

Metal Binder Jetting Additive Manufacturing: A Literature Review

Ming Li^a, Wenchao Du^a, Alaa Elwany^a, Zhijian Pei^a, Chao Ma^{a,b,*}

^a Department of Industrial & Systems Engineering, Texas A&M University, College Station, TX

^b Department of Engineering Technology & Industrial Distribution, Texas A&M University, College Station, TX

* cma@tamu.edu

ABSTRACT

Binder jetting is an additive manufacturing process utilizing a liquid-based binding agent to selectively bind the material in a powder bed. It is capable of manufacturing complex-shaped parts from a variety of materials including metals, ceramics, and polymers. This paper provides a comprehensive review on currently available reports on metal binder jetting from both academia and industry. Critical factors and their effects in metal binder jetting are reviewed and divided into two categories, namely material-related factors and process-related parameters. Reported data on density, dimensional and geometric accuracy, and mechanical properties achieved by metal binder jetting are summarized. With parameter optimization and a suitable sintering process, ten materials have been proven to achieve a relative density of higher than 90%. In-depth discussion is provided regarding densification as a function of various attributes of powder packing, printing, and post-processing. A few grades of stainless steel obtained equivalent or superior mechanical properties compared to cold working. Although binder jetting has gained its popularity in the past several years, it has not been sufficiently studied compared with other metal AM processes such as powder bed fusion and directed energy deposition. Some aspects that need further research include the understanding of powder spreading process, binder-powder interaction, and part shrinkage.

Keywords: Additive manufacture, binder jetting, density, dimensional and geometric accuracy, mechanical properties, literature review

1 INTRODUCTION

Since its inception in the 1980s, additive manufacturing (AM) technologies have demonstrated notable application potential across many industries, including the aerospace, biomedical, and automotive industries [1-12]. Unlike conventional fabrication methods such as formative and subtractive manufacturing, components are fabricated in a layer-by-layer fashion in AM processes [13]. This makes the AM processes suitable for producing parts with high degrees of geometric complexity. Furthermore, they can be used to process a variety of materials including metallic, ceramic, and polymeric materials [14]. Technical committees ISO 261 and ASTM F42 classified commonly used AM technologies into seven categories: binder jetting, directed energy deposition (DED), material extrusion, material jetting, powder bed fusion (PBF), sheet lamination, and vat photopolymerization [13].

Most commonly used feedstock forms of metal AM are powder and wire [1], although other feedstock forms (such as sheets, foils, and slurry) have also been used [15-17]. Several types of powder-based AM technologies were introduced and have witnessed notable advancements. Perhaps most common ones are PBF, DED, and binder jetting. PBF and DED employ thermal energy sources (e.g., laser or electron beam) to fuse the material in an inert atmosphere or vacuum [1]. Therefore, the rapid heating and cooling cycles pose difficulties in microstructure prediction and control [18]. Parts manufactured by PBF and DED are typically accompanied by residual stresses which can lead to cracks and failures [19-21]. Compared to PBF and DED, fewer studies have been conducted on binder jetting, whose working principle is different from PBF and DED.

Binder jetting is a powder-bed-based AM technology similar to PBF. The key difference lies in the mechanism used to form successive layers. In contrast to directly fusing the raw feedstock to build the part, binder jetting separates the process into two phases. In the printing process, liquid binding agents are first selectively deposited onto the powder bed, guided by the CAD model, to form the cross section of each layer. Curing and depowdering of the printed part are conducted afterwards. Next, the debinding and sintering processes are performed, where

the printed parts are placed in a homogeneous thermal environment to enhance the mechanical integrity. Therefore, the printing process in binder jetting has no demand for an enclosed environment of vacuum or inert protective atmosphere and the grain structure from binder jetting tends to be more equiaxed compared to that of PBF or DED [22-25]. In addition, the combination of low-temperature shape formation and controlled consolidation processes makes binder jetting suitable for fabricating a wide variety of materials. Binder jetting is capable of working with many material systems including polymers, ceramics, metals, and their composites. Since its invention, multiple companies have commercialized this AM technology, including 3D Systems (formerly Z-Corp), Desktop Metal, Digital Metal, ExOne, HP, Microjet, and Voxeljet. Specifically, ExOne and Desktop Metal have been marketing several metal binder jetting printers (e.g., X1 160Pro™ from ExOne, DM P2500 from Digital Metal, and Production™ from Desktop Metal) [26-28].

Advantages and drawbacks of commonly used metal AM processes are listed in Table 1. The first advantage of binder jetting is its relatively low machine cost. The cost structure of metal AM process built by Lindemann et al. confirmed that machine cost substantially contributes to the lifecycle cost of a part [29] and it is known that the required initial investment of PBF and DED is typically high. The second advantage is the wide range of available materials. Unlike the AM technologies using a high energy beam to directly fuse the part, binder jetting can be more capable of processing metals with 1) high optical reflectivity, 2) high thermal conductivity, and 3) low thermal stability. Binder jetting has a high scalability because numerous nozzles can be employed simultaneously. Though binder jetting requires certain opening on the parts for depowdering like the other powder-based AM processes, it does not need explicit support structures to act as heat sinks or mechanical anchors for overhang geometries, enabling more possible geometries (e.g., internal cavity). However, the final density of most metal parts processed by binder jetting is not as high as that of parts made by powder metallurgy or other metal AM processes [23, 30, 31].

Table 1. Comparison of metal AM processes

AM process	Advantages	Disadvantages
Binder jetting	<ul style="list-style-type: none"> • Relatively low machine cost • Ability to print a wide range of materials • High scalability • No explicit support structures required 	<ul style="list-style-type: none"> • Relatively low density
Powder bed fusion [18, 19, 21-23, 32-44]	<ul style="list-style-type: none"> • High accuracy • Fully dense parts • Good mechanical properties 	<ul style="list-style-type: none"> • High cost (both machine depreciation and operation) • Significant residual stress • Support material required
Direct energy deposition [20, 45-55]	<ul style="list-style-type: none"> • Large build volume possible • Graded materials capability • Good mechanical properties • Ability to build on or repair parts 	<ul style="list-style-type: none"> • High cost (both machine depreciation and operation) • Low resolution • Significant residual stress • Relatively rough surface

Several excellent review papers on binder jetting are available in the literature [10, 31, 56-62]. Ziaee and Crane provided a review on processes, challenges, and applications of binder jetting [58]. Their review paper covered the details of each step of binder jetting and the current development and challenges of binder jetting. Lores et al. focused on metallic materials and provided an in-depth review on several important factors of binder jetting and their effects [57]. Mirzababaei et al. summarized the existing studies specifically on stainless steel 316L components fabricated by binder jetting [60].

Complementary to the existing review papers, the objectives of this work are 1) to direct readers through the almost countless research articles in the literature by grouping them according to the investigated factors and their effects and 2) to reveal currently achievable printing quality by collecting comprehensive data (e.g., density, shrinkage, and mechanical properties) from both academia and industry. The paper starts with an overview of metal binder jetting in Section 2. Section 3 categorizes the research articles by the factors of interest and their

effects. Based on a large dataset collected in this work, Section 4 summarizes the density evolution during the entire process chain from apparent and tap densities of the feedstock powder, powder bed density, to green and sintered densities of printed parts. Sections 5 and 6 present the state of the art on dimensional and geometric accuracy and mechanical properties, respectively. Finally, the current knowledge gaps and future perspectives are identified in Section 7.

2 OVERVIEW OF METAL BINDER JETTING

As a non-fusion AM method, binder jetting first forms the shape of metallic parts, followed by post-processing for densification. The typical process is illustrated in Figure 1. Section 2.1 describes how the printing process forms the part in a powder bed. Section 2.2 introduces post-processing methods for the printed part. Section 2.3 gives an overview of the metallic materials reported in the literature.

Figure 1. Process flow of metal binder jetting

2.1 Printing Process

Figure 2 shows a schematic of the printing process of binder jetting. Typically, a binder jetting system consists of a powder supply platform, build platform, leveling roller, and binder printhead. The printing process is essentially a three-dimensional version of inkjet printing. The CAD model of the part is first sliced into layers of the selected thickness. A layer of powder is spread by the roller across the build platform, on which a liquid binder is then selectively deposited to bond the loose powder particles within the cross-sectional area of the part. The build platform then descends by a distance equal to the predetermined thickness of each layer. This process is repeated until the entire part (called the *green part* at this stage) is completed. In most cases, the strength of green

parts is not sufficient to satisfy most applications. Some subsequent processes (i.e. post-processing) are needed to enhance the density and thus the mechanical properties of the final part.

Figure 2. Schematic of the printing process of binder jetting

2.2 Post-processing

Similar to many other AM processes, post-processing is necessary for parts made by binder jetting. Prior to removing the loose powder particles around a green part (depowdering), drying and curing are usually conducted in an ambient environment to slightly strengthen the green part for better handling. Sintering is a common method to eliminate voids in the parts and improve the mechanical properties. Before the sintering process, the binder in green parts needs to be removed. The sintering process is usually combined with debinding in a single heat treatment process. Here is a typical thermal profile for binder jetting parts: 1) the green part is heated at a low temperature (usually 175–450 °C) for several hours to completely burn out the binder; 2) the debound part (*brown part*) is then sintered at an elevated temperature; and 3) the sintered part is cooled down. If debinding is incomplete, the residual binder can result in unexpected compositions. Unlike the curing process, debinding and sintering are usually conducted in a protective atmosphere (e.g., argon) or vacuum to avoid oxidation. If the material is easy to oxidize at high temperature, such as copper, pure hydrogen or a forming gas (mixture of hydrogen and argon) could be used for sintering [23, 63-65].

2.2.1 Sintering

Reduction of the surface energy of powder particles is the driving force of sintering [66]. Generally, the atoms in the powder are not active enough for sintering at a low temperature. However, the mobility of atoms increases with raised temperature and eventually activates the sintering. During sintering, metallic bonds are formed and mass transport occurs between powder particles, reducing the system energy [66]. There are two categories of

sintering mechanisms, *non-densifying* and *densifying*. At a lower temperature, sintering is dominated by non-densifying sintering, such as surface diffusion, lattice (volume) diffusion on the particle surface, and vapor transport. These mechanisms couple with particle coarsening and negligible neck growth. Densifying mechanisms begin to dominate as the temperature increases. For metals, grain boundary diffusion and lattice diffusion between particles are the dominant densifying mechanisms. The densifying mechanisms are favored to produce dense parts [66].

Figure 3 shows three stages of the sintering process: the initial, intermediate, and final stages. The initial stage occurs at a low temperature dominated by the non-densifying sintering, which does not generate obvious densification and particle movements [66, 67]. The size of interparticle neck is less than 1/3 of the particle size [67]. Pores are distributed across the entire part due to the voids existing in the powder bed. The size of pores is relatively small compared to the two latter stages. Generally, the density of the part is below 70% of the theoretical density in this sintering stage [67].

The intermediate stage occurs when the temperature increases to a certain material-dependent threshold. The sintering mechanisms are dominated by grain boundary diffusion and lattice diffusion between particles, which promote neck growth and mass movement [67, 68]. As the sintering process progresses, the necks grow to a point where their size is approximately 1/2 of the particle size. Along with the growing interparticle necks, the large pores start to merge with the others and become tubular while the fine pores are gradually eliminated. It densifies the part to a density ranging from 70% to 92% of the theoretical density [67]. In the first two stages, the pores remain open to the external surface of the part, allowing gas passing in and out freely.

The sintering enters the final stage in a similar sintering temperature range of the intermediate stage [68]. The highest sintering densification can be achieved if the sintering conditions permit. The pores become isolated and, if possible, are eliminated during sintering in the final stage [67, 68]. When the sintering temperature is high enough, liquid-phase sintering occurs with melting on particle surfaces. If a material is heated to a temperature

between its solidus and liquidus, supersolidus liquid phase sintering (SLPS) occurs. The densification is enhanced as liquid forms and spreads to wet the particles [25, 67]. The presence of liquid is beneficial for densification but can also lead to part distortion [25, 69].

Figure 3. Illustration of microstructure evolution during sintering [67].

The sintering parameters are determined by material composition, particle size, and powder packing. The required energy for densification can be affected by the chemical composition and particle size so the sintering parameters are powder-dependent [24, 25, 69]. Sintering temperature and sintering time are critical sintering parameters. The sintering temperature is a dominant sintering parameter for final density and the densification rate [67]. As already discussed, high sintering temperature can trigger atom motion and mass transport, and meantime, with sufficient sintering time to promote densification. The total surface energy and surface contact area vary with particle sizes. Smaller particles have larger surface energy, hence, the higher particle bonding rate during sintering [67]. A higher contact area facilitated by the powder packing can also shorten the sintering time.

The sintering parameters should be selected based on the property requirements. Practically, within the temperature range for acceptable densification, a lower temperature should be selected to not only avoid the grain coarsening but also mitigate the dimensional distortion.

2.2.2 Other Densification Techniques

In some cases, additional post-processing techniques can be applied to binder jetting parts. Sintering additive and infiltration are the common methods used to increase densification. Metallic powders with a lower melting point than the primary material of the part are often chosen as sintering additives or infiltrants. Sintering additives are usually blended with the primary powder material prior to binder jetting process [30, 70, 71]. Infiltrants are introduced to the part before, during, or after the sintering process [72-75]. Special attention must be paid to the

composition, dimensional accuracy, and mechanical properties [70]. By using an infiltrant similar to the matrix material, homogenous infiltration technique shows a potential to mitigate the impact of soft infiltrant materials on the mechanical properties [76-78]. Hot isostatic pressing (HIP) was also conducted as post-processing to obtain high density and superior mechanical properties [64, 73].

2.3 Reported Materials

To date, the number of studied metallic materials on binder jetting is relatively smaller than that of PBF or DED. Among all metallic materials reported in the 82 research articles collected in this review, as Figure 4 shows, the most investigated materials are pure iron and ferrous alloys (38 articles) [30, 70-74, 79-110], followed by nickel and its alloys (13 articles) [24, 25, 69, 111-120], titanium and its alloy (9 articles) [68, 86, 121-127], copper (9 articles) [23, 63-65, 86, 128-131], and other materials [84, 110, 132-143]. Some researchers printed metal matrix composites or cermets by mixing pure metals or alloys with ceramic materials [118, 133-136, 138-142] to combine the stiffness and thermal stability of ceramics and the ductility and toughness of metals [144, 145].

Figure 4. Proportions of investigated metallic materials using binder jetting and corresponding numbers of reports

3 CRITICAL FACTORS OF BINDER JETTING

3.1 Summary of Critical Factors and Their Effects

The quality of metal parts fabricated via binder jetting depends on the materials-related factors and the process-related parameters which can be considered as two main sets of factors. This section summarizes the factors involved in binder jetting and their impacts on the physical and mechanical properties.

The factors and their associated effects are listed in Table 2. The material-related factors include the properties of feedstock powder and binding agents. The properties of the powder play a significant role in determining the powder bed conditions (e.g., powder bed density) and densification of the green parts. Moreover, the geometry and strength of the green parts are greatly affected by the nature of binder. The process-related parameters for binder jetting can be divided into: 1) parameters for the printing process (e.g., layer thickness and binder saturation) and 2) parameters for the post-processing (e.g., temperature-time profile and additional densification aids such as sintering additives and infiltrants). The parameters related to post-processing are mainly about the sintering process. The number of studies about the other post-processing steps is still limited. Among all listed factors, the five most critical ones are introduced in detail.

Table 2. Investigated binder jetting factors and related properties

Category	Factor	Related properties
Feedstock Powder	Particle size	Compatibility with binder [108] Powder densities [23, 91, 108, 111] Green density [63, 64, 68-70, 84, 91, 108, 111, 121, 126] Final density [23, 25, 63, 64, 68, 69, 84, 91, 97, 126] Final porosity [68, 69, 84, 97, 121, 126] Surface finish [91, 108] Oxidation [68, 70, 126] Microstructure [25, 68, 69, 84, 91, 126] Geometry or dimension [23, 25, 63, 68, 69, 84, 91, 108, 121, 126] Mechanical properties [91, 97, 104, 121]
		Powder densities [63] Green density [68, 69, 126] Final density [63, 68, 69, 97, 126] Microstructure [69] Geometry or dimension [63, 69, 121] Mechanical properties [121]

Feedstock Powder	Particle morphology	Powder densities [97] Green density [24] Final density [24, 97] Final porosity [97, 112, 122] Geometry or dimension [24, 91]
Binding Agent	Binder material	Compatibility with powder [106, 130, 131] Green density [65, 83, 128, 131] Final density [65, 128, 131] Composition [83, 106, 107] Microstructure [65, 106, 128] Final porosity [131] Geometry or dimension [65, 83, 106, 107, 128, 131] Surface finish [131] Mechanical properties [128]
Printing Process	Powder spreading strategy	Green density [94, 103, 104] Mechanical properties [94]
Printing Process	Layer thickness	Green density [103, 104] Final density [111] Final porosity [111] Microstructure [111] Geometry or dimension [80, 81, 109] Surface finish [80] Mechanical properties [72, 94]
Printing Process	Binder saturation	Green density [103, 104, 128] Final density [23, 104, 128] Geometry or dimension [80, 81, 109, 128] Surface finish [80, 81] Mechanical properties [94, 128]
Printing Process	Printing speed	Geometry or dimension [91, 92] Build time [91, 92]
Printing Process	Part location (build plate plane or build direction)	Green density [68, 126] Final density [68, 104, 122, 126] Geometry or dimension [30]
Printing Process	Part size and orientation	Green density [64] Final density [64] Final porosity [64] Geometry or dimension [64, 91, 92] Mechanical properties [72]

Debinding and Sintering Processes	Processing time	Final density [23, 63, 64, 97, 104]
		Composition [104]
Debinding and Sintering Processes	Processing temperature	Geometry or dimension [30, 63, 64, 70, 98, 104]
		Surface finish [104]
Debinding and Sintering Processes	Heating rate	Mechanical properties [104]
		Final density [23-25, 30, 63, 64, 68, 69, 71, 97, 104, 111, 112, 120, 126, 131, 143]
Debinding and Sintering Processes	Atmosphere	Final porosity [69, 111, 120, 143]
		Composition [120]
Other	Sintering additives and infiltrants	Microstructure [24, 25, 69, 71, 111, 112, 143]
		Geometry or dimension [23-25, 63, 64, 69-71, 89, 98, 101, 104, 111, 112]
		Surface finish [104]
		Mechanical properties [23, 24, 70, 71, 97, 104, 112, 121, 143]
		Geometry or dimension [89, 98]
		Final density [23, 70, 116]
		Porosity [116]
		Composition [70, 116]
		Microstructure [70, 116]
		Oxidation [23, 70, 86, 116]
		Geometry or dimension [23]
		Final density [30, 70-72, 101]
		Microstructure [30]
		Geometry or dimension [30, 70, 71, 101]
		Surface finish [30, 70]
		Mechanical properties [70, 71]

3.2 Material-Related Factors

3.2.1 Particle Size and Its Distribution

Particle size and its distribution noticeably affect the flowability and the sinterability of powder, which are the dominant properties in the printing and post-processing of binder jetting, respectively. A good flowability facilitates the powder spreading process during printing [61]. The powder flow characteristics can be measured using flowmeters (e.g., Hall flowmeter funnel or Carney funnel), according to the ASTM standard [146-148]. As

an alternative, the ratio (*Hausner ratio*, HR) of apparent density (ρ_{ap}) to tap density (ρ_t), which is defined by Equation (1), has been used to compare the flowability between different powders [149].

$$HR = \frac{\rho_t}{\rho_{ap}} \quad (1)$$

The smaller the HR , the better the flowability. Bai et al. investigated the flowability of powders with different average sizes of 77.9 μm , 26.4 μm , and 5.5 μm , which demonstrated HR of 1.16, 1.25, and 1.33, respectively [63]. Finer powder generally demonstrates a lower flowability due to the more significant effects of particle interactions (e.g., van der Waals, electrostatic, and capillary interaction) [10, 64, 68, 84, 91, 97, 150]. In contrast, the flow of powder with a larger particle size is less affected by the interparticle forces due to the larger inertia and fewer contact points.

With different particle sizes, the powders could have distinct impacts on the powder bed and green parts. When spreading spherical Inconel 718 powder, Turker et al. found that the printer had no spreading issue with the coarse powder (<53 μm), however, it failed to spread the fine powder (<20 μm) due to powder agglomeration [111]. The powder spreading issues caused by the presence of agglomerated fine powders were reported by many other researchers [68, 84, 97]. The agglomeration of fine powder particles leaves more pores in the powder bed, thus decreasing the green density. According to Turker et al., parts printed from the fine powders achieved very low green densities due to the spreading difficulty [111]. Similar dependency of green density on particle size was observed in other experiments: a higher green density can be achieved by coarse powder than fine powder. Dourandish et al. reported that the 75 μm Co-Cr-Mo powder yielded a relative green density of 54% whilst the 20 μm powder yielded a lower green density of 49% [84]. On some newly released binder jetting printers, the spreading difficulty with fine powder is mitigated by advanced spreading mechanisms, such as ultrasonic recoating and powder compaction, which can significantly reduce the printable particle size to lower than 5 μm [26, 151].

The particle size has a critical impact on the inherent sinterability of powder. Sinterability can be used to evaluate the sintering performance of powder. Sinterability is defined by Equation (2) [9],

$$\varphi = \frac{\rho_s - \rho_g}{\rho_{th} - \rho_g} \quad (2)$$

where ρ_s , ρ_g , and ρ_{th} are the sintered density, green density, and theoretical density. Fine powder typically has a high sinterability. The increased surface area of fine powder allows for higher sintering driving forces [63]. For instance, the sintering neck of the 7 μm Inconel 718 powder developed to near the particle size at 1230 °C while that of the 70 μm powder was still invisible [25].

The particle size distribution (PSD) also has a direct influence on both the printing and sintering processes. Mixing different unimodal powders can improve powder packing and green density. Bai et al. mixed coarse and fine copper powders with a 73:27 or 27:73 weight ratio by a rotating drum [63]. Both the apparent density and tap density of coarse powders (77.9 μm , 26.4 μm and 17 μm) increased by adding 27 wt.% of 17 μm or 5.5 μm fine powders. In the meantime, adding 27 wt.% of coarse powder (26.4 μm) to the fine powder (5.5 μm) could substantially increase the green density from 44% to 51.4%. The work by Mostafaei et al. compared the green and sintered Inconel 625 parts from powders with different PSDs [69]. Unlike the wide PSD powder (16-63 μm) which yielded nearly a full density when sintered at 1285 °C, the powders with narrower PSDs (16-25 μm and 53-63 μm) showed more incomplete sintering areas.

3.2.2 Particle Morphology

Owing to its influence on the spreading and powder arrangement in a powder bed, the shape of the powder particles affects the powder bed condition, green density, and final density. Spherical powder is preferred in binder jetting due to the low internal friction and thus good flowability [61]. Verlee et al. found that both green density and the average of apparent density and tap density of the non-spherical powder were only the half of those of the spherical one [97]. Haeri et al. studied the effects of particles with various aspect ratios on the powder bed density

and surface smoothness using discrete element method (DEM) [152]. The highest density was obtained by rod-shaped particles with an aspect ratio of 1.5 for roller spreading while by spherical particles for blade spreading. The surface smoothness decreased with increasing aspect ratio for both roller and blade spreading. The sinterability of spherical powder is considered to be better than that of powder in irregular shapes because of the more effective powder packing [24, 97, 122]. It is possible that the irregular-shaped powder has less interparticle contact area, and therefore, leaving more and larger pores in the green part.

Thus, many researchers used atomized powders for binder jetting because of their high sphericity [23, 24, 63]. Schade et al. and Mostafaei et al. compared the gas-atomized and water-atomized powders and reached the same conclusion that the gas-atomized powder is more spherical and preferred for binder jetting [24, 153]. According to Mostafaei et al., the difference in particle morphology of water-atomized and gas-atomized powders can affect the green density [24]. The green part from water-atomized powder exhibited a relative density of 42% while the gas-atomized obtained an increase to 55% [24].

3.2.3 Binder Materials

Since the geometry of the part is formed through the deposition of binding agents, the binder plays a key role in the quality of binder jetting parts. Utela et al. summarized eight available binder classes, including acid/base, hydration based, metal salts, inorganics, organics, phase changing materials, solvent, and thermal behavior alteration [62]. The compatibility of binder and powder is critical for successful printing. The main criteria of binder selection are the wettability and permeation ability which determine the spreading of binder in a powder bed and the strength of green part [61, 62, 130]. Figure 5 illustrates the binder-powder interaction and binder deposition process. Starting with the initial contact with the powder bed (Figure 5(a)), the binder droplet permeates the powder bed (Figure 5(b)) and form the powder into agglomerates (primitives) within and between the printing layers [130, 154]. The newly deposited droplets overlap with the previous one to ensure a continuous

bonding (Figure 5(c)). The binder deposition is controlled by the droplet volume as well as the spacing between binder droplets.

Figure 5. Illustration of binder deposition and powder primitive formation

Two other binder selection criteria concern the debinding and sintering temperatures and the residue composition. For most binders which require full decomposition before sintering, a distinct temperature gap between the binder decomposition and powder sintering is necessary [128]. The decomposed binder could leave a residue that affects the composition of the base material. For example, carbon- or oxygen-rich residues form carbides or oxides that degrade the microstructure of materials like Ti-6Al-4V [86], Inconel 625 [24], and stainless steels [70, 86].

A binder-powder compatibility test should be conducted to identify a suitable binder for the feedstock powder. Figure 6 shows three different methods to examine the binder-powder interaction. Two benchtop tests were summarized and introduced by Utela et al. [61]. As shown in Figure 6(a), the binder is introduced to a pile of feedstock powder using a syringe. The strength of the binder-powder mixture is then evaluated after drying. Figure 6(b) illustrates another method that manually mixes the binder and powder with a designated ratio. Then the strength and edge sharpness of the mixture are examined after shaping it into a bar or a cube. Alternatively, the contact angle of binder and the powder bed was introduced to indirectly evaluate the binder compatibility by Stevens et al., as shown in Figure 6(c) [122]. A low contact angle shows a good binder-powder wettability and thus is considered to be compatible. A suitable binder material should be absorbed by the powder easily and provide the green part with enough bonding after curing. A thermogravimetric analysis (TGA) can be carried out to examine the decomposition or sintering characteristic once a new binder-powder system is selected.

Figure 6. Binder-powder compatibility tests [61, 122]

3.3 Process-Related Parameters

3.3.1 Layer Thickness

Layer thickness is an important process parameter that controls the amount of powder spread onto each layer of the powder bed. The selection of layer thickness is dependent on the powder particle size [62]. Meier et al. applied discrete element method (DEM) that involved particle-to-particle and particle-to-wall interactions to simulate the powder spreading process [155]. They found that both the density and surface smoothness of the powder bed can be improved by increasing the layer thickness. A layer thickness of approximately three times the maximum particle size is considered to be optimal due to the sufficient space for the powder rearrangement and less influence from the top and bottom boundaries. Dourandish et al. reported their spreading experiments of fine (20 μm) and coarse (75 μm) powders with different layer thicknesses (75 μm , 100 μm , and 150 μm) [84]. The best printing quality was obtained at a layer thickness of 75 μm for the fine powder and 150 μm for the coarse powder. Using Inconel 718 powder of 26 μm , Turker et al. studied the density of parts printed with different layer thicknesses but sintered at the same temperature (1260 $^{\circ}\text{C}$) [111]. The density of the parts with 200 μm layer thickness was about 88% while that with 100 μm layer thickness was about 92%. Shrestha et al. tested the transverse rupture strength of sintered stainless steel 316L samples with variable layer thicknesses [94]. The strength obtained a trend that first increased and then slightly decreased when the layer thickness was changed from 80 μm to 100 μm and 120 μm and the powder particle size was maintained at 30 μm .

3.3.2 Binder Saturation

Binder jetting controls the deposition of binder via the level of binder saturation (S_a), which is the volume fraction of binder in the void space within a predefined powder bed, as defined by Equation (3),

$$Sa = \frac{V_b}{V_v} = \frac{V_b}{(1 - \rho_{pb}') \times V_{pb}} \quad (3)$$

where the ρ_{pb}' represents the relative packing density of the powder bed, V_{pb} is the volume of the predefined powder bed, V_b represents the volume of the binder, and V_v is the volume of the void spaces. Relative packing density refers to the volume fraction of powder in the powder bed, which is defined by Equation (4),

$$\rho_{pb}' = \frac{V_p}{V_p + V_v} \quad (4)$$

where V_p is the volume of the powder in the powder bed.

Binder saturation affects surface quality and dimensional and geometric accuracy. Inadequate binder saturation (i.e., undersaturation) can cause powder to drop from the green part and deteriorate the surface finish and dimensional and geometric accuracy [80, 81]. If the binder saturation is too high (i.e., oversaturation), the binder may migrate to outside the defined area (a phenomenon commonly called bleeding), bonding excessive powder and thus worsening surface finish and dimensional and geometric accuracy as well [80, 81].

Binder saturation also influences the density and mechanical properties. Undersaturation can cause inadequate bonding between layers or within one layer, leaving pores in the part that could deteriorate the properties [94]. Shrestha et al. tested the transverse rupture strength of stainless steel 316L samples printed with different binder saturations (35%, 70%, 100%) [94]. They reported that the strength of sintered samples was obviously lower for the 35% binder saturation than that for the others. Oversaturation leads to a lower volume fraction of powder and creates more pores after debinding [23]. Thus, the neck formation during sintering is hindered, resulting in decreased sintered density. But if the binder saturation is within a suitable range, there is no obvious impact on the sintered density because of the binder removal process (debinding). As reported by Bai et al., both 60% and 80% binder saturation provided similar sintered densities for the same copper powders with a particle size of 15 μm [23].

To predict the suitable binder saturation, a physics-based model was developed by Miyanaji et al. to estimate the capillary pressure based on the binder-powder interaction in the equilibrium state [156]. The predicted binder saturation agreed well with the experimental results on Ti-6Al-4V. This work indicates that the binder-powder interaction in the powder bed is driven by the capillary pressure over the interfaces of binder and air. Therefore, the selection of binder saturation should consider the interactions of binder, powder, and air.

4 DENSITY

The density of additively manufactured parts is one of the essential properties driving the quality of functional parts. Pores in the parts concentrate the local stresses, thus deteriorating the mechanical performance [157]. Different terminologies of density and porosity and their definitions were summarized by Du et al. [10]. This section discusses the densities in different stages with a focus on the effects of the critical factors and then summarizes the densities of the feedstock powder, powder bed, green part, and final part obtained by different post-processing technologies reported in prior works.

4.1 Powder Bed Density

Like many other powder-bed-based AM technologies, powder bed density is a critical factor of the binder jetting process. The powder bed density demonstrates how dense a predefined powder bed region is. For example, if the powder bed density is 55%, there is void space of 45% in powder bed region.

4.1.1 Measurements of Powder Bed Density

There are a few methods to measure the powder bed density. For example, a number of researchers printed a cup in the powder bed [63, 91, 119]. The powder bed density is calculated by dividing the mass of the powder contained in the cup by the volume of the cup. It is important to remove powder from the cup completely before weighing. Another measurement, reported by Ziaee et al., involves spreading a number of layers of powder on the build platform. Once the powder is spread, a tube with thin walls and sharp edges is vertically inserted into

the powder bed. The mass of the powder contained in the tube is measured after removing the powder around [101]. The final powder thickness in the tube has to be measured accurately.

4.1.2 Factors of Powder Bed Density

The powder flowability and the powder spreading condition are the two main factors affecting powder bed density. As mentioned in Section 3, powder flowability can be influenced by particle size, distribution, and morphology [24, 63, 69, 97, 119, 152]. Besides the inherent powder properties, there are reports on the effects of the spreading process on the formation of powder bed. Using discrete element method (DEM), Haeri et al. simulated the powder spreading process using rod-shaped particles with various aspect ratios to examine the effects of spreader type, spreading velocity, and layer thickness [152]. Their results showed that both the powder bed density and surface smoothness were more significantly affected by the spreader type and spreading velocity than the layer thickness. Budding et al. and Rishmawi et al. experimentally investigated the powder bed densities achieved via different shapes and motions of powder spreader [104, 158]. The counter-rotating roller demonstrates higher powder bed density and smoother surface than the forward-rotating roller, static roller, and blade. Budding et al. claimed that the combination of blade and forward-rotating roller has the potential to achieve a higher powder bed density than that using a counter-rotating roller [158]. A roller with a larger diameter or a blade that has a wider head profile is also beneficial because of the increased compaction area and pressure [152, 159]. The powder spreading velocity and layer thickness are the two major process-related parameters that affect powder bed density. DEM simulations demonstrated that slower powder spreading and decreasing layer thickness both lead to a denser and smoother powder bed [152, 160].

4.1.3 Density Variations within Powder Bed

A uniform powder bed ensures a consistent part quality in binder jetting. However, density variations in powder bed have been reported. Do et al. reported that the shrinkage of green parts varied with regards to the location of the powder bed [30]. They explained that, due to the movement of the roller spreading mechanism,

the powder was pushed towards the end of the build platform. More powder was accumulated and therefore higher localized powder bed density occurred at the further end from the powder supply, causing the green density difference and thus the shrinkage variation.

Lee et al. reported the downward displacement of the powder bed caused by compressive pressure (e.g., the weight of subsequent layers) [161]. The displacement of powder layers was a function of particle morphology and packing density. It was found that the displacement was more significant for the middle region of powder bed compared to the top or bottom region. This downward displacement could raise concerns about the powder bed uniformity.

4.2 Green Density

Geometry method is commonly used to measure the green density of regular shapes (e.g., cubes and cylinders). For parts with complex shapes, geometry method can be inaccurate. In this case, computed tomography (CT) could be used. The green density of binder jetting parts is usually 40–60% of the theoretical density. Once the printing process is finished, the green part typically consists of more than 30 vol.% voids and 10 vol.% binder [61]. The green density plays a key role in the final density and the shrinkage induced by the densification post-processing. Since the part is printed from the powder bed, the quality of green part is governed by the density and uniformity of powder bed. Therefore, the factors (i.e., powder flowability and powder spreading condition) influencing the powder bed density lead to consistent consequences to the green density. The detailed effects of the two major types of factors are discussed in Section 4.1.2.

4.3 Sintered Density

The driving force for the densification in sintering is the reduction in surface energy. The powder with a large specific surface area (e.g., fine powder) is preferred for densification. For example, the fine spherical stainless steel 316L powder (38 μm) obtained a density of 89.4% after sintered at 1432 °C for 90 min while the coarse

spherical powder (73 μm) obtained only a density of 71.6%, though both powders had similar powder bed densities [97]. The detailed effects of powder properties on sintered density are discussed in Sections 3.2.1 and 3.2.2.

In addition to the powder properties, the sintering temperature and time have direct impacts on the densification. As presented in Figure 7, the higher sintering temperature yields a higher sintered density as sintered density is determined by the amount of energy provided to the sintering. The required sintering temperature varies with the composition, powder properties, and application, as discussed in Section 2.2.1. For example, the sintering behavior of Inconel 718 parts was discussed in the study of Nandwana et al. [25]. At 1185 °C, no obvious neck formation occurred in the 21 μm and 70 μm powders because only initial sintering stage was reached. As the sintering temperature increased to 1230 °C, intermediate-stage sintering was activated on both powders where the mass started to transport between the contacting particles. As the sintering temperature increased from 1290 °C to 1330 °C, the sintered density of 21 μm powder reached 99.7% as the relatively large and tubular pores were reduced to small and spherical ones. Meantime, a sufficient sintering time is required for the neck growth between the powder particles. Bai et al. sintered the copper green parts in a mixed hydrogen and argon atmosphere for different sintering times [23]. By increasing the sintering time from 120 min to 360 min, the sintered density increased from 76% to 81%. Longer sintering time and higher sintering temperature could potentially increase the final density whilst the grain size may grow remarkably. Mostafaei et al. measured the grain sizes of Inconel 625 samples sintered at different temperatures for 4 h [24]. The samples sintered at 1225 °C had a relative density of 85% with a grain size of $39 \pm 4 \mu\text{m}$. As the temperature increased to 1300 °C, the sintered density increased to 99% whilst the grain size grew by about four times to $106 \pm 27 \mu\text{m}$.

Figure 7. Effects of sintering temperature on sintered density [23, 68, 73, 111, 112, 143]

4.4 Density by Sintering Additive

Mixing sintering additives with feedstock powder has been reported by some researchers. One of the important effects of sintering additive is the introduction of liquid phase to the parts during sintering, which can significantly increase the sintered density. Almost pore-free stainless steel parts can be achieved with sintering additives including silicon nitride, boron, boron carbide, and boron nitride [30, 70, 71]. Sun et al. used a powder mixture of stainless steel 420 (35 μm) and silicon nitride (2 μm , 0–12.5 wt.%) for binder jetting [71]. At 1300 °C, the sintered density of stainless steel 420 with no sintering additive was 64% while it increased with the silicon nitride amount. The highest sintered density reached 99.8% with 12.5 wt.% silicon nitride. A similar increase in sintered density was reported by Do et al. using boron-based sintering additives (i.e., boron, boron carbide, and boron nitride) [30, 70]. In their studies, bimodal stainless steel 316L (14+4 μm) and 420 (30+6 μm) powders were mixed with the sintering additives ($\leq 1 \mu\text{m}$) of up to 1 wt.%. The optimal sintering temperature was dependent on the material and the amount of sintering additive. The highest sintered density of stainless steel 420 reached up to 95.5% by adding 1 wt.% boron nitride. The mechanism of the enhanced densification is that the eutectic temperature of ferrous alloys is decreased by adding a small amount of elements, such as silicon, boron, carbon, and nitrogen [70, 162]. However, increases in porosity, distortion and even collapse may occur if excessive liquid phase is induced by further increasing the amount of sintering additives or sintering temperature [30, 71]. With sintering additive, the sintering profile needs to be adjusted. Moreover, the material specification is compromised due to the sintering additive. It is also worth noting that the difference in thermal expansion of the primary and additive materials may cause failure [71].

4.5 Density by Infiltration Process

Infiltration can be applied to increase the final part density. Inaekyan et al. infiltrated bronze into cured iron parts at 1100 °C in argon and achieved a final density of 85% with a transverse rupture strength 25 times better than the iron parts processed by HIP [73]. In the work by Doyle et al., the cured stainless steel 420 samples were infiltrated with tin-bronze (90 wt.% copper and 10 wt.% tin) at ~1100 °C in an argon atmosphere [72]. Liquid phase sintering of the tin-bronze infiltrant was observed. A low porosity (~1%) of the composite was measured by optical microscopy. Tungsten and stainless steel (316L and 420) obtained a density of above 95% after infiltrated with bronze, as reported by ExOne [110]. However, similar to the effect of adding sintering additives, the purity has to be sacrificed in this case.

4.6 Summary of Achieved Density

Due to the sequential steps involved, density should be tracked through each of the steps to understand the whole process. Table 3 summarizes the density evolution during the entire process chain and its correlation with the particle size. The reported materials include cobalt alloys, pure copper, nickel-based alloys, pure iron and ferrous alloys, pure titanium and its alloy, and tungsten. About 60% of prior works that investigated densification have demonstrated the possibility of reducing porosity to less than 10%. The studies on the effects of particle size and its distribution pointed out their significance to the densities. With parameter optimization and a suitable sintering process, ten materials have been proven to achieve a density of higher than 90%. The highest relative density achieved for each material is listed in Table 4. However, the number of materials that have reached a high density in binder jetting is still very limited compared with those in other metal AM processes such as powder bed fusion and directed energy deposition.

Table 3. Powder, green, and sintered densities of different materials with their feedstock powder particle sizes

Material	Particle size (μm)	Powder density (%)	Green density (%)	Sintered density (%)	Density by other densification techniques (%)	Note	Reference
Co-Cr-Mn	20	P*: 53	49	75	/**	/	[84]
Co-Cr-Mn	75	P: 53	53	81	/	/	[84]
Co-Cr-Mn	72.5 \pm 21.2	/	44.1	97.2	/	/	[143]
Cu	15.3	P: 56	/	85.5	/	/	[23]
Cu	16.5	P: 63	/	77.6	/	/	[23]
Cu	75.2	P: 55	/	63.2	/	/	[23]
Cu	Bimodal 5 (73 wt.%) + 30	A: 54.4, T: 61.2	51.4	92.3	/	/	[64]
Cu	Bimodal 15 (73 wt.%) + 5	A: 54.6, T: 67.4	53.4	85.5	/	/	[63, 64]
Cu	Bimodal 30 (73 wt.%) + 5	/	/	90.8	/	/	[129]
Cu	Bimodal 30 (73 wt.%) + 5	A: 53.7, T: 63.9	52.2	87.1	/	/	[63, 64]
Cu	Bimodal 30 (73 wt.%) + 5	/	/	/	99.9	Treated with HIP	[64]
Cu	Bimodal 75 (73 wt.%) + 15	A: 59.7, T: 66.9	57.2	74.5	/	/	[63, 64]
Cu	17	/	47	87.4	/	Cu nanosuspension as binder	[65, 128]

IN 625	22.5 (16–25)	/	45	98.2	/	/	[69]
IN 625	31.8 (16–63)	/	51.5	99.9	/	/	[69]
IN 625	31.8 (16–53)	/	53	99.6	/	/	[112]
IN 625	32 (18.6–44.2)	/	55	99.2	/	/	[24]
IN 625	32	/	/	>99	/	/	[114]
IN 625	32	/	/	98.9	/	/	[113]
IN 625	34.5 (17.6–53.6)	/	42	95	/	/	[24]
IN 625	53.1 (53–63)	/	47.5	97.5	/	/	[69]
IN 718	7.09	/	/	99.9	/	/	[25]
IN 718	19.75	/	/	92	/	/	[25]
IN 718	65.72	/	/	99.9	/	/	[25]
IN 718	26 (<53)	A: 50, T: 63.4	/	99	/	/	[117]
IN 718	26 (<53)	A: 50, T: 63.4	/	98.5	/	/	[111]
Ni-Mn-Ga	~25	/	/	66.3	/	Ball milled magnetic shape memory material	[115]
Ni-Mn-Ga	~40	/	/	~55	/	Ball milled magnetic shape memory material	[116]
Ni-Mn-Ga	<63	/	/	99	/	Ball milled magnetic shape memory material	[120]
Iron	34.1 (<63)	/	48.1	91.3	/	Mixed with 1 wt.% PVA	[103, 104]
Iron	29.1	A:44.3, T:50.7	40	43	/	/	[73]

Iron	29.1	A:44.3, T:50.7	40	/	53	Treated with HIP	[73]
Iron	29.1	A:44.3, T:50.7	40	/	82	Infiltrated with bronze	[73]
SS 17-4H	<15	T:52.8 P:43	43	~100		Coated with polymer ammonium polymethacrylate; Vibration spreading employed	[105]
SS 17-4H	/	/	/	98	/	Provided by ExOne	[110]
SS 304L	/	/	/	97	/	Provided by ExOne	[110]
SS 316L	/	/	/	98	/	Provided by ExOne	[110]
SS 316L	/	/	/	/	>95	Provided by ExOne; Infiltrated with bronze	[110]
SS 316L	Bimodal 14 (60 %) + 4	P: ~60	60	/	~99	Mixed with 1 wt.% BN additive; Sintered in vacuum	[70]
SS 316L	14 (5–25)	P: 51	53	80	/	/	[91]
SS 316L	15–30	P: 57	/	78	/	/	[90]
SS 316L	20	P: 53	52	88	/	/	[84]
SS 316L	<22	A:44, T:55, P: 56.5	56.5	93.9	/	/	[101]
SS 316L	22	P: 58.6	/	97.5	/	/	[97]
SS 316L	30 (22–43)	/	/	50	/	Lattice structure	[95]
SS 316L	30	/	/	52.4	/	/	[100]

SS 316L	31	P: 57.6	/	98.7	/	/	[97]
SS 316L	45–90	P: 55.5	/	71.6	/	/	[97]
SS 316L	55	A:41, T:48, P: 56	/	96	/	Cured agglomerate of powder <22 μm as feedstock	[101]
SS 316L	75	P: 53	54	80.5	/	/	[84]
SS 316L	78 (44–106)	P: 61	58	72	/	/	[91]
SS 420	/	/	/	/	95	Provided by ExOne; Infiltrated with bronze	[110]
SS 420	30	/	/	/	96.98	Mixed with 1 wt.% B additive	[30]
SS 420	30	/	/	/	99	Infiltrated with 0.45 vol.% bronze	[72]
SS 420	35 (22–53)	/	57	/	99.8	Mixed with 12.5 wt.% Si ₃ N ₄ additive	[71]
SS 420	Bimodal 30 (60 %) + 6	P: ~60	60	/	99.6	Mixed with 1 wt.% BN additive; Sintered in vacuum	[70]
Fe-Mn	<44	/	/	60.5	/	Ball milled bio- material	[88]
Fe-Mn- Ca	<44	/	/	47.1	/	Ball milled bio- material	[88]
Ti	45–75	/	/	68	/	Mixed with 3 or 5 wt.% PVA	[121]
Ti	45–150	/	/	59	/	Mixed with 5 wt.% PVA	[121]
Ti	45–106	/	47.9	70.5	/	Mixed with 3 wt.% PVA	[68]

Ti	75–90	/	/	71.7	/	Graded material; Mixed with 3 wt.% PVA	[125]
Ti	106–150	/	57.6	71.5	/	Mixed with 3 wt.% PVA	[68]
Ti	bimodal: 0– 45 (50 wt.%) + 106–150	/	53	84.6	/	Mixed with 3 wt.% PVA	[68]
Ti	bimodal: 0– 45 (50 wt.%) + 45– 106	/	45.9	82.7	/	Mixed with 3 wt.% PVA	[68]
Ti6Al4V	44–147	/	/	81.9	/	/	[122]
W	/	/	/	/	97	Provided by ExOne; Infiltrated with bronze	[110]

Note: * A: apparent density, T: tap density, P: powder bed density; ** /: Not specified

Table 4. Materials with reported relative final density of higher than 90%

Material	Number of articles	Highest relative density (%)
Iron	1 [104]	91.3
Stainless steel 17-4PH	1 [110]	98
Stainless steel 304L	1 [110]	97
Stainless steel 316L	5 [70, 97, 101, 110]	98.7
Stainless steel 420	5 [30, 70-72, 110]	99.8
Inconel 625	5 [24, 69, 112-114]	99.9
Inconel 718	3 [25, 111, 117]	99.9
Ni-Mn-Ga	1 [120]	99
Copper (Cu)	3 [64, 129]	99.9
Tungsten (W)	1 [110]	97

5 DIMENSIONAL AND GEOMETRIC ACCURACY

5.1 Dimensional Accuracy

The dimensional accuracy of binder jetting parts might be affected by the characteristics of powder and binder materials and process-related parameters [30, 70, 80, 81, 91, 92, 108, 127, 156]. Some of the processing parameters, including printing orientation and speed, binder saturation, and layer thickness have been empirically studied [80, 81, 91, 92, 105, 127, 156]. Seluga reported that the use of vector printing on the part outlines followed by filling the content using raster printing can possess a better surface definition compared to a complete raster printing [105]. Miyanaji et al. reported that the printing orientation and speed have impacts on the dimensional accuracy due to the initial velocity of binder droplets from the printhead [92]. They investigated the accuracy of the formation of single and multiple tracks with different printing orientations and speeds. The widths of tracks printed along the direction of printhead movement were more dimensionally accurate and consistent than those oriented perpendicularly to the movement direction. With increasing printing speed, the width of printed tracks decreased, and the consistency became worse as more unsaturated spots were observed on the tracks. Lu and Reynolds investigated the effects of binder saturation and layer thickness on the dimension of printed TiNiHf meshes using powders of 5.5 μm [127]. Three binder saturations (55%, 110%, and 170%) and layer thicknesses (20 μm , 35 μm , and 50 μm) led to different mesh widths, which were falling in the range of 280–340 μm while the designed is 200 μm . Bleeding was more pronounced at 20 μm layer thickness due to oversaturation. The most accurate mesh was printed with 35 μm layer thickness and 55% binder saturation achieving average width of 280 μm with the best consistency among all samples.

One of the biggest concerns that aggravate the dimensional accuracy is the shrinkage induced during sintering [23, 70, 72, 105]. To achieve a high final density, green parts must be sintered to at least the intermediate stage where the powder undergoes significant diffusion. As a result, shrinkage occurs due to the reduction of pores via

grain boundary diffusion and volume diffusion of particles. Volumetric shrinkage (S) is given by the relative volume change before and after sintering, i.e., the relative difference between green (V_g) and sintered (V_s) volumes:

$$S = \frac{V_g - V_s}{V_g}$$

$$= 1 - \frac{V_s}{V_g} \quad (5)$$

Mass is conserved in most sintering processes without considering the weight loss during debinding. In this case, the volumetric shrinkage can be rewritten as

$$S = 1 - \frac{\rho_g}{\rho_s} \quad (6)$$

This equation implies that the shrinkage dictates the ratio of green density to sintered density. In other words, densification is at the expense of increasing shrinkage given the same green density.

Figure 8 shows the shrinkages of different materials with the green and sintered densities. The volumetric shrinkage is calculated if linear shrinkages are reported. Most samples with relative sintered density over 80% have an average volumetric shrinkage of higher than 40% as most of green densities are 40–55%. This paper finds that the attainable density of green part may not be greater than 60% due to the non-optimal spreading process and the powder packing limitation. Some possible modifications to further retain the dimensions of the part are discussed in Section 7.3.

Figure 8. Shrinkage and relative densities of binder jetting parts [23-25, 63-65, 69, 73, 88, 101, 112, 114, 117, 121, 125, 128]

Many researchers have investigated the relationship between the level of shrinkage and the properties of the feedstock powder [25, 63, 69, 84, 97, 122]. Nandwana et al. evaluated the shrinkage of sintered Inconel 718 parts

from gas atomized powders with different sizes [25]. The fine powder (7 μm) obtained an increase in shrinkage from 31 vol.% at 1185 °C to 46 vol.% at 1290 °C. However, for the coarse powder (70 μm), no obvious dimensional change was observed until the temperature became higher than 1230 °C. It is indicative of the better sinterability of the fine powder, leading to higher shrinkage. Mostafaei et al. investigated the shrinkage of three Inconel 625 powders with different mean sizes and size distributions [69]. They reported that the green density was 45% for the fine powder (16–25 μm), 48% for the coarse powder (53–63 μm), and 52% for the powder with a wide particle size distribution (16–63 μm). For sintering temperatures below 1270 °C, the sintered density of fine powder was higher than those of the other two powders. The fine powder also led to the larger shrinkage after sintering at temperatures from 1225 °C to 1285 °C. The higher sintered density and larger shrinkage of the fine powder are probably due to its higher sinterability. The addition of nanoparticles to the green part was found to mitigate the shrinkage level through increasing the green density [65, 75, 79, 128, 131]. Bai et al. reported that, after adding copper nanoparticles to an organic binder, the sintered density was similar to that without nanoparticles while the shrinkage decreased [128]. The reason is that the jetted nanoparticles fill the powder bed voids, thus increasing the green density and decreasing the sintering shrinkage.

In addition to the overall dimensional deviations after sintering, the linear shrinkage along the build direction (z-axis) was observed to be greater than that in the powder bed plane (x-y plane) [64, 69]. Two possible reasons are: 1) the presence of more porosity in the z-direction than in the x-y plane due to the layering process and the spreading of binder and 2) the gravity effect during sintering process. Non-uniform shrinkage after sintering is another issue for metal AM parts [71, 75]. In binder jetting, the sintering could be very different from what has been studied in traditional powder metallurgy due to the complicated geometry.

5.2 Geometric Accuracy

In the current literature, only a few studies reported the accuracy of the parts with complex geometries. Sun et al. measured the inner corner angle of L-shaped stainless steel 420 samples and compared it to the design [71]. The as-printed samples acquired an angle of 90 ± 0.2 deg. As the sintering temperature increased above 1150 °C, the inner corner angle was increased by 0.5 – 1.0 deg. The shape was more distorted with increasing temperature as higher fraction of liquid phase formed. Geometric accuracy issues were also reported by other studies on simpler geometries (e.g., cylinders and cubes) [30, 69, 70]. More significant shape changes (e.g., distortion or even collapse) occurred when the sintering temperature exceeded the critical liquidation temperature. However, there is still limited investigation of the accuracy of complex geometry.

6 MECHANICAL PROPERTIES

In contrast to PBF and DED, only a few investigations have been conducted on mechanical properties of binder jetting parts to date. Table 5 shows the yield strength (YS), ultimate tensile strength (UTS), and elongation reported in the literature and the datasheet provided by ExOne and Desktop Metal. Values in the parentheses are the mechanical properties obtained by cold working. Among the surveyed papers, only eight of them investigated the mechanical strength of parts via binder jetting. Among all of the reported mechanical strength values, more than 30% are reported by the ExOne and Digital Metal. With the help of conventional aging treatment, the UTS of Inconel 625 increased by 12% from 644 ± 16 MPa to 718 ± 14 MPa [24]. In particular, stainless steel 17-4H, 316L, and 420 have demonstrated an equivalent or superior UTS compared to the cold worked samples [163]. Doyle et al. [72] reported that parameter optimization for stainless steel 420 has demonstrated promising mechanical strength that is higher than that reported by ExOne.

Table 5. Yield strength, ultimate tensile strength, and elongation of binder jetting (compared with cold working) parts

Material	Final Density (%)	Yield Strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Reference
Iron	91.3	30.6 (50)	/ (540)	/	[164, 165]
Stainless steel 17-4PH	98	730–1034 (980)	900–1317 (1060)	8.5–12 (8)	[110, 166, 167]
Stainless steel 304L	97	205 (215)	579 (550)	60 (70)	[110, 168]
Stainless steel 316L	95–98	180–224 (170)	494–582 (425)	51–61.9 (40)	[97, 110, 166, 169]
Stainless steel 316L	95*	283* (170)	580* (425)	14.5* (40)	[110, 169]
Stainless steel 420	95–99*	249.9–455* (345)	682–737.3* (655)	2.3–2.7* (25)	[72, 110, 170]
Fe-Mn Alloy	60.7	189.7	228.1	/	[88]
Inconel 625	98.9–99.6	327–376 (414)	612–644 (827)	40.9–47 (30)	[24, 112, 170]
Inconel 625	99.2**	394** (952)	718** (1269)	29.1** (32)	[24, 165]
Ti6Al4V	/	790 (880)	890 (950)	8 (14)	[165, 166]
Copper (Cu)	85.5	/ (333)	116.7 (344)	/	[23, 165]
Tungsten (W)	97*	420* (750)	427* (980)	0	[110, 165]

Note: *infiltrated with bronze; ** treated by aging.

7 KNOWLEDGE GAPS AND FUTURE PERSPECTIVES

7.1 Powder Spreading Process

In binder jetting, the powder spreading process is crucial since it affects not only the density but the homogeneity of the part. There are some studies about the effects of powder spreading process in powder-bed-based AM [152, 158, 160, 171, 172]. Some process optimization efforts have been conducted experimentally in binder jetting regarding the powder spreading parameters such as layer thickness and spreading speed, leading to improved properties of the green part [72, 80, 81, 84, 94, 109, 164]. However, the underlying physical aspects in terms of the dynamic flow behavior of the powder during spreading are very complicated and have not been sufficiently investigated.

As discussed in Section 3.2, flowability has a noticeable influence on powder spreading and it is a function of some critical powder properties (e.g., average particle size, particle size distribution, and particle shape) [69, 84, 111, 153, 173]. During the powder spreading process, the forces acting on the particles include the gravity, van der Waals, and electrostatic and frictional forces between the particles. It is also known that the effects of spreader type and spreading strategy on powder bed are significant [152, 160].

Powder segregation was observed, especially when the powder had a wide particle size distribution. Wheat et al. used CT images to analyze the green and sintered titanium parts from plasma atomized powders with three different sizes (0–45 μm , 45–106 μm , and 106–150 μm) and their mixtures [68]. Periodic powder heterogeneity was observed along the z-axis. Powder particles tended to segregate depending on their sizes, thus causing the localized variation. A cause of this periodic segregation could be that the particles with a similar size have a similar movement during powder spreading, owing to gravity and the interparticle forces. Therefore, the segregation of a group of similar particles from the others occurs in each layer. Further investigations are still needed to confirm the explanation. Similar heterogeneous microstructure was also observed in Inconel 625 [69].

However, the collective effects of powder properties and spreading conditions on the dynamic flow behavior are still not clear. Further knowledge to control and improve the powder spreading process is necessary. With the knowledge of the resultant conditions of powder spreading process, the powder bed of binder jetting is more predictable, leading to better mechanical properties and homogeneity for the printed parts. Moreover, the comprehension of powder bed formation may enable delicate control of the porosity of binder jetting parts. It could advance the application of binder jetting in a wide range of industries such as healthcare and tooling [114, 132, 174].

7.2 Binder-Powder Interaction

The interactions between the binder and powder particles significantly influence the strength and geometry of green parts and the quality of the final parts. Stevens et al. summarized three stages of binder-powder interaction [122]. In this review, the three stages are modified considering other studies, especially Parab et al.'s recent work on real time observation using high-speed X-ray imaging [108, 112, 130, 154, 156, 175, 176]. In the first stage, the powder is impacted by the jetted binder droplet. The droplet brings disturbance to the powder bed, possibly accompanying splashing, bouncing, and powder ejection. The second stage is the binder spreading, during which the binder migrates into the gaps between surface particles. The third stage is the capillary action of the binder contributing to the migration to the adjacent particles until a capillary pressure equilibrium is reached. As a result, the saturated particles are pulled together in response to the surface tension of liquid.

The binder deposition is controlled by numerous process-related parameters, including binder saturation, printing speed, and binder drying time. Binder saturation affects surface quality, dimensional and geometric accuracy, density, and mechanical properties of the part. The desired amount of binder deposited to a part is coupled with the powder bed density, on which particle size and morphology show great impacts. The fine and irregular-shaped particles generally require a higher binder saturation likely due to the lower powder bed density [154].

Moreover, the binder can be engineered to offer more features. For example, a number of efforts have been made to improve the density of green parts and mitigate sintering shrinkage with nanosuspension binders [65, 75, 79, 83, 128, 130]. In the series work of Bai et al., a nanosuspension binder was introduced to the green part during printing [65, 128, 130, 131]. Both the density and strength of green parts could be enhanced by adding more nanosuspension binder [128]. As another result, the sintered shrinkage level was decreased due to the increased green density.

There is still a large room for the research on the binder-powder interactions. The overall effect of the binder deposition and migration on the powder bed is not clear yet because of the limitation of predictive models for binder-powder interaction and inadequate knowledge about the effects of process-related parameters. Therefore, further investigation of the empirical observation coupled with modeling analysis is required to provide insight into the binder-powder interactions. To empirically study the binder-powder interactions, high-speed video can be used to capture the transient dynamics. The morphology and structure of binder-powder mixture can be analyzed by the micrographs and CT images of cured parts.

7.3 Part Shrinkage

From the existing literature, the densification-induced shrinkage can lead to substantial dimensional deviations on a variety of materials [25, 30, 69, 70, 111, 122]. Therefore, it is of importance to mitigate the impact of high-level shrinkage to better benefit from the complex-shape manufacturing ability of binder jetting. The requirement of a low shrinkage level and a high dimensional accuracy contradicts with the nature of densification. To mitigate this contradiction, a higher green density is needed. One of the effective solutions is to increase the green density by employing multimodal powders [9, 61, 63, 68, 173]. However, the sintered density may not always increase with the increased green density [69, 97]. Multimodal powder is known to cause layer-wise density variation [68]. The presence of localized density variation may lead to non-uniform shrinkage or even cracking. Moreover, as discussed in Section 7.1, the optimal powder spreading mechanism and strategy can be developed to attain a higher green density. Nanoparticles can be also introduced to the binder to increase the green density and reduce the shrinkage level [75, 79, 128]. Another method to retain the dimension is to infiltrate the green part [83, 85]. Ultimately, when designing parts for binder jetting, geometric and dimensional compensations can be applied. In this case, the understanding of dimensional change in complex shapes must be developed. Considerations need to be given to sintering parameters and other factors such as part geometry and orientation of the part during sintering [64, 69-71].

8 SUMMARY

Over the past decade, binder jetting of metals has received increasing attention due to its low cost and high scalability, making it a popular and viable alternative to other AM processes based on high energy beams such as powder bed fusion and directed energy deposition. This paper summarizes the available data from both academia and industry and analyzes the important aspects of metal binder jetting, including density and mechanical properties. A final density higher than 90% is attainable for ten materials. A few grades of stainless steel obtained equivalent or superior mechanical properties compared to cold working. Critical factors that affect part properties in binder jetting are identified and correlated with the corresponding effects. Powder properties such as powder particle size and morphology play an important role in the formation of powder bed and green part and the densification process. Small particle size and spherical shape are proven beneficial to a high density. Approaches like the use of multimodal powder and addition of nanoparticles to the binder have a potential to enhance the part quality. However, the occurrence of high-level part shrinkage in contradiction to full densification is among the most notable challenges for metal binder jetting. The fundamental knowledge related to the powder spreading process and binder-powder interaction is inadequate.

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FIGURE CAPTION LIST

Figure 1. Process flow of metal binder jetting

Figure 2. Schematic of the printing process of binder jetting

Figure 3. Illustration of microstructure evolution during sintering [67]

Figure 4. Proportions of investigated metallic materials using binder jetting and corresponding numbers of reports

Figure 5. Illustration of binder deposition and powder primitive formation

Figure 6. Binder-powder compatibility tests [61, 122]

Figure 7. Effects of sintering temperature on sintered density [23, 68, 73, 111, 112, 143]

Figure 8. Shrinkage and relative densities of binder jetting parts [23-25, 63-65, 69, 73, 88, 101, 112, 114, 117, 121, 125, 128]

TABLE CAPTION LIST

Table 1. Comparison of metal AM processes

Table 2. Investigated binder jetting factors and related properties

Table 3. Powder, green, and sintered densities of different materials with their feedstock powder particle sizes

Table 4. Materials with reported relative final density of higher than 90%

Table 5. Yield strength, ultimate tensile strength, and elongation of binder jetting (compared with cold working) parts