jetted.
4	What are the different techniques researchers employ to create metal-binder powder mixtures?
	Metal-binder powder mixtures can be created with different approaches. Authors have been testing dry and wet mixing processes using mechanical processes. The process must generate sufficient energy to promote particle interaction, with or without rotating elements like SS, zirconia, or tungsten carbide balls. In the literature, researchers employ rotary tumblers and jar mills and adjust each case's rotation and process time. Typical velocities vary between 120 and 200 rpm for durations from 30 min to 48h. An optimal velocity corresponds to 76% of the critical rotation, which occurs when the gravitational forces equal the centrifugal forces. With the wet drying approach, a liquid solution with metallic powder, a polymeric component, and a solvent is synthesized. After a homogenous interaction, the solution is evaporated, milled, and sieved.

4. CONCLUSION

The present paper contributes to the literature by conveying several studies exploring BJT processes with thermal inkjet heads to manufacture metallic parts. With the research, it is possible to understand how researchers use this technology and the advantages of BJT processes aided with these types of heads.

The review highlighted the versatility of BJT in processing various metallic materials. Some experiments demonstrated successful BJT printing without requiring an additional in-bed binder, using commercial liquid binders or specific organic binders for effective particle bonding. Granules and hybrid binder strategies were also explored to improve powder packing and mitigate segregation during printing.

One of the key considerations in BJT is the selection of suitable binders and powder properties. Powder flowability, morphology, and particle size distribution significantly impact the processability and quality of BJT parts. Proper wettability of the liquid binder is crucial for achieving desired printing resolution and part features. Controlling binder viscosity and surface tension is essential for optimal printing performance, and researchers have experimented with customizing their own fluids to meet specific requirements.

In conclusion, the review presents a comprehensive overview of the advancements and challenges in metallic BJT technology, showcasing its potential for manufacturing complex metal parts with precision and minimal residual stresses. The varied approaches and binders used in BJT processes demonstrate ongoing research and development in this field, opening new possibilities for the future of AM with metallic materials.

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