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CONTROLLED WETTING OF SPREAD POWDER AND ITS IMPACT ON LINE FORMATION IN BINDER JETTING

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ABSTRACT
Binder Jetting (BJ) has increased in popularity and capability since its development at MIT as it offers advantages such as fast build rates, integrated overhang support, low-power requirements, and versatility in materials. However, defects arise during layer spreading and printing that are difficult to remove during post-processing. Many of these defects are caused by particle rearrangement/ejection during binder deposition. This study explores methods of reducing particle rearrangement and ejection by applying small amounts of moisture to increase the cohesive forces between powder particles. A moisture application system was built using a piezo-electric disk to atomize water to apply a desired liquid to the BJ powder bed without disruption. The moisture is applied after spreading a new layer. Lines of binder were printed using varying droplet spacings and moisture levels. Results show that the moisture delivery system applied moisture levels across the entire application area with a standard deviation under 23%. The moisture levels delivered also had a single position test-to-test uniformity standard deviation under 21%. All tested levels of moisture addition showed mitigation of the balling defects observed in lines printed using dry powder under the same parameters. Moisture addition decreased effective saturation and increased line dimensions (height and width), but lines printed using the smallest amount of moisture tested, showed similar saturation levels and line widths to lines printed in dry powder while still partially mitigating balling.

Keywords: Inkjet, Binder Jetting, saturation, balling, additive manufacturing, moisture

NOMENCLATURE

S	Effective Saturation
ρ_b	Binder Density
ρ_{pb}	Powder Bed Density
P_f	Packing Fraction
m_b	Binder mass
m_p	Part mass

1. INTRODUCTION

1.1 Binder Jetting — An Additive Manufacturing Process

Binder Jetting (BJ) was first developed at MIT in the 1980s and has been shown to have numerous advantages as a manufacturing process. The printing process is accomplished by using a roller to pack and spread thin smooth layers of powder (30-50 μm) and using an inkjet printhead to selectively deposit a binder within the spread powder to form a 2D cross-section of an object. More powder is then spread, and the printing is repeated for a new cross-section. Layer by layer, a complete object is formed resulting in what is known as a green part [13] (FIGURE **1**).

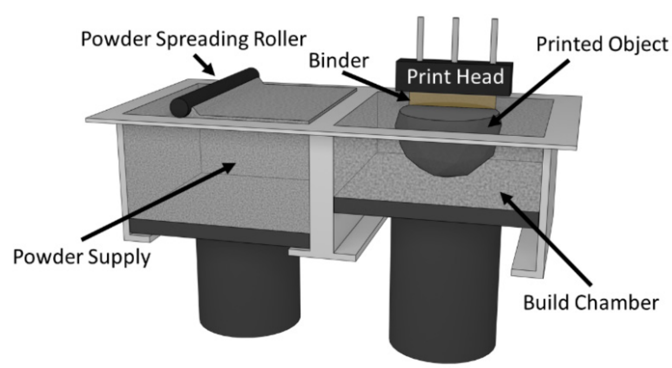


FIGURE 1: BINDER JETTING PROCESS OVERVIEW

The part extraction begins with heating the powder bed to evaporate the solvents within the binder, effectively leaving behind the binding agent to hold the powder together before sintering. This is known as curing the binder, and the resultant part is known as a green part. Afterward, the part has sufficient strength to be extracted from the print bed by removing any unbound powder [13]. For post-processing, the extracted green part is typically placed in a high-temperature furnace to increase strength through sintering and/or infiltration to reach final part properties [7].

BJ offers some unique advantages compared to other AM processes. Because the parts are printed into a uniform powder bed, the unbound powder serves as support material for any overhangs a printed part may have. This is opposed to other AM processes, where support material is incorporated into the design and removed as a post-process. BJ is versatile in its ability to process virtually any material that can be supplied in powder form. After an object has been bound, it can be post-processed according to material-specific specifications. The process also has relatively high build rates and build areas compared to other AM processes [13]. Lastly, BJ does not require a high-power input because it uses minimal thermal cycling during the part build.

In BJ, powder delivery is typically accomplished using either the piston method or the hopper method [12, 13]. In the piston method, two chambers are oriented next to one another, with one serving as a supply and the other as a build chamber. The supply starts full of unbound powder and feeds fresh powder to the build chamber which begins empty and is filled as a part is built. When a new layer is needed, a piston at the bottom of the supply chamber raises to provide powder and a piston at the bottom of the build chamber is lowered to make room for the new layer. The provided powder from the supply is then spread over the build chamber and printing resumes (

FIGURE 1). In the hopper method, the supply chamber is replaced with a hopper positioned above the build chamber, and powder is supplied from above when needed.

Typically, the fresh powder is spread and leveled using a rotational roller, with either the roller or the build chamber being moved linearly to spread the powder. The roller usually has a rotation counter to the linear motion.

Like any manufacturing process, the goal of a part is to have sufficient strength and dimensions to perform its intended purpose. BJ green part quality has been measured through part formation, dimensions, and saturation [2, 4].

1.2 Research Motivation

Common defects found in BJ—such as porous regions—often diminish part material properties compared to more traditional methods of manufacturing, like milling and casting. As BJ is still a relatively new technology, the causes of these disadvantages have not been fully recognized or resolved.

The interaction between binder and powder has shown to cause powder rearrangement and ejection [6, 10]. Through high-speed x-ray imaging of the BJ printing process, Parab et al. [10] showed that as a binder droplet impacts a powder bed it creates an impact crater that rearranges the particles and, in some cases, causes particle ejection from the bed (FIGURE 2). The intensity of the impact crater and particle ejection on printed parts was shown to change with particle size and shape. As new layers are printed, the particle rearrangement and ejection may be the cause of porosity which is then preserved between layers. Any imperfections in the packed powder within the final green part, remain throughout the sintering process and have a large impact on the final part properties. Research shows, that even small amounts of porosity within a part can have drastic effects on final material properties [9, 11]. For BJ to reach its full potential in industry, the causes of porosity within parts needs to be understood and their formation mitigated. It is theorized that powder rearrangement during printing may be a key source of voids in the green parts.

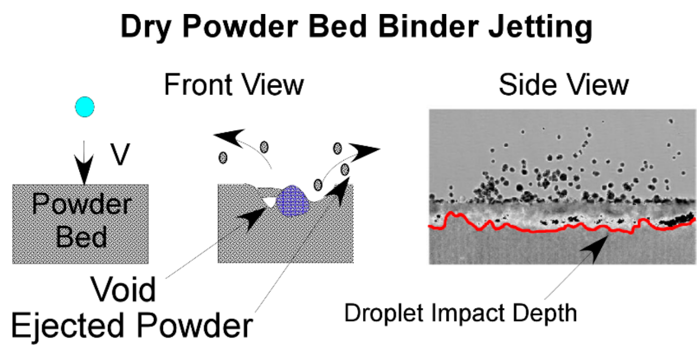


FIGURE 2: LEFT — OVERVIEW OF PARTICLE REARRANGEMENT AND POSSIBLE VOID CREATION. RIGHT — X-RAY IMAGING SHOWING PARTICLE EJECTION. ADAPTED FROM [6].

It is theorized that introducing small amounts of moisture into a powder bed could increase cohesion (FIGURE 3) enough to reduce defect formation during printing (FIGURE 2). In addition to decreased particle ejection, research shows that droplets absorb much more quickly in wetted powders than dry powder. This may enhance total print speed during BJ [8].

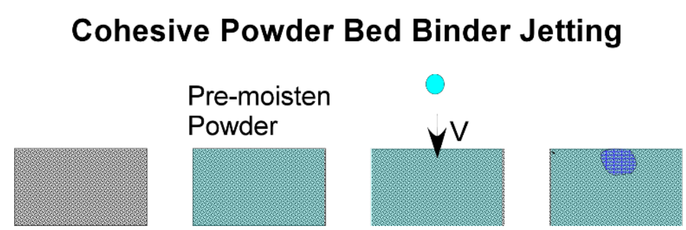


FIGURE 3: OVERVIEW OF PROPOSED CONCEPT FOR UTILIZING SMALL AMOUNTS OF MOISTURE IN THE POWDER BED TO MITIGATE PARTICLE REARRANGEMENT

This paper focuses on the development of a moisture delivery method and the early stages of moisture effects on line formation, surface roughness, and saturation levels.

1.3 Line Formation

Line printing tests have been used in BJ to determine the effect of printing parameters on BJ parts [2]. One main parameter used is the spacing between droplets during the printing process. Colton and Crane [2] showed that lines become unstable with increasing droplet spacing typically due to a defect known as balling. Balling occurs when droplets are spaced too far apart and create an elongated pool that beaks up into spheres. When this happens balls of powder are individually formed along the printed area (FIGURE 4a).

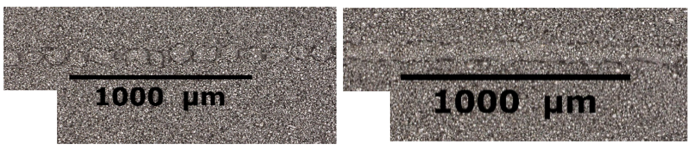


FIGURE 4: COMPARISON OF PRINTED LINES (BALLING VS LINE FORMATION) IMAGED IN THE POWDER BED. A — BALLING DEFECT IN A PRINTED LINE. B — SUCCESSFUL l FORMATION.

Successful line formation is a preliminary indication whether specific printing parameters will result in the formation of successful BJ parts.

1.4 Surface Roughness

The impact crater formed during the binder-powder interaction increases the surface roughness of the powder bed and may cause porous regions within the material (FIGURE 2) [10]. Colton et al. [4] showed that, for the first 4 layers of a print, the surface roughness is greater than the roughness of the dry powder bed. The first layer is rougher than the powder bed, followed by a decrease in surface roughness with each successive layer until it approaches an equilibrium roughness similar to that of the dry powder bed. These results indicate that the interaction between the fresh layer and the previously wetted layer appears to have an impact on the binder/powder interaction.

Some research done by Fan [6] on printing lines, used moisture within the powder bed to mitigate the increase in surface roughness. His results showed that added moisture reduces particle ejection and can drop the surface roughness compared to parts printed in dry powder under the same parameters. Using steam to increase the cohesion between particles showed the surface roughness of the misted parts being up to half the roughness of the dry parts. Later work done by Colton et al. [4] in printing layers showed similar results. One major problem with this method is that the moisture was applied using a humidity chamber or a steamer which either took hours to take effect or increased the moisture content more than desired resulting in increased part dimensions.

1.5 Saturation

A parameter used to characterize test prints in prior work is saturation [1-3]. In BJ, saturation is defined as the fraction of void space within a bound powder region that is filled with binder. Typically, the user chooses a target saturation, and the machine software changes parameters such as droplet and line spacing to achieve the desired saturation. However, the effective saturation —measured after printing— can vary from the target saturation. An excess in binder deposited into the powder bed can cause regions of powder to be wet outside the intended part geometry. This result is known as “bleeding” and causes the effective saturation to be less than the target saturation. In contrast, if the supplied binder is less than needed, the effective saturation is less than the target saturation. Either of these results can be influenced by chosen printing parameters, drying conditions, or binder/powder properties [5].
Effective saturation can be calculated according to:

$$S = \frac{\frac{m_b}{\rho_b}}{\frac{m_p}{\rho_{pb}} * (1 - P_f)} \tag{1}$$

where S is effective saturation, ρ_b is binder density, ρ_{pb} is powder bed density, P_f is the packing fraction, m_b is binder mass, and m_p part mass [5].

As moisture is added to the powder bed above a critical saturation level, the added moisture will create a continuous fluid network within the powder bed. Binder will preferentially travel along this network. This may reduce particle rearrangement, but it can also lead to bleeding and lower effective saturation levels [4].

1.6 This Research

In order to deposit the thin powder layers required for BJ at high density, low cohesion between particles is desired. However, increased cohesion during printing may decrease particle rearrangement and pore formation during jetting. To reconcile these competing interests, a method of moisture delivery into the surface of the powder bed after spreading was developed to create powder-bed cohesion. Tests were conducted to test the repeatability and uniformity of the moisture delivery method. Lines were printed into pre-moistened powder to assess the impact on line formation, line dimensions, and saturation levels. The ideal treatment will expand the printing regime without significantly changing the saturation and line dimensions.

2. MATERIALS AND METHODS

All testing was done in a humid environment kept at 80-90% humidity. This allowed for testing where evaporation of moisture within the powder was significantly delayed and moisture absorption from the environment was negligible [4].

2.1 Moisture Delivery Repeatability and Uniformity

A 113KHz Ultrasonic Mist Atomizer was used to introduce moisture into the powder bed with minimal particle disruption (FIGURE 5). The piezo-electric transducer atomizes water placed on one side of the perforated membrane (FIGURE 5b) to create a fine mist. Varying the duty cycle enables control over the quantity of the mist exiting the atomizer.

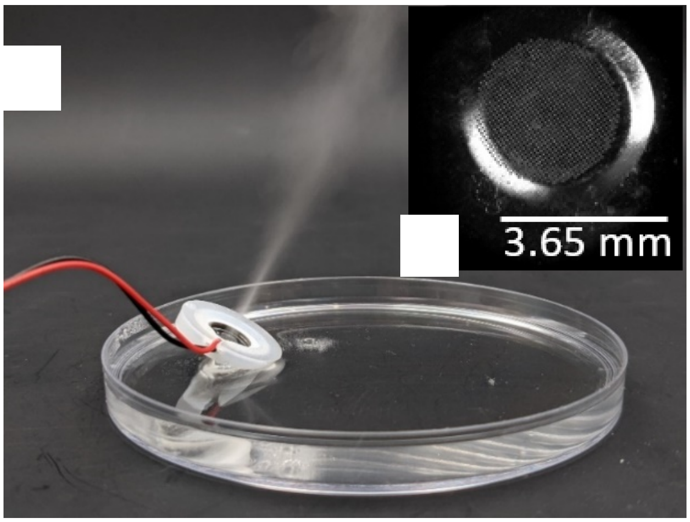


FIGURE 5: PIEZO-ELECTRIC ATOMIZER. A — DISK ATOMIZING WATER TO MIST. EACH DISK HAS A SILICONE COVERING AROUND THE PERIMETER OF THE DISK TO AID IN SEALING. B — PERFORATIONS IN DISK WHICH ATOMIZE WATER WHEN THE DISK IS ACTUATED AT A FREQUENCY OF 113K.

A custom conduit was 3D printed (FIGURE 6a) for repeatably applying mist to powder beds (FIGURE 7a). The atomizers attach to the top of the conduit. A space of 197 mm between the atomizers and the powder bed allows for uniform dispersion across the application area before moisture reaches the powder. The conduit has a built-in catch reservoir to collect any condensation that forms on its walls during misting. The conduit is setup to use up to three atomizers, but only two atomizers positioned on the ends of the conduit were used in these experiments. Each atomizer had variable control for its duty cycle in order to tune them independently. These experiments were conducted with duty cycles of 6.6% and 5.8%.

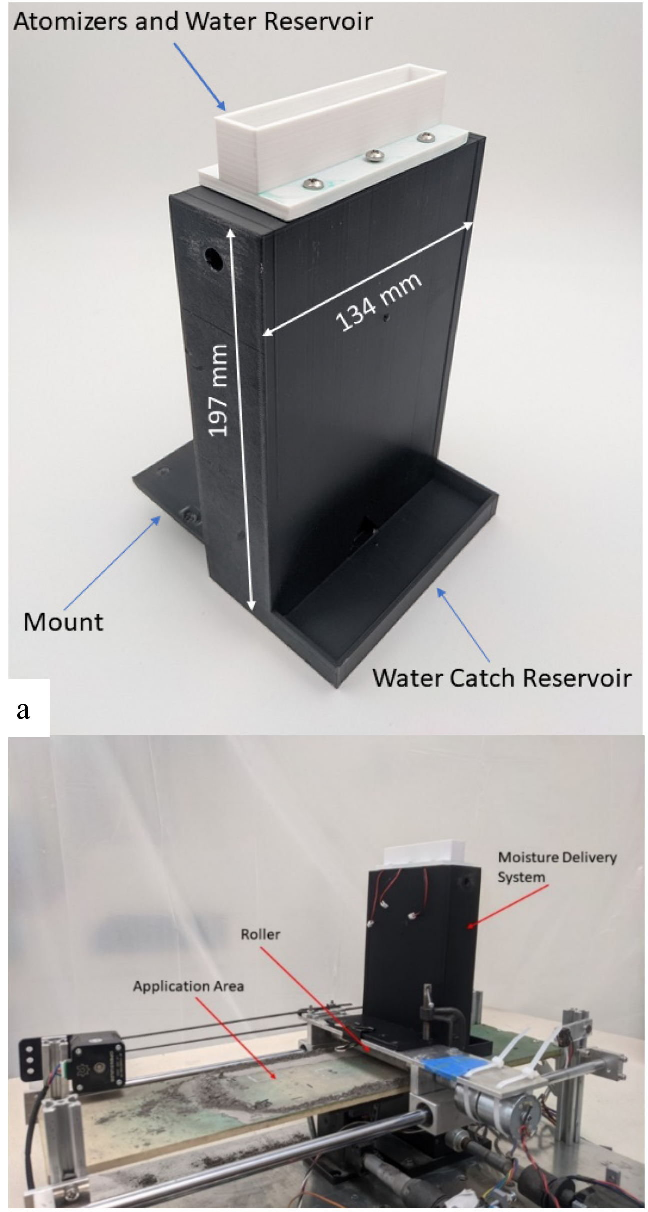


FIGURE 6: A — MOISTURE DELIVERY CONDUIT. THE WHITE PORTION POSITIONS THE ATOMIZERS AND SUPPLIES WATER. THE MOUNT IS USED TO SECURE THE CONDUIT TO THE LINEAR PORTION OF THE APPLICATOR AS SHOWN IN B. THE WATER CATCH RESERVOIR COLLECTS ANY WATER THAT MAY CONDENSE ON THE SIDES OF THE CONDUIT DURING MISTING. THE CONDUIT IS WIDE ENOUGH TO COVER THE APPLICATION AREA AND TALL ENOUGH TO ALLOW FOR MIST DISPERSION. B — THE CONDUIT ATTACHED TO A CUSTOM POWDER SPREADING SYSTEM. THE SPREADER IS MADE UP OF A ROLLER MOUNTED TO LINEAR RAILS WHICH MOVES ACROSS THE APPLICATION AREA.

Mist exposure time was adjusted by altering the traverse velocity of the moisture delivery system over the application area to control the quantity of water delivered to and absorbed by the powder bed. A custom spreader was used for consistent moisture application (FIGURE 6b). The spreader consists of a roller mounted to two linear rails. A belt attached to a motor mounted on one side of the mechanism, the roller system, and a pulley on the opposite side of the mechanism allows the roller to be moved linearly across the spreading area. The roller rotates counter to the direction of linear movement. The spreader was not used to spread powder in these tests. The moisture applicator mounts onto the roller portion of the spreader and was activated after a power bed was placed in the application area (FIGURE 6b).

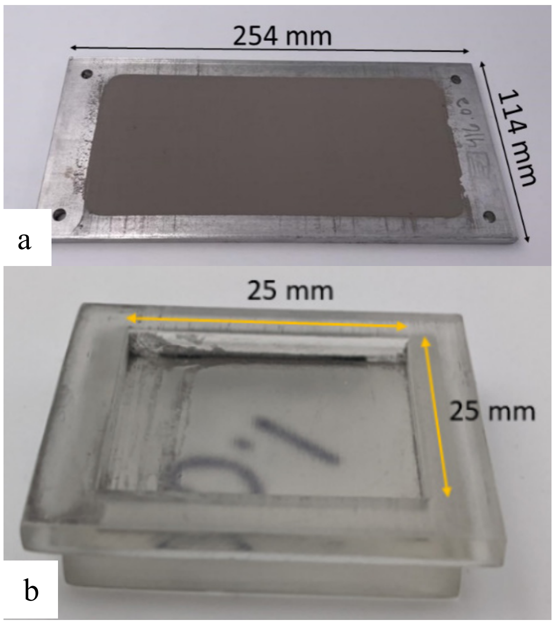


FIGURE 7: **A** – LARGE ALUMINUM POWDER BED PACKED WITH 316L SS USED FOR LINE PRINTING. **B** – SAMPLE CUP PRINTED ON A STEREOLITHOGRAPHY 3D PRINTER USED IN THE REPEATABILITY AND UNIFORMITY TESTING OF THE MOISTURE APPLICATION SYSTEM.

To determine the repeatability and uniformity of the moisture delivery system, an initial test was conducted using an aluminum plate with a powder cavity (FIGURE 7a) prepared with generic granulated sugar to a packing fraction of 0.5. The plate was filled, tapped, and leveled with a straight edge until the desired packing fraction was obtained. The plate was then misted using water mixed with food coloring to dye the sugar and visually tune the applicator (FIGURE 8a). Sugar was used in these tests due to its ease of use, cost, and ability to observe the color of the absorbed mist.

The application appeared visually uniform (FIGURE 8a). The uniformity of moisture distribution was quantified by preparing sample cups (FIGURE 7b) filled with granulated sugar. Samples were filled with sugar and leveled using a straight edge. Each sample was tapped to densify the sugar until a packing fraction of 0.5 was obtained. Samples (FIGURE 7b) were misted at locations 1-5 (FIGURE 8b) and weighed before and after misting. All weight measurements were taken using a OHAUS Adventurer Analytical scale with a ±0.1 mg resolution. Measurements for the weight gain due to water within powder samples are taken near the limits of the scale. This provided a quantitative value of moisture absorbed into samples at each position.

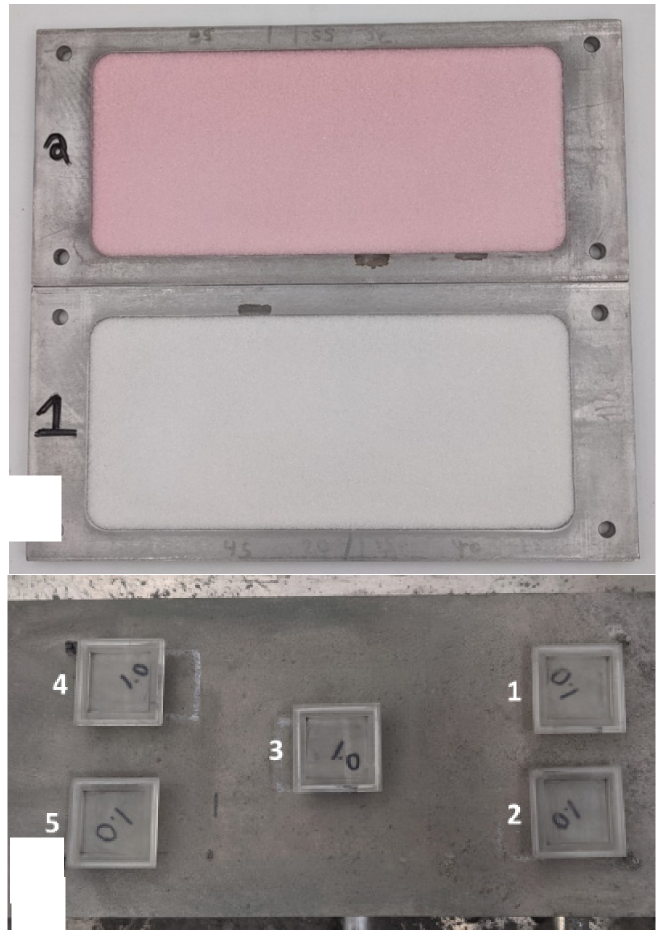


FIGURE 8: a — COMPARISON OF THE VISUALLY UNIFORM MISTED POWDER BED (TOP) COMPARED TO THE ORIGINAL WHITE SUGAR (MIDDLE). b — SAMPLE CUP DISTRIBUTION ACROSS APPLICATION AREA USED TO TEST THE REPEATABILITY AND DISTRIBUTION OF THE MOISTURE DELIVERY SYSTEM. TESTS WERE REPEATED AT EACH LOCATION (1-5) TO TEST HOW REPEATABLY THE MOISTURE APPLICATION SYSTEM DELIVERED MOISTURE TO A DESIGNATED AREA. EACH LOCATION WAS THEN MISTED AND COMPARED AGAINST EACH OTHER TO OBTAIN HOW WELL DISTRIBUTED THE MOISTURE WAS APPLIED THROUGHOUT THE SPACE.

Testing was repeated five times. This testing allowed quantitative data to be collected showing how the moisture delivery varied across the application area and from test to test. To collect the data each sample was weighed before and after misting to calculate the weight gain from the applied moisture. The values of each sample position were averaged, and a standard deviation calculated for each of the five tests. Similarly, the repeatability was calculated by averaging the moisture gain for one sample position from all five test runs and calculating a standard deviation.

2.2 Line Printing

The basic primitive of binder jetting are lines of binder in powder. In multi-nozzle printheads, each nozzle creates its own line and consecutive lines form together into layers by subsequent passes/printheads. To print lines, a custom BJ apparatus was used [2] (FIGURE 6). The apparatus was controlled using a LabVIEW VI and a NI cRio device and consisted of a single MicroFab MJ-AB printhead and a Techno DaVinci CNC router modified with a Gecko G540 controller. The nozzle was controlled using MicroFab's Jetserver program and an external signal controlled through the LabVIEW VI. Droplet spacing and print velocity were controlled allowing for reliable printing.

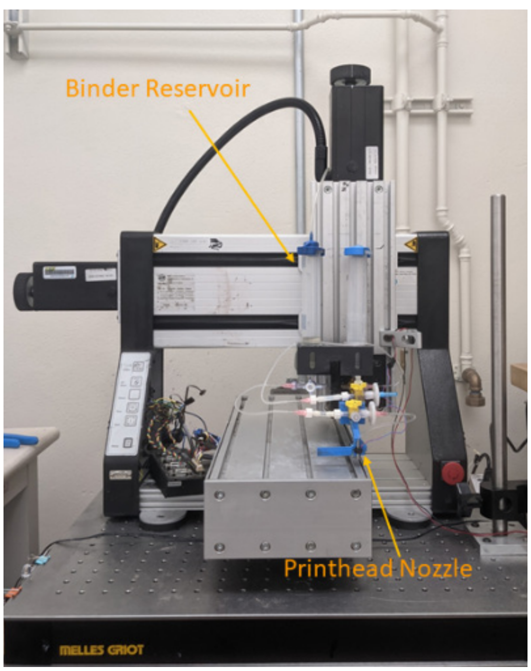


FIGURE 9: CUSTOM BJ SETUP CONTROLLED USING A LABVIEW VI AND A NI CRIO DEVICE AND CONSISTED OF A SINGLE MICROFAB MJ-AB PRINTHEAD AND A TECHNO DAVINCI CNC ROUTER MODIFIED WITH A GECKO G540 CONTROLLER [3].

The line tests were conducted using ExOne's 316L stainless steel powder with an average particle size of 7.6 microns[2]. ExOne's BA005 Aqueous Binder was used in Line printing. The chemical makeup of the binder is proprietary.

For line printing, powder beds were prepared by filling the aluminum bed (FIGURE 7a) void cavity with loose 316L SS powder then using a flat strait edge to smooth the powder. Each powder bed was weighed before and after spreading to calculate a packing fraction. An average packing fraction of 0.54 was obtained. The packing fraction was determined by weighing the powder bed, calculating the density of the powder based on the volume of the void space filled with powder, then comparing the calculated density to the known density of the material. Some beds were tapped during spreading to increase densification when the packing fraction was recorded below 0.54.

Different moisture treatments were used in testing — reported in mg/cm^2 of applied moisture. The five moisture treatments used were: dry powder, 0.115 ± 0.011 mg/cm^2 moisture treatment, 0.064 ± 0.007 mg/cm^2 moisture treatment, 0.044 ± 0.002 mg/cm^2 moisture treatment, and 0.024 ± 0.003 mg/cm^2 moisture treatment. Moisture treatment values were obtained by misting onto a thin light sheet of plastic of a size (20cm x 9.5cm) that filled the application area. The plastic was weighed before and after moisture application to obtain a total water weight, then a mass per unit area calculated. The moisture was applied using the moisture delivery conduit mounted to the custom spreader (FIGURE 6b).

The Lines were deposited into the powder bed using printing parameters as follows:

TABLE 1: PRINTING PARAMETERS USED IN LINE PRINTING FOR THIS EXPERIMENT.

Parameter	Value
Printing Frequency	1000 Hz
Droplet Velocity	~ 7.8 m/s
Droplet Spacing	15–45µm (5µm step increase)
Line Length	20 mm

Six lines were printed for each droplet spacing using a custom BJ setup (FIGURE 9), cured in a Hotentogler Binder Series ED Avantgarde Drying and heating chamber at 180 ℃ for at least thirty minutes, and extracted from the powder bed by inserting two small prongs under the lines and lifting them from the bed. An average line weight was calculated for extracted lines by weighing all extracted lines together and dividing by the total number of lines. An effective saturation was calculated for each set according to equation (1) using the average line weight. The depths and widths of a single line per droplet spacing were measured on a VHX-7000 Keyence digital microscope. The magnification used was 100x.
To compare results, lines were imaged in the bed before extraction to record the particle disruption during printing and again after extraction from the bed to measure the line width. Pictures of lines in and out of the powder bed and line

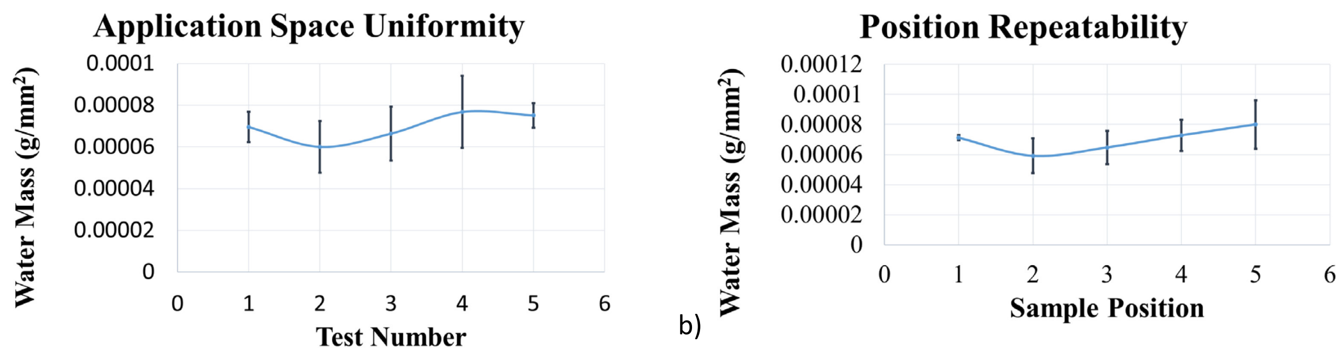


FIGURE 10: A — TEST NUMBER VS. AVERAGE WEIGHT GAIN OF WATER. EACH TEST WAS COMPLETED BY APPLYING MIST TO POSITIONS 1-5 OF THE APPLICATION AREA AND RECORDING THE WEIGHT GAIN. ERROR BARS REPRESENT ONE STANDARD DEVIATION. B — THE WEIGHT GAIN DUE TO MOISTURE WAS AVERAGED FOR EACH SAMPLE POSITION FROM EACH OF THE FIVE TESTS AND A STANDARD DEVIATION CALCULATED.

dimensions (width and height) were obtained using the Keyence digital microscope at a magnification of x20.

3. RESULTS AND DISCUSSION

The experiments described in the methods section are grouped into two categories. First, the moisture delivery system is analyzed for its ability to apply moisture uniformly both spatially and repeatable from test to test. Second, lines were printed and analyzed to determine how the added moisture effected line formation, dimensions, and saturation.

3.1 Spatial Uniformity and Repeatability of Moisture Delivery

The measurements of the moisture distribution showed that the moisture in the five measured locations had standard deviation values less than 23% (
FIGURE **10**). In conjunction, the results for repeatability measurements showed standard deviation values under 21%. The variation in the distribution and repeatability had variations in measurements equal to the resolution (±0.1 mg) limit of the OHAUS Adventurer Analytical scale. These results show that the applicator can mist fairly uniformly spatially and is repeatable from sample position to sample position in the application area. After atomization, the piezoelectric disks often build up some condensation on the face that emits mist. If not removed by hand, this condensation halts atomization for a few seconds. This could be the cause of some error within the results. Atomizers controlled and/or manufactured more precisely may also result in more consistent levels of moisture delivery.

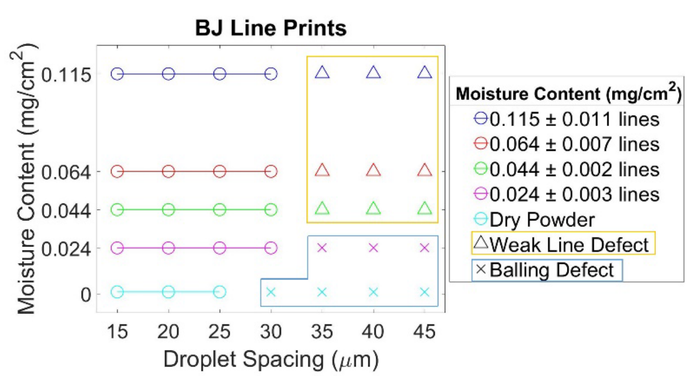
The capabilities of the system should be sufficient to further experimentation and test the effects that moisture within the BJ system have on final BJ part properties.

3.2 Line Printing Using Pre-Moistened Powder

Lines are a quick and easy way to study the effects of moisture on the effective saturation, and dimensional tolerances (width and height) within BJ parts. Much can be told through visual observation of lines, saturation measurements, and dimension measurements.

3.2.1 Success in Line Formation

Line formation is considered successful when lines can be extracted from the powder bed while holding their form. Two modes of failure exist for lines. The first is balling. Balling occurs when the droplets are far enough apart that they don't interact when jetted into the powder and revert to a spherical shape (FIGURE 4a, FIGURE 11c.3). The second mode of line failure is due to low saturation levels. When this occurs, the binder wets the powder, but after the line has been cured the binder content is too low to hold the line together for extraction.



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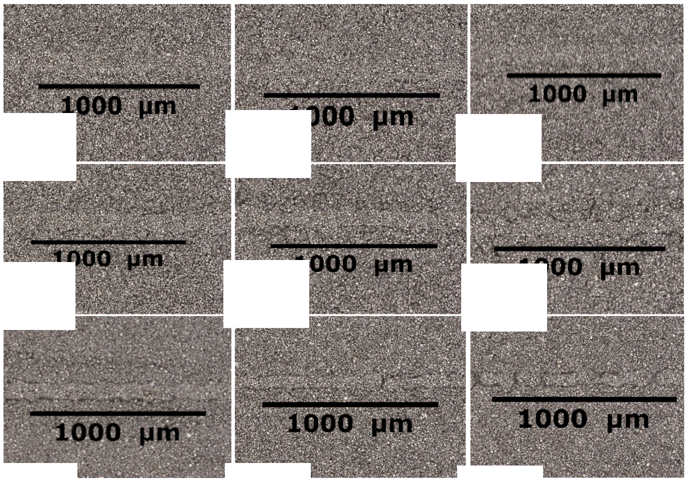

FIGURE 11: TOP – SUCCESSFUL LINE FORMATION FOR LINES PRINTED. CIRCLES REPRESENT LINES THAT WERE ABLE TO BE EXTRACTED (SUCCESSFUL) AND X'S AND TRIANGLES REPRESENT LINES WHICH DID NOT FORM WELL ENOUGH TO BE EXTRACTED DUE TO BALLING AND LOW STRENGTH RESPECTIVLY. IN ALL CASES OF MOISTURE ADDITION, LINES WERE ABLE TO BE EXTRACTED WITH DROPLET SPACINGS THAT FAILED IN DRY POWDER. THE MOISTURE WITHIN THE POWDER BED ALLOWED LINES TO FORM WITHOUT BALLING WHEN PRINTED WITH PARAMETERS WHICH CAUSED BALLING IN DRY POWDER (COMPARE PICTURES FOR 35 µm DROPLET SPACING). BOTTOM — LINE COMPARISON BETWEEN DRY(TOP), MOISTURE APPLICATION WITH 0.115 ± 0.011 mg/cm^2 (MIDDLE), AND 0.064 ± 0.007 mg/cm^2 (BOTTOM). MOISTURE WITHIN THE POWDER BED ALEIVIATED BALLING AND DECREASED POWDER DISRUPTION CAUSED DURRING PRINTING.

The overall goal of these experiments was to determine if lines could be printed into pre-moistened powder beds to improve printability without decreasing saturation and increasing dimensions. The results of the line printing tests are summarized in Figure 11 as a function of the droplet spacing of the printed lines and level of added moisture.

At each moisture level, the lines were extractable at small droplet spacings but failed to extract as droplet spacing increased. However, the line printing failure mode was different for the dry and wet powder. Both the dry powder and the powder moistened with a 0.024 ± 0.003 mg/cm^2 moisture level, exhibited balling as the failure. The other powders with moisture, experienced failures due to low strength causing them to break apart during extraction.

For all lines printed in moistened powder, lines could still be extracted at 30 µm droplet spacings where dry powder lines at 30 µm droplet spacing resulted in a balling failure. In moisture treatments of 0.115 ± 0.011 mg/cm^2, 0.064 ± 0.007 mg/cm^2, and 0.044 ± 0.002 mg/cm^2, balling was entirely eliminated at droplet spacings across the entire tested range (up to 45 µm droplet spacings). While the lines could no longer be extracted when spacing increased above 30 µm, they still appeared to form continuous lines in the powder bed. Colton et al. [4] showed that layers (composed of many adjacent lines) can successfully be formed and extracted when printed under conditions which do not form single lines. If balling is occurring as individual lines are printed but the lines stitch together to form a layer, the increased surface roughness caused by balling may result in porous regions. The reduced balling in lines shown in Figure 11 could mitigate large pore formation. Because balling would be mitigated, moisture added to the powder bed may also increase the range of parameter sets which allow for successful printing, although a stronger binder may be needed to have sufficient strength to extract the parts.

FIGURE 11 not only shows balling mitigation, but shows that in lines that are extractable, as moisture levels increase, lines become smoother and harder to differentiate from the unbound powder. This indicates that using moisture to increase cohesion is mitigating powder rearrangement as hypothesized. However, to determine the overall effects moisture within a powder bed can have the methods described above need to be applied to both layers and multi-layer parts.

3.2.2 Line Dimensions

FIGURE 12 shows that moisture addition increases the width and height of lines. The paths—connecting void space within the powder—formed by water content, facilitate in binder distribution in the powder, but decreases the amount of binder needed to overcome the capillary forces keeping the binder within the desired dimensional tolerances. Interestingly, the lines treated with moisture of 0.064 ± 0.007 mg/cm^2 showed a higher increase in width than the 0.115 ± 0.011 mg/cm^2 moisture treatment lines. Because the moisture treatment of 0.115 ± 0.011 mg/cm^2 takes longer to mist, evaporation may be reducing the moisture content within the bed to a level lower than the 0.064 ± 0.007 mg/cm^2 moisture treatment before actual printing is accomplished. The 0.024 ± 0.003 mg/cm^2 moisture treatment lines have widths comparative to lines printed in dry conditions, indicating that moisture can be applied without significantly altering certain dimensional tolerances. This suggests that at lower moisture levels, the added moisture may not be exciting the critical saturation to achieve an interconnected liquid network in the pores before the binder is added.

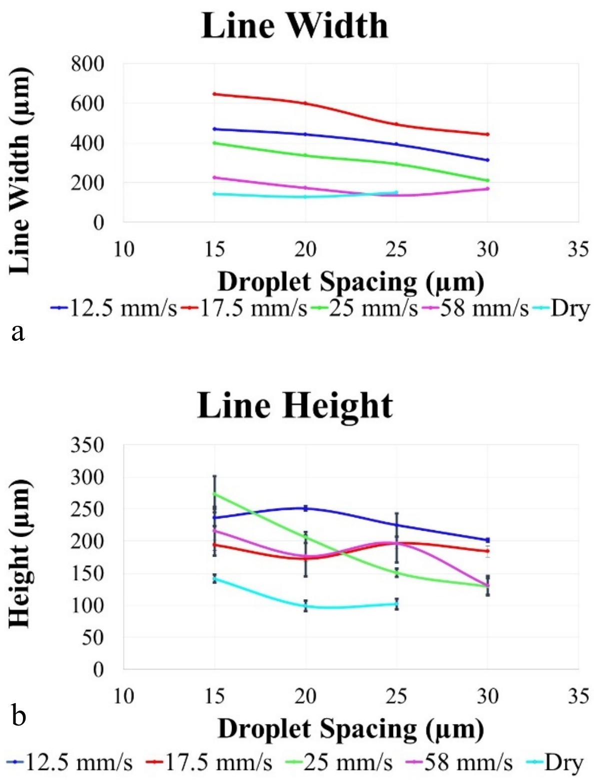

FIGURE 12: A — DROPLET SPACING VS. LINE WIDTH. MEASUREMENTS WERE TAKEN ON ONE OF SIX LINES FROM EACH DROPLET SPACING. BECAUSE THE WIDTH WAS ONLY TAKEN ON ONE OF THE SIX LINES NO ERROR BARS ARE PRESENT. LINE WIDTH INCREASES WITH MOISTURE CONTENT (SMALLER VALUES Of $v_{traverse}$). THE TWO LONGEST EXPOSURE TIMES SHOW THE OPPOSITE OF THE EXPECTED. THIS MAY BE DUE TO EVAPORATION OCCURRING DURING THE LONGER MOISTURE ADDITION, CAUSING A LOWER MOISTURE LEVEL THAN THAT OF THE MOISTURE TREATMENT OF 0.064 ± 0.007 mg/cm². THESE RESULTS SHOW THAT COMPARABLE DIMENSIONAL TOLERANCES CAN BE OBTAINED WITH MINIMAL AMOUNTS OF MOISTURE CONTENT AS OPPOSED TO DRY POWDER. B — DROPLET SPACING VS. LINE HEIGHT. MEASUREMENTS WERE TAKEN ON ONE OF SIX LINES FROM EACH DROPLET SPACING. LINE HEIGHT IS LARGER IN SAMPLES WITH MOISTURE. IN EVERY CASE OF MOISTURE ADDITION HEIGHT INCREASES. THIS INDICATES THAT THE MOISTURE IS FACILITATING BINDER TO PENETRATE DEEPER INTO THE POWDER BED.

The line height is increased in each case of moisture addition, indicating that moisture addition helps the binder to spread further into the powder bed than in dry powder conditions. Theoretically, larger depth penetration would increase the minimal layer thickness that can be printed. Without testing using 3D parts, the full effects of the height results cannot be determined, but it may allow for a part to be printed using less binder. If less binder could be used the binder composition would have to be altered to obtain the same green part strength as parts printed without moisture addition.

3.2.3 Line Saturation

Saturation levels provide valuable insight into the distribution of binder in the parts. Low effective saturation levels indicate that the binder if spreading out farther into the bed. This can be helpful for speeding the printing process but reduces the minimum feature size. Unfortunately, the green strength usually decreases with decreasing saturation as well. The ideal treatment will suppress balling while also maintaining similar saturation levels to the dry powder.

Most of the lines printed in moist powder showed a significant drop in saturation levels. The one exception was the lines printed into powder moistened with a 0.024 ± 0.003 mg/cm² treatment, which had saturation levels comparable to dry powder (FIGURE 13). In two out of the three data points that are comparable between dry, 0.024 ± 0.003 mg/cm² moisture treatment, and 0.024 ± 0.003 mg/cm² moisture treatment is either close to the same or higher in saturation than the dry lines. While this low moisture level, still had balling at the largest droplet spacings, it did still extend the successful line formation from 25 µm droplet spacings to 30 µm droplet spacings. This provides evidence that the printing process was improved by added moisture.

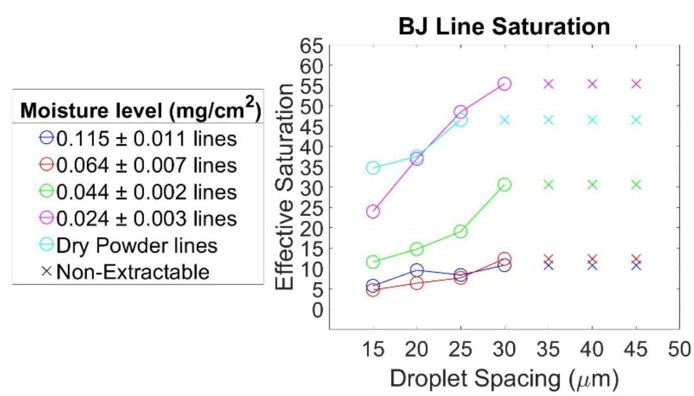

FIGURE 13: COMPARISON OF LINES PRINTED IN DRY POWDER AND MOIST POWDER. THE MAJORITY OF LINES IN PREMOISTEND POWDER HAVE LOWER SATURATION VALUES THAN THAT OF DRY POWDER, BUT THE LINES WITH 0.024 ± 0.003 mg/cm² TREATMENT ARE COMPARABLE TO DRY. THE DATA POINTS MARKED WITH AN X INDICATE NON-EXTRACTABLE LINES. Xs WERE REPORTED AT THE LAST EFFECTIVE SATURATION VALUE TO HELP DIFFERENTIATE BETWEEN DATA SETS, BUT THESE VALUES ARE NOT REPORTING AN EFFECTIVE SATURATION FOR THESE DATA POINTS.

The decrease in saturation of the powder moistened at slower traverse rates is likely due to moisture paths allowing binder to travel farther within the powder bed. As binder is spread further the binding agent within the binder is less concentrated. Future experimentation will focus on low added moisture levels in order to keep saturation levels comparable to the dry powder and see if the reduced balling can still be maintained. Experiments are also needed to see how the moisture addition benefits formation of layers and 3D parts.

Line printing results show that lines are highly affected by moisture content within the powder bed. Higher levels of moisture altered both dimensional tolerances and saturation levels significantly but increased the droplet spacing range in which the BJ processes successfully formed lines. Though most of the data sets utilizing moisture showed undesirable results such as decreased saturation, the moisture treatment of 0.024 ± 0.003 mg/cm^2 showed results in both width measurements and saturation levels comparable to lines printed in dry powder. The lines with a moisture treatment of 0.024 ± 0.003 mg/cm^2 also allowed for successful line formation using parameters which caused balling in dry powder. The lines with moisture treatment of 0.024 ± 0.003 mg/cm^2 did have increased line height, but the effects of this cannot be realized without further testing with multi-layer parts.

4. CONCLUSION

This study has shown that with small amounts of moisture from atomized water added to the powder bed, lines can be printed and extracted using parameters which cause failure in dry powder without sacrificing saturation or feature sizes. Particle rearrangement during printing also seems to be significantly suppressed by the moisture addition. Future work will consist of testing with moisture in both layers and multi-layer parts.

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