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REVIEW ARTICLE

Hadi MIYANAJI, Morgan ORTH, Junaid Muhammad AKBAR, Li YANG

Process development for green part printing using binder jetting additive manufacturing

Abstract Originally developed decades ago, the binder jetting additive manufacturing (BJ-AM) process possesses various advantages compared to other additive manufacturing (AM) technologies such as broad material compatibility and technological expandability. However, the adoption of BJ-AM has been limited by the lack of knowledge with the fundamental understanding of the process principles and characteristics, as well as the relatively few systematic design guideline that are available. In this work, the process design considerations for BJ-AM in green part fabrication were discussed in detail in order to provide a comprehensive perspective of the design for additive manufacturing for the process. Various process factors, including binder saturation, in-process drying, powder spreading, powder feedstock characteristics, binder characteristics and post-process curing, could significantly affect the printing quality of the green parts such as geometrical accuracy and part integrity. For powder feedstock with low flowability, even though process parameters could be optimized to partially offset the printing feasibility issue, the qualities of the green parts will be intrinsically limited due to the existence of large internal voids that are inaccessible to the binder. In addition, during the process development, the balanced combination between the saturation level and in-process drying is of critical importance in the quality control of the green parts.

Keywords binder jetting, additive manufacturing, green part, process optimization, process development

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Hadi MIYANAJI, Li YANG (✉)
Department of Industrial Engineering, University of Louisville, Louisville, KY 40292, USA
E-mail: li.yang.1@louisville.edu

Morgan ORTH, Junaid Muhammad AKBAR
Department of Mechanical Engineering, University of Louisville, Louisville, KY 40292, USA

1 Introduction

Originally developed by Massachusetts Institute of Technology in late 1980s, the binder jetting additive manufacturing (BJ-AM) is among the earliest additive manufacturing (AM) technologies that were developed [1]. BJ-AM utilizes binder to selectively assemble powder from powder feedstock in order to form 3D geometries. Figure 1 shows the typical process steps for the BJ-AM process with commercial platforms such as ExOne and Voxeljet. For the fabrication of each layer, after a layer of powder material is spread on top of the powder bed, a printhead selectively deposits certain amount of binder droplets at designated locations of the powder bed. After binder deposition, the entire powder bed surface is then subjected to external heating applied via a radiation heat source in order to partially cure the binder and ensure adequate mechanical strength for consequent printing processes. After the drying/curing, a new layer of powder will be added to the powder bed, and the process repeats until the entire green part is printed. Due to the use of binder for geometry creation, BJ-AM process possesses various advantages over other AM processes, such as the elimination of thermally induced defects (e.g., distortion, unwanted grain growth) and broad compatibility with exotic materials such as ceramics and refractory metals. A broad range of material types that are generally difficult to process, such as engineering ceramics (e.g., alumina [2–5], zirconia [6], silicon carbide [7], silicon nitride [8,9]), bioceramics (e.g., calcium phosphate [10,11], bio-glasses [12], hydroxyapatite [12,13]), functional ceramics (e.g., Ti_3SiC_2 carbide [14], $BaTiO_3$ [15], Ni-YSZ [16]), and tooling materials (e.g., WC/Co composite [17]).

On the other hand, the green parts fabricated by the BJ-AM printing process possess only limited strength and often require additional post-processing such as sintering and infiltration in order to achieve mechanical strength [7,18–20]. Therefore, the quality of the final parts is not only dependent on the printing process but also the post-printing processes. During the green part printing stage,

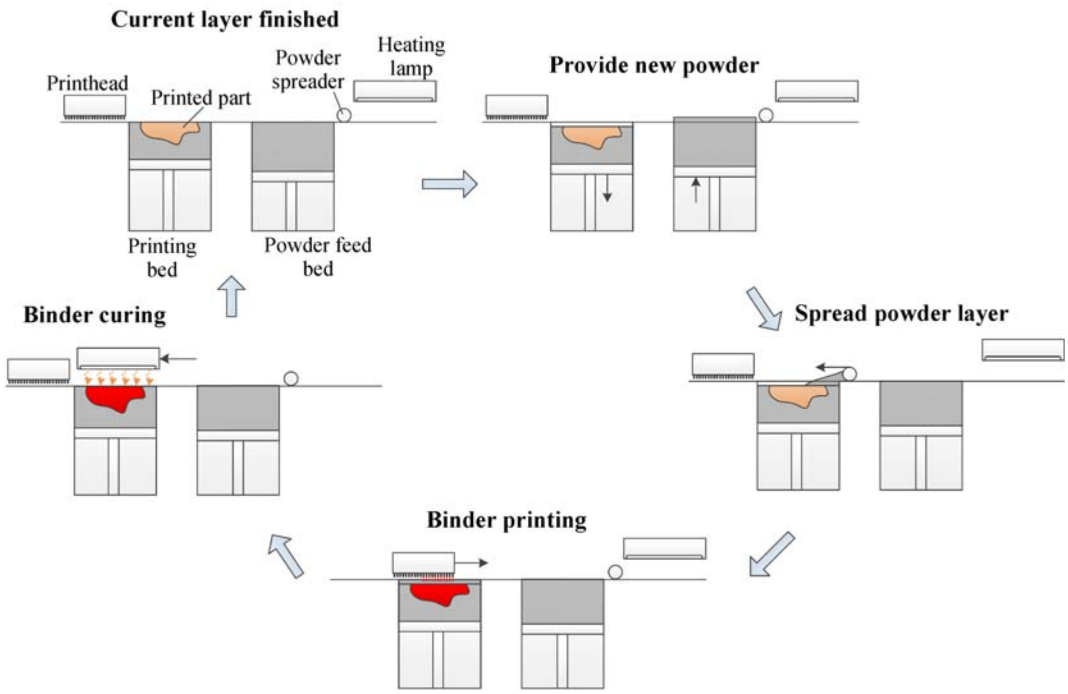

Fig. 1 Schematics of BJ-AM process steps

various quality characteristics could exert significant influence on the final part quality, such as geometrical accuracy, dimensional accuracy anisotropy, green part density, green part strength, and surface roughness [21]. During the post-printing process stage, additional process quality errors could be introduced by various mechanisms such as de-binding distortion, part shrinkage, and sintering distortion.

The post-printing processing of BJ-AM green parts is very similar to the green part post-processing for traditional powder metallurgy parts. The post-printing processes generally involve the debinding step aiming to remove the binder chemical followed by a densification step that reduces or eliminates internal voids and enhances mechanical properties of the final structures. The guidelines for post-processing are well-established from traditional powder metallurgy engineering and can largely be applied to the BJ-AM green parts. On the other hand, there currently exist relatively limited knowledge related to the design guideline of green part printing process. Many of the earlier works [8,9,18,22,23] in this area focus on the development and investigation of the binder formulation. Due to the different surface chemistry with different material-liquid combinations, it is rather difficult to develop a generic binder that is optimized for all powder feedstock. In addition, the feasibility of the binder system is also dependent on the printer hardware (e.g., printhead, droplet control), which further complicate the issue [24]. On the other hand, several universal binder solutions currently offered by system manufacturers provide a relatively broad range of material compatibility. For specific binder and material combination, a rich body of works exist in the development of process and the characterization of the green part qualities, and most of them take experimental-based approaches. Various literatures [25–27] investigated the effect of part orientation and feature geometry on the dimensional accuracy of the green parts using benchmark evaluation parts, and it was found that the accuracy of the parts is dependent on both part orientation and part locations in the printing envelope when using the Z-Corp system. Other works [28,29] showed that the powder feedstock characteristics, such as particle size and distribution, have significant effect on the densities of the green parts as well as the residual strain of the sintered final parts. Various printing parameters including saturation level, in-process drying powder, in-process drying time were found to have significant influence on the green part integrity and strength with the ExOne system [21,30,31]. In addition, other factors, such as in-process printing delay [27,32] and layer thickness [27,33], were also investigated for their effects on part qualities. Despite the abundance of information, it is often difficult for researchers and engineers to establish clear process development protocols for BJ-AM when working with a new material due to the lack of systematic understanding of the relationships between process inputs and green part qualities. This paper attempts to offer a more comprehensive understanding of the process design principles for BJ-AM and the general guidelines for process development.

2 Powder feedstock considerations

During the green part manufacturing in the BJ-AM, the creation of the green part geometry is realized by the application of binder selectively on the powder bed, which in turn could be described as a classic liquid-porous media interaction problem. Therefore, the binder-powder interaction is largely determined by the characteristics of the binder material and powder feedstock. Similar to the powder bed fusion AM processes, in the BJ-AM the powder might be spread on the powder bed via a spreading mechanism such as roller or blade. Therefore, the flowability of the powder becomes important in determining the powder bed packing densities. Powder with more regular shape morphology (i.e., spherical) exhibits higher flowability and therefore promotes better powder packing during the spreading process. In addition, the use of bi-modal particle size distribution could also improve the powder bed density without introducing significant issue with powder flowability. The effect of several powder spreading mechanisms, including blade, forward-rolling roller and backward-rolling roller, has been investigated in various contexts [34–36]. It was shown that the backward-rolling roller mechanism would result in the highest powder bed density [36,37].

When low flowability powder is used, the low flowability of the powder might cause powder bed spreading defects even with the use of roller mechanism such as the one shown in Fig. 2. In Fig. 2, the graphite powder (Superior Graphite, Chicago, IL, USA) exhibits irregular particle morphology and very low flowability. When mixed with nylon 12 powder and spread with the roller mechanism in the ExOne M-Lab system, the high graphite-content mixture exhibits significantly larger amount of defects after powder spreading. This issue could be alleviated via various methods. The mixing of powder with flow agent could often improve the powder flowability, although the flow agent could potentially introduce impurity into the parts that is unacceptable [31]. During the powder spreading, excess powder supply could be used to partially compensate for the spreading defects. This is done by setting the amount of powder supply per layer to be $>100\%$ of the required powder. The lower the powder flowability is, the higher such supply-to-spread ratio is required. For example, as shown in Fig. 3, for very low-flowability powder such as the BAG-bioglass (confidential source), a supply-to-spread ratio of 5 was needed to accomplish spreading, while for alumina (Sigma Aldrich USA) and 420 stainless steel (ExOne LLC, Pittsburgh, PA, USA) powders, such ratios were 3 and 1 respectively and the spreading quality were also higher. On the other hand, higher supply-to-spread ratio is not always desired. Depending on the powder feedstock storage mechanism with the fabrication system, excess powder supply might cause low powder utilization and consequently the reduction of the total number of layers that can be built. In addition, when roller mechanism is employed for powder spreading, the use of lower spreading speed is also beneficial with low-flowability powder.

Another factor to be considered when choosing the powder feedstock is the minimum feature resolution. It is well-known that the layer thickness of a powder bed-based AM process is limited by the mean powder particle size and its distribution. The mean powder particle size determines the minimum layer thickness and therefore the minimum feature resolution achievable in the z-direction (i.e., build direction). In addition, in determining the minimum feature resolution in the x and y directions, the large-size particles in the powder bed usually set the thresholds. On the other hand, it should be noted that the minimum feature resolution of the BJ-AM process is determined by various factors. Even with fine-

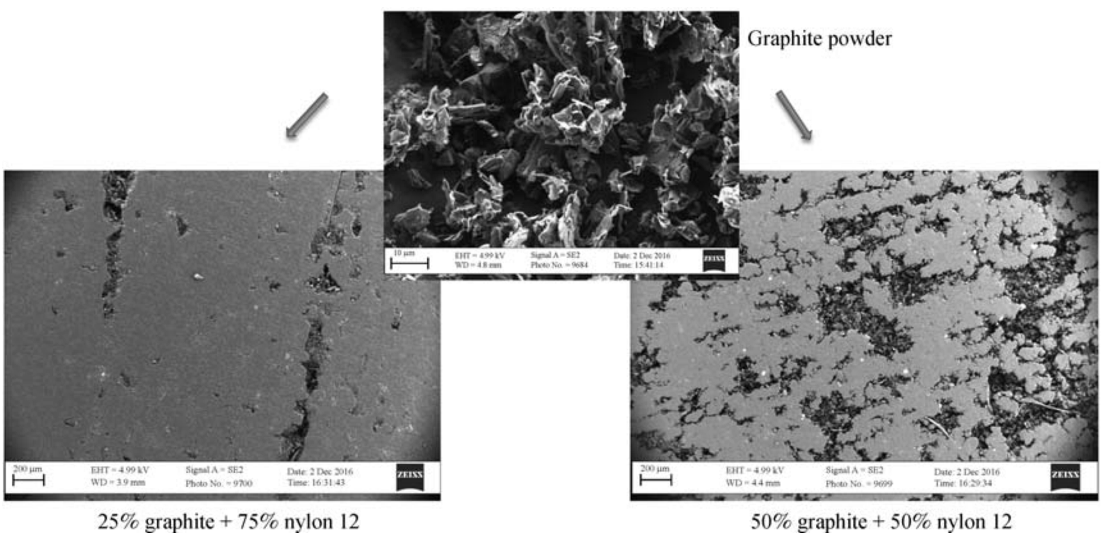

Fig. 2 Powder spreading defects with low-flowability powder

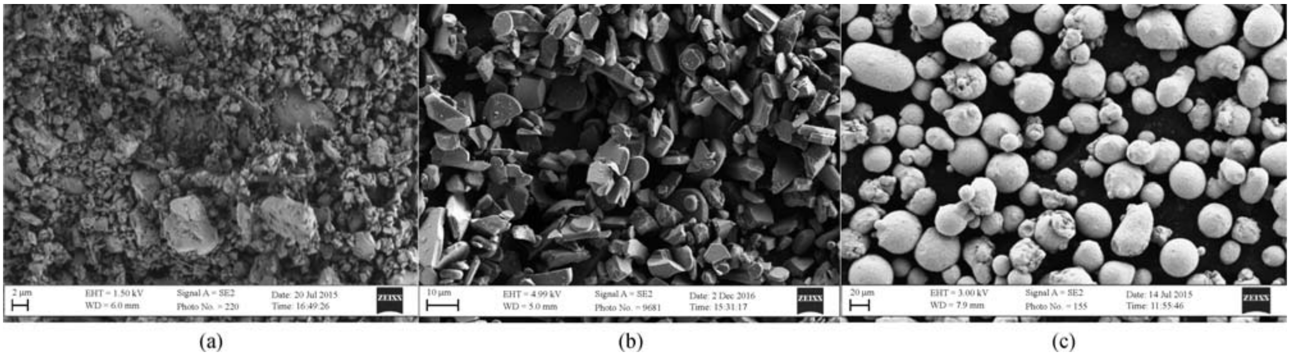

Fig. 3 Supply-to-spread ratio for powders with different flowabilities. (a) BAG-bioglass (supply-to-spread ratio is 5); (b) alumina (supply-to-spread ratio is 3); (c) 420 SS (supply-to-spread ratio is 1)

particle powder bed of narrow size distributions, the process resolution could still be low if the binder droplet size is not optimized.

3 Printhead considerations

Most of the commercial BJ-AM systems use drop-on-demand printhead, which selectively sprays binder droplets at designated locations. For specific binder system, the printhead control must be optimized to ensure rapid and precise delivery of binder droplets with controlled volumes. With some systems, the printheads are capable of delivering droplets with adjustable volumes, whereas with other systems such parameter has fixed values. On the other hand, the ability of the printheads to deliver varying amounts of liquid to specific locations is closely associated with the binder saturation control in the process. The binder saturation is defined as the ratio between the binder liquid volume and the volume of all the pores/voids within the defined printing volume. For printhead with fixed droplet volume, the minimum saturation level resolution is largely determined by the volume of the single droplet as shown in Fig. 4(a). The adjustment of the saturation level can be achieved by either overlapping droplets or oeverlaying droplets, as shown in Figs. 4(b) and 4(c), respectively. Overlapping droplets allows for saturation level control with very fine "step size" due to the fact that the overlapping ratio is continuously adjustable. On the other hand, overlaying droplets generally results in high saturation levels in a relatively narrow and deep region, therefore might be favorable for the printing of thicker layers.

It is often desired that the printing could be carried out at high speed to facilitate productivity. For BJ-AM, this can be realized by using higher printing speed (i.e., higher printhead moving speed), shorter in-process drying time or faster powder spreading. The benefit of slower powder spreading speed was discussed in Section 2, and the process considerations for the in-process drying will be discussed in Section 4. For the printing speed, care must be taken since the printhead speed will directly impact the droplet behavior when it initially contacts the powder bed. High printhead speed would translate into high lateral speed of droplet when it impacts the powder bed, which might result in droplet rebounding or spreading [38]. Additionally, as the printheads have specific operation frequency ranges, high printing speed might also cause the loss of printing accuracy and resolution due to insufficient printhead response rate. At high printing speed, the dimensional accuracy anisotropy becomes more significant. As shown in Fig. 5, for the slot feature with 0.25 mm slot width oriented in the x direction (perpendicular to printhead motion), the loss of dimensional accuracy is considerably more significant with increasing printing speed. On the other hand, for slot oriented in the y direction (along the printhead motion), such effect is less significant. For the particular BJ-AM system used in this study (ExOne

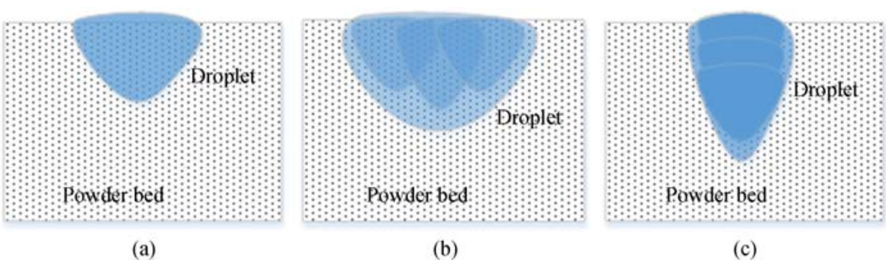

Fig. 4 Saturation level control methods. (a) Single droplet; (b) overlapping droplet; (c) overlaying droplet

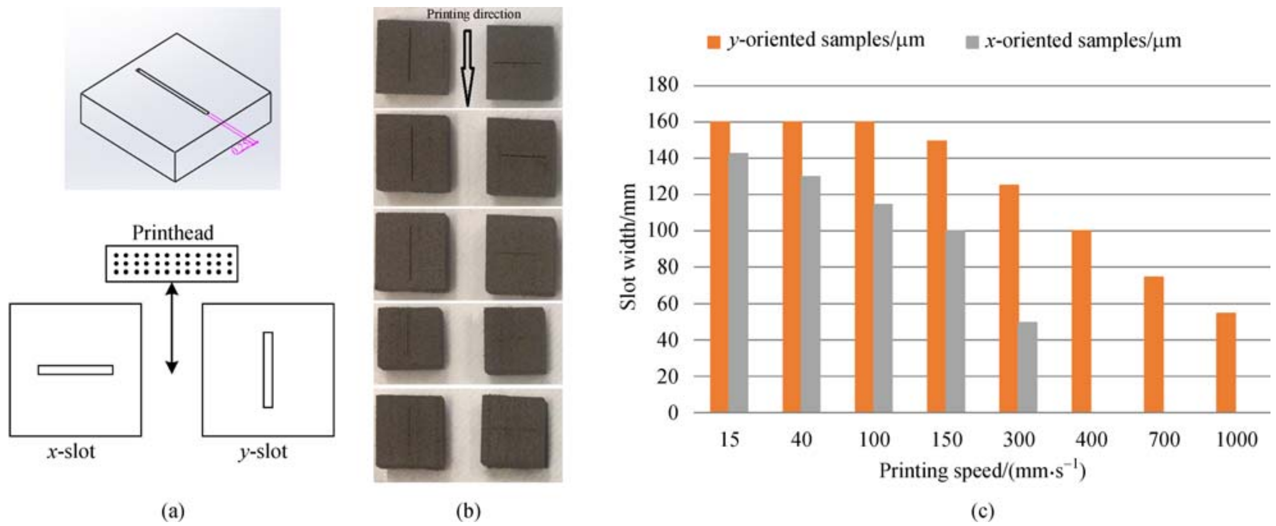

Fig. 5 Effect of printing speed on feature accuracy for ExOne M-Lab. (a) Slot feature; (b) experimental results; (c) dimensional accuracy

M-Lab), significant loss of accuracy occurs when the printing speed exceeds 150 mm/s, which can be consequently used as the design guideline for printing speed adjustment.

Another commonly encountered issue with the development of new materials and binders with the BJ-AM is the printhead clogging issue, which might not be of much concern for research platform but poses significant challenge for commercial systems. Most of the BJ-AM system utilizes thermally-activated binder system for rapid printing. However, such characteristic could backfire when unwanted evaporation of curing takes place within the fluid channels. This might cause the change of viscosity with the binder fluid or the generation of solid phase that does not flow well. Due to the small dimension of the printhead nozzles, shear effect tends to be more significant in the printhead, which further aggregates the issue. When nozzle temporarily clogs during the printing operation, the missing printing lines might cause part disintegration, which could be identified readily from the straight and clean cleavage lines on the printed parts as shown in Fig. 6.

Fig. 6 Nozzle clogging-induced printing defects

4 Binder-powder bed interaction considerations

The interaction between the binder and the powder bed determines the generation of the green part geometry and is therefore directly related to the quality of the parts. Upon contact with the powder bed, the binder droplet usually has an initial impact speed which dissipates quickly. For ExOne systems such initial "settling" period is adequately short that it could be effectively neglected for process development purpose. Once the droplet begins to permeate into the powder bed, the behavior is largely governed by the intrinsic characteristics of both the liquid and the powder bed, including liquid viscosity, liquid-powder material contact angle and surface tension. The migration of binder liquid in the powder bed is largely driven by capillary force, whereas gravity could be effectively neglected for pico-liter high-precision droplet application. Once the equilibrium is achieved, the printed region will be uniformly saturated by the binder with particular saturation ratio pre-determined by the program as shown in Fig. 7. Sufficient wetting between the binder and the powder is of critical importance in ensuring the quality of the green part, as later in the process chain the continuity of the binder will largely determine the strength and integrity of the parts.

During the printing, in-process drying and saturation level setup are two highly coupled process setting that must be tailored carefully. As illustrated in Fig. 8, higher saturation level generally facilitates more sufficient binder permeation into the powder bed, whereas sufficient in-process drying is required to ensure adequate structural strength for the continuous execution of the printing. For powder with low flowability, powder aggregation is often significant, which means that large voids might be formed which is unfavorable for binder permeation. In order to partially overcome this, excess amount of binder liquid might be needed, which leads to saturation level that could exceed 100%. From the definition of saturation level, over 100% saturation implies that there will be more liquid phase than that can be accommodated by the voids in the designated region, and excessive binder permeation into surrounding regions is inevitable (Fig. 9(a)). Therefore, while excessive saturation levels might enable the printing of difficult powder feedstock, the quality of the printed parts might be very limited.

The functions of the in-process drying is also multi-folded. Due to the surface tension limitation of the binder liquid, hydraulic force is not the primary contributor to green part strength, and binder curing/setting must be introduced to ensure that the newly printed layer could sustain the shear force induced by the powder spreading

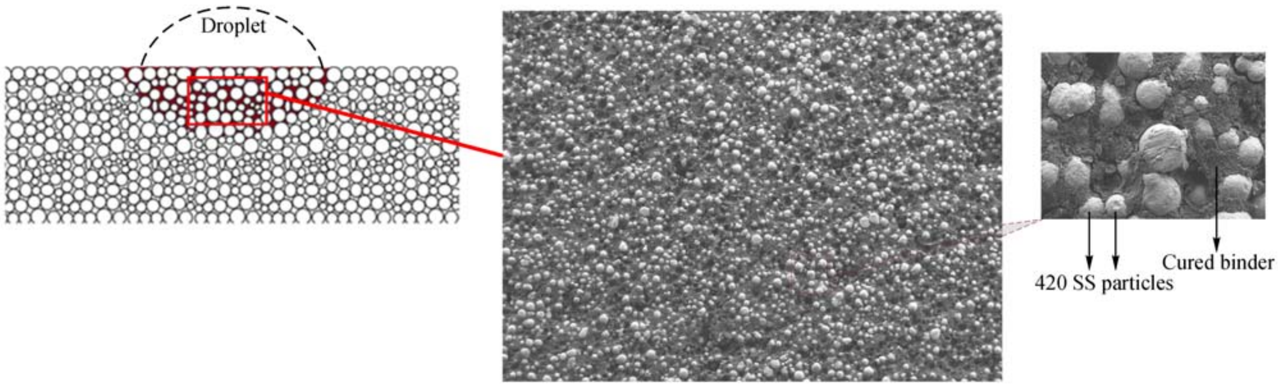

Fig. 7 Binder permeation into the powder bed

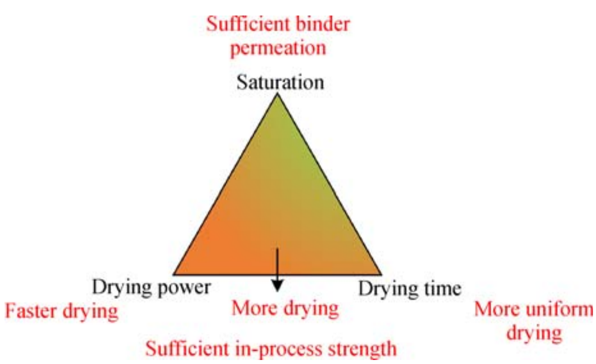

Fig. 8 In-process printing parameters

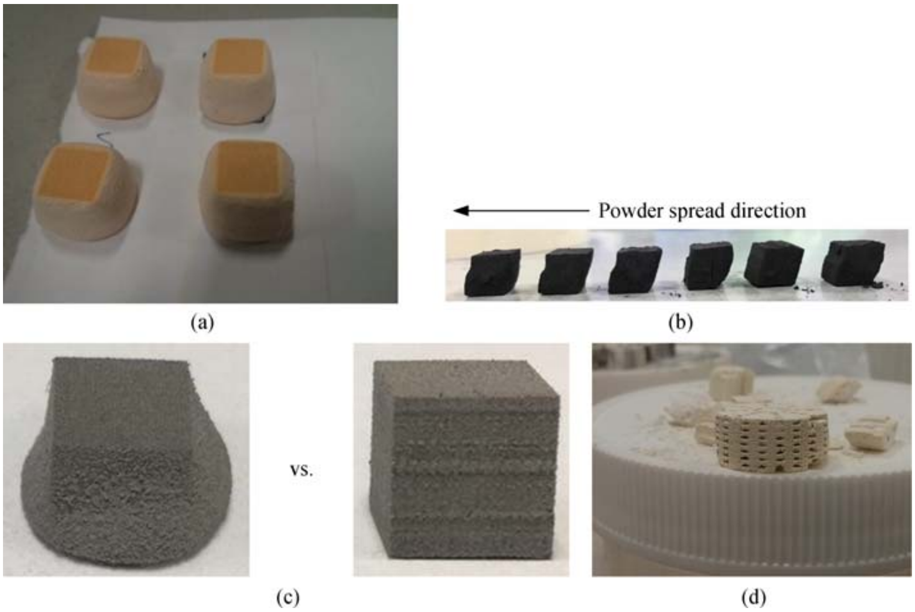

Fig. 9 Common BJ-AM in-process defects from saturation-drying setting. (a) Excessive saturation, adequate drying; (b) adequate saturation, insufficient drying; (c) excessive saturation, insufficient drying; (d) insufficient binder permeation

mechanism. Therefore, inadequate in-process drying often manifests as “shearing” defects shown in Fig. 9(b), where the newly printed layer is slightly displaced by the roller spreading mechanism with an ExOne M-Lab system, which accumulates over multiple layers and results in macroscopic part shearing. For non-contact powder spreading mechanism such issue is largely eliminated.

On the other hand, when excessive in-process drying is introduced, the inter-layer bonding of the green parts might be significantly reduced. This can be rather metaphorically explained by the fact that excessive drying would result in less residual liquid phase on the current surface, which prevents further binder permeation. As a result, when a new layer is added, the binder liquid could not effectively form continuous liquid phase across the interface and therefore causes the loss of inter-layer strength.

In addition, the adjustment between in-process drying time and in-process drying power should also be considered carefully. Considering that the in-process drying usually takes place in the form of directional heating from above the powder bed, higher in-process drying power would introduce higher heat flux, which could potentially cause non-uniform curing. On the other hand, while longer in-process drying time facilitates more uniform heating and curing, it could significantly extend the process time and reduce productivity.

5 Conclusions

In BJ-AM process, the green part fabrication must be subjected to careful process design in order to ensure optimized part quality before post-processing. Various factors must be considered, including the powder feedstock, the binder, the printhead hardware and control, and the rather complex relationships between the saturation and in-process drying setting. For powder with good flowability, once the suitable binder can be identified, the process development can be carried out rather straightforwardly. However, for powder with low flowability, various methods are needed to facilitate powder spreading, binder permeation and part quality. This work attempts to provide a comprehensive perspective of the relationships between various process design parameters and the underlying process principles, which establishes a more unified picture about the process development issues for the BJ-AM.

It must be noted that after the green part is printed, it must be subjected to further post-processing such as additional drying/curing before the sintering/infiltration processes. There might exist additional coupling issues between the green part printing process setting and the post-printing process parameter setting that could impact the final quality of the parts. While this is beyond the scope of this work, the importance of such insights is obvious.

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