Assessing the impact of binder saturation on print quality of binder jetted green samples of regular morphologies

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Abstract: A pivotal process parameter in binder jetting additive manufacturing (BJAM) is binder saturation, defined as the volumetric ratio of binder deposited to voids within the powder bed. Improperly tailored binder saturation may lead to printing issues such as binder overspread, increased surface roughness, and layer delamination. These existing issues may be further exacerbated with the use of irregular morphological powders, which have a higher degree of interparticle friction and therefore tend to form powder beds with larger pores. This then slows down binder imbibition into the bed. This research will examine the effect of varying binder saturation on a regular (sphericity of 0.95) powder morphology and the resulting green part qualities using C18150 copper alloy powder. A metric used to assess quality is dimensional fidelity, evaluated using image processing techniques to compare designed vs. actual feature size of key geometric structures such as fine through holes and horizontal slots. Additionally, the green density of prints was evaluated with a precision balance and calipers on cubic samples. It was found that, for regular morphology powders, dimensional error did not scale with decreasing feature size. Thus, uniform compensation factors may be implemented into future CAD designs to improve dimensional accuracy.

Keywords: Binder jetting, copper, powder morphology, dimensional accuracy, binder saturation.

1. Introduction

Binder jetting additive manufacturing (BJAM) is a powder-based manufacturing process in which a (typically) polymeric liquid binder is used to selectively join powder particles together layer by layer to produce a three-dimensional (3D) component. This results in a loose structure that is then cured using heat, allowing it to be removed from the loose powder which surrounds it. After curing, the components are referred to as green parts, requiring further densification through a thermal de-binding process, in which the binder undergoes pyrolysis, followed by sintering at high temperatures to achieve a near-full density [1].

Of particular interest in BJAM is its reliable and accurate production of fine features, which may be incorporated into various applications ranging from intricate heat exchangers [2] to thin mesh structures [3]. As this manufacturing process continues to develop, there exists a necessity for thorough design rules within the field [4,5]. These design rules may be in the form of guidelines outlining the limitations of the process [4] or dimensional compensation factors which account for part shrinkage due to heat treatments [2]. However, the relationship between process parameters and subsequent part properties is quite complex [3,6]. One such process parameter is the binder saturation (BS), defined as the ratio of binder volume deposited onto the powder bed to the volume of void space between packed powder particles. While high BS values provide a component with good green strength [6], it may also cause the binder to spread excessively beyond its deposition area [1,3,6], potentially causing fine features to be rough [1,6], dimensionally inaccurate [1], or not exist entirely. Alternatively, too low of a BS value may result in issues such as layer delamination and damaged components due to insufficient green strength [1,6]. The impact of BS on part quality is further affected by powder characteristics such as particle size distribution (PSD) and morphology [1]. Miyanaji et al. [7] found significant factors impacting a print's equilibrium BS value include particle surface area and packing density, both of which are functions of PSD. Irregular morphological powders, while lower-cost [8], have lower packing densities than their spherical counterparts as a result of their shape. Consequently, the presence of macro-voids within the powder bed which inhibit binder imbibition is much higher [1], or harder to predict. Evidently, the BS value of a BJAM print, while being a key parameter in resulting part resolution, also requires optimization based on powder characteristics to consistently achieve high-quality components.

The purpose of this study is to determine the geometric fidelity of various fine features in the green state, while examining the impact of varying BS and, in future work, powder morphology. Quantifying the inaccuracy resulting from BJAM printing, its process parameters, and the powders employed will allow for dimensional compensation factors to be applied to future CAD models. The following manuscript will outline results achieved thus far using spherical, metal injection molding grade powder.

2. Materials and methods

2.1. Powder selection

This study utilized C18150 (CuCrZr) copper powder produced using nitrogen-atomization to yield a regular morphology. The powder's nominal composition is listed in Table 1. Particle size distribution analysis was performed using dynamic image analysis (Particle Size Analyser CAMSIZER X2) and found a median powder size (D_{50}) of 12.90 µm. The powder may be seen under SEM (Vega3, Tescan) in Figure 1.

Table 1. Chemical composition of powder used.

Powder Morphology	Cr [wt.%]	Zr [wt.%]	Cu [wt.%]
Spherical	0.50-1.20	0.03-0.30	Bal.

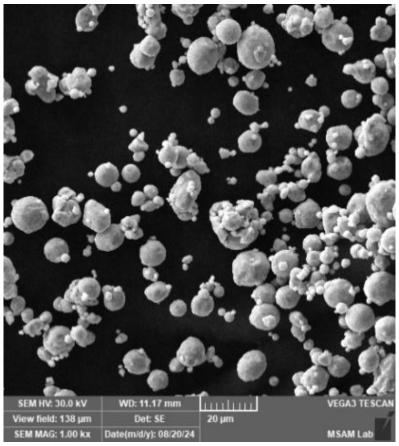

Figure 1. C18150 powder as seen under SEM.

2.2. Green part fabrication

Green parts were produced using a commercial ExOne MFlex and an aqueous-based binder, AquaFuse. Two components were designed, with either through holes or with horizontal slots of varying sizes, as seen in Figure 2. Component dimensions are provided in Table 2. Both sets of components were printed in both the X and Y aligned cases to examine the additional effect of part orientation, which may impact print quality due to the roller spreading direction [1]. Four horizontal slot components were needed to print all the desired feature sizes at each orientation. A set of ten 1 cm^3 cubes were also produced for green density analysis.

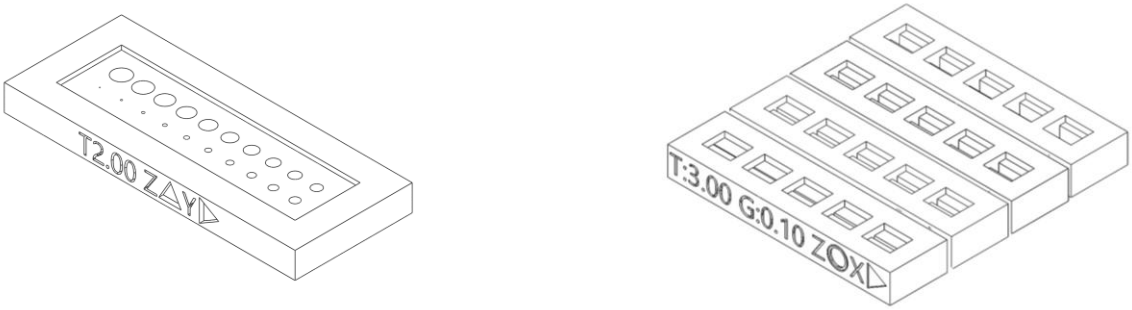

Figure 2. Example component design for through hole features (left) and horizontal slot features (right).

Table 2. Component designs specifications. Feature sizes were varied in 0.1 mm increments.

Component type	Length [mm]	Width [mm]	Height [mm]	Feature sizes [mm]
Through holes	33.5	13.5	2.0	0.1 – 2.0
Horizontal slots	39.0	10.0	3.0	0.1 – 2.0

Table 3 summarizes key process parameters used in each of the prints. Layer thickness was selected based on recommendations in literature depending on particle size distribution [1]. BS was obtained using the ExOne MFlex software. All other printing parameters were determined through obtaining even layers during print setup. After printing, the build beds were placed inside a retort under argon atmosphere for one hour before curing for six hours at 120 °C. The green components were de-powdered using a brush and a syringe with a fine needle to remove all possible loose powder.

Table 3. Process parameters used for green part fabrication.

Powder morphology	Layer thickness [µm]	Recoat speed [mm/s]	Roller traverse speed [mm/s]	Binder saturation [%]
Spherical	40	60	10	30
				35

2.3. Geometric fidelity evaluation methodology

Once de-powdered, each part was photographed under an optical microscope (Keyence VHX7000) at 20x magnification. A backlight was placed under the samples to increase contrast. The images were then brought into a custom code workflow, further outlined in [5], and binarized using image processing techniques. These images could then be directly overlayed onto a cross-section of the CAD model for a visual representation of the difference between the nominal and achieved feature size. The binarized image was also enlarged and cropped to examine each individual feature for analysis. A maximum or minimum feature diameter was measured using circumscribed and inscribed circles, respectively, while a maximum or minimum feature width was measured using the largest or smallest width that fit within the projection contour. A best fit approximation was taken for both feature types and used as a direct comparison between the nominal feature size provided in the CAD model. Figure 3, below, provides a graphical overview of the analysis method.

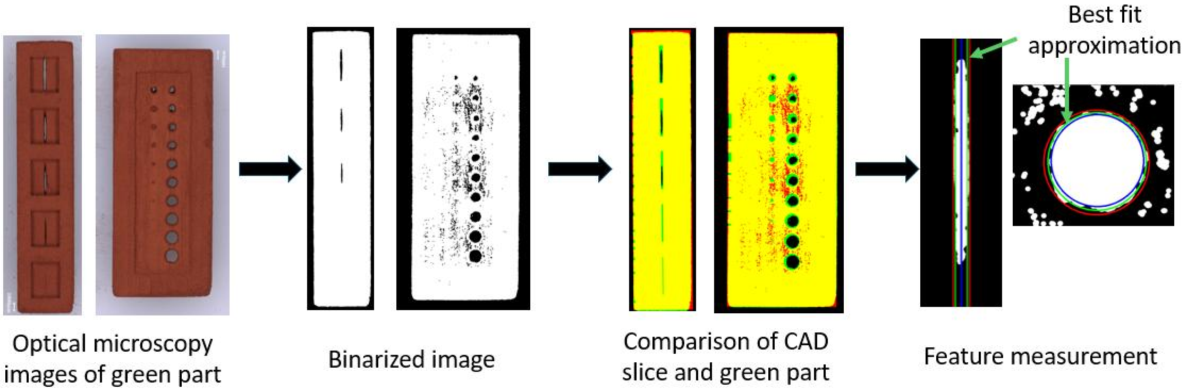

Figure 3. Summary of feature measurement workflow.

3. Results and discussion

To understand the effects of varying BS values and part orientation, the measured feature size collected from imaging was plotted against the nominal feature size as dictated in the CAD model. Figure 4 highlights the results of the best fit approximation analysis on the green parts printed with spherical powder, where the diagonal dotted line represents the ideal condition in which there is no difference between the CAD model and printed part. If a feature was unable to be de-powdered, no measurement was taken. Horizontal slot features below 0.3 mm in nominal width were unable to be de-powdered regardless of the BS value applied or the part orientation. While binder overspread is not necessarily larger in these areas, the feature size is now small enough that the overspread is significant and the feature is closed. Similarly, through hole features below 1.0 mm in nominal diameter were unable to be de-powdered at a BS value of 35% regardless of part orientation. Features below 0.6 mm and 0.8 mm were unable to be de-powdered at a 30% BS value for through hole components oriented in the X and Y direction, respectively, due to low green strengths damaging components before analysis rather than orientation-related discrepancies. However, Yang [5] found that components printed along the Y plane, had slightly higher degrees of dimensional error. In the case of fine features, an increase in dimensional error due to print orientation will result in binder overspread closing a feature at a larger nominal size. Additionally, an increase in BS will result in larger overspread [1,5], also closing features at larger nominal sizes. While components printed at 30% BS were able to print slightly finer features overall, the low binder content within the parts resulted in noticeably poorer green strength.

From the selected process parameters, there appears to be a consistent negative offset between a feature’s measured and nominal dimension. The negative offset is a likely a result of lateral binder spread into pores surrounding the deposition area [1]. These results suggest that the dimensional error of a fine feature may not scale proportionally in relation to feature size but is instead consistent for a specific feature type for the part thickness and powder studied here [5]. ANOVA analysis was performed for both sets of data to determine there were no statistically significant differences between each set of BS values and part orientations. Therefore, a single compensation factor may be calculated and applied to future CAD models for each feature type within the size range and BS values examined.

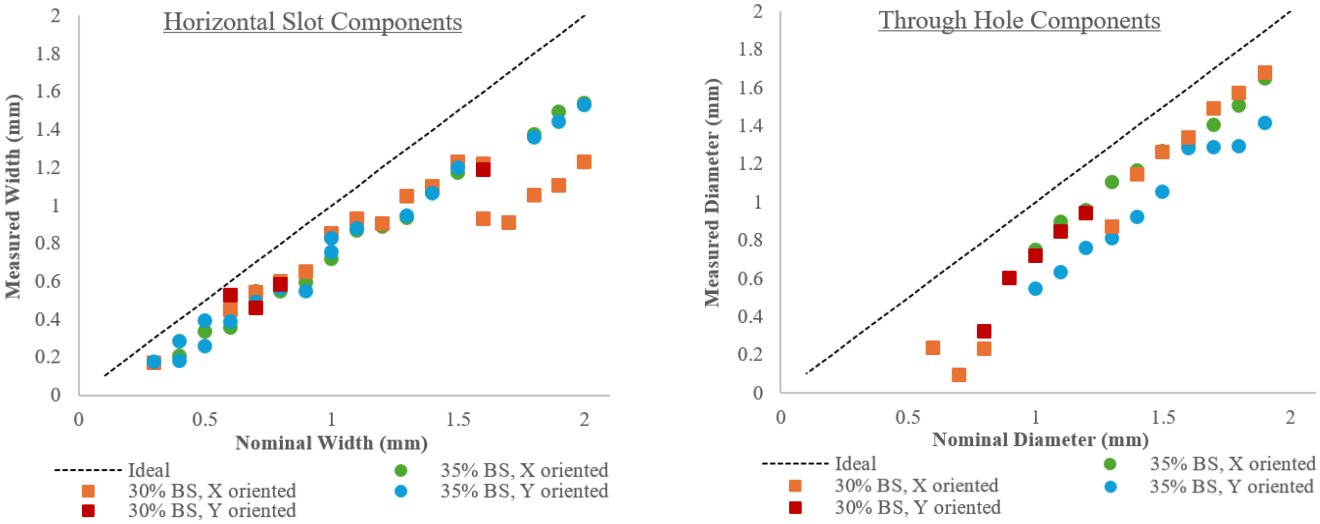

Figure 4. Measured feature dimension compared to nominal dimension at varying binder saturations and part orientations for horizontal slot components (left) and through hole components (right) for spherical powder prints.

4. Conclusion

The work presented investigates the effect of varying binder saturation on the resulting geometric fidelity of fine features such as through holes and slots in green parts produced using BJAM. For regular-shaped powders, the results indicated that, over the range examined, there was no significant differences between dimensional error resulting from variation in BS or part orientation in the two feature types tested. To achieve fine features which are dimensionally accurate in the green state in future prints, a uniform compensation factor will be applied in the CAD model by enlarging a feature to include the dimensional error observed here. Future work will further consider the effect of particle morphology by employing the same methodology with irregularly shaped C18150 powders. Further understanding on how to produce fine features which are reliably dimensionally accurate in the field of BJAM will undoubtedly enhance this manufacturing process' application in industry.

5. Acknowledgments

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6. Conflicts of interest

The authors declare that there are no financial or personal interests that affected the work reported in this manuscript.

7. References

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