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The Impact of Inkjet Parameters and Environmental Conditions in Binder Jetting Additive Manufacturing

Trenton Miles Colton
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The Impact of Inkjet Parameters and Environmental Conditions in
Binder Jet Additive Manufacturing

Trenton Miles Colton

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT

The Impact of Inkjet Parameters and Environmental Conditions in Binder Jet Additive Manufacturing

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Binder jetting is an additive manufacturing process in which a part is fabricated layer-by-layer using inkjet technology to selectively dispense binder into powder layers in a designated area. The approach gives this process significant advantages over other additive manufacturing processes such as lower cost, capability to print in a wide range of materials, and little to no heat applied. Although binder jetting has many advantages and has been successfully implemented in various industries, its overall rate of adoption is slow compared to other processes. This is largely due to poor mechanical properties and consistency in printing which stems from a poor understanding of the interaction between the binder droplets and the powder bed. This is evident as print parameters for new machines and new materials are primarily determined by trial and error. The purpose of this thesis is to report the impact of various inkjet print parameters and humidity on the printing process in binder jetting.

The binder/powder interaction is complex and highly dynamic where picoliter-sized droplets impact the powder bed at velocities of 1-10 m/s. Current methods of predicting this interaction assume that it is based only on binder and powder properties. This work studies the impact of inkjet printing parameters that are often overlooked with these assumptions. The impact of droplet velocity, droplet spacing, and droplet inter-arrival time was evaluated based on single line formation and effective saturation levels when printed into various powder material and sizes. Higher droplet velocities were found to decrease effective saturation with larger droplets (92-212 pl). However, droplet velocity had a negligible impact on saturation when printing with smaller droplets from 30 µm orifice (29-65 pl). Line formation was dependent on both droplet inter-arrival time and droplet spacing. Max droplet spacing correlated to the square root of inter-arrival time. These results can guide selection of printing parameters that maximize build rates and reduce defects in printed parts.

As the binder/powder interaction is difficult to observe and often line formation has been used as a method of observation. However, no report relating line formation to full layer parts exists. Optimal parameters determined in line printing are used for full feature parts. In addition, the impact of ambient humidity on the printing process is studied. The direct use of parameters optimized for line printing in printing a part was shown to be ineffective. When droplet spacing, line spacing, and layer thicknesses are comparable, single and multiple layers can be formed. Over short exposure periods of powder to ambient humidity produces negligible difference however, extended exposure periods significantly reduce the saturation and increase part size. Surface roughness is identified as a possible source of printing defects. Surface roughness increases significantly when printing the first layer but decreases with successive layers. This demonstrates a strong interaction between layers. The surface roughness and effective saturation was insensitive to line and droplet spacing below 60 µm. Steam powder conditioning reduces sensitivity of both
surface roughness and saturation to printing parameters but causes bleeding beyond the part boundaries.

Further research should include improved methods of predicting ideal printing parameters and connecting it based on geometry and parts size. Further research is needed to confirm impact of surface roughness on defects in binder jetting parts. Research of methods to control spread of binder in premoistened powder is needed to take advantage of its potential.

Keywords: additive manufacturing, binder jetting, Washburn infiltration, Inkjet, surface roughness
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1. RESEARCH MOTIVATION AND OBJECTIVE

1.1 Background

Binder jetting is an additive manufacturing process that uses inkjet technology to selectively dispense liquid binder on thin layers of powder to form a desired cross section. Powder is then spread on top and the process is repeated until a full part is formed [1]. Binder jetting was invented in the early 1990’s at MIT [2]. Since then, several companies have become successful in developing binder jetting machines including ZCorp (acquired by 3D Systems in 2012), ExOne, and Voxeljet [3, 4]. Initial patents on binder jetting have recently expired and a new wave of interest has come. HP launched its first metal binder jetting system in 2018 [5], GE Additive will begins selling its binder jetting system in 2021 [6], and startup Desktop Metal’s recent round of funding valued the company at $1.5 billion [7]. Binder jetting’s potential and advantages has allowed it to gain significant interest and investment.

Binder jetting has unique advantages when compared to other additive manufacturing processes including relatively low cost, high build rates, and material flexibility (i.e., metals, ceramics, polymers). In contrast to other additive manufacturing processes no fusion takes place during printing and relatively little heat is applied during the printing process. This eliminates potential flaws caused by heating seen in other processes. In addition, no additional structures need to be added for support or heat dissipation. This removes the inconveniences of designing and removing support structures which can be labor intensive and expensive. These advantages have
made binder jetting a process of interest for various industries including aerospace, automotive, foundry, and biomedical. Despite the potential uses of binder jetting, its implementation in industry is behind other processes due to insufficient understanding of the fundamental physics in the process. Current methods to identify print parameters and select new materials suitable for printing are driven by trial and error. A lack of predictive methods wastes resources and slows development of binder jetting. The binder/powder interaction is fundamental to binder jetting is poorly understood by industry and academia. Improved understanding will decrease cost, decrease print time, improve part mechanical properties, and reduce printing defects.

1.2Objective

Current methods for determining suitable print parameters and identification of new materials hinder implementation of binder jetting in industry. More efficient methods are dependent on understanding the binder powder interaction. Therefore, the goal of this research is to improve understanding of the effects of print parameters and environmental conditions on the binder/powder interaction. This will be done by evaluating the impact of the following:

1. Droplet velocity, spacing, inter-arrival time on line formation and saturation,
2. Evaluation of line printing and humidity on single- and multi-layer parts.

1.3Thesis Organization

Chapter 1 provides a brief background to binder jetting and outlines the objectives of the thesis. Chapter 2 presents a literature review on various factors to binder jetting. Chapter 3 outlines the design and function of the experimental apparatus built for these experiments. Chapter 4 provides background, motivation, and results pertaining to experiments conducted on line formation and saturation. Chapter 5 investigates the influence of inkjet printing parameters on
multilayer parts, in addition, it investigates the impact of ambient humidity on multilayer parts.

Chapter 6 presents conclusions from the research and describes possibilities of future work.
2. LITERATURE REVIEW

2.1 Additive Manufacturing

Additive Manufacturing (AM) has become a key part of the manufacturing industry world-wide due to benefits such as customization, geometry, decreased lead time and lower costs for low volume production. AM (also known as 3D printing or rapid prototyping) technology refers to the process of forming or patterning materials layer by layer using information generated from 3D models.

AM is different from traditional methods that shape features by “subtracting” from bulk material, AM continually joins material together using bulk feed material often in powder or filament form, leaving little to no waste material. According to ASTM 52900 standard, AM processes categories are separated into seven distinct groups: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization [8].

Products and services revenue related to AM grew in 2019 by 21.4% to almost $12 billion and projected to grow to $35.6 billion by 2024 [9, 10]. A major focus of the industry has been to move from a prototyping process to manufacturing end use parts. This has occurred to large degree in the biomedical implant industry and is advancing in aerospace. AM adoption is driven by part elimination, weight reduction, complex geometry fabrication, and part customization [11, 12]. SpaceX recently made headlines by using AM built Inconel engine chamber in launches [13].
biomedical AM is used in custom fit ceramic and metal implants [12] and an interesting capability being studied is bioprinting, printing of tissue and organs [14-16]. In the general consumer market, Nike and New Balance are using AM technology to increase shoe customization and improve design [17]. An extremely successful sector of AM has been in producing parts with materials that have traditionally been challenging or expensive such as titanium alloys, super nickel alloys, magnesium alloys, and ceramics [12, 18]. AM has made large strides in materials, applications, and capability with a continued expectation of rapid growth.

One process, Binder Jetting (BJ) is behind other processes in implementation and interest in industry largely due to issues related to the lack of understanding the fundamental processes and challenges in post-processing of the printed parts. However, BJ has advantages that makes it a potential candidate for widespread adoption such as relatively low production cost, wide range of potentially suitable materials, and no need for support material.

2.2 Binder Jetting

2.2.1 Overview

BJ is an AM process first developed at MIT in the early 1990’s [2]. The process spreads a thin layer of powder over the surface of a build piston. Layer geometry is patterned by inkjet printing depositing a liquid binder into the powder to bond a cross section together as illustrated in Figure 2-1. The surface is typically heated slightly to partially evaporate the binder before depositing the next layer. The build piston is lowered, and the process repeated layer-by-layer until the desired part is made [2]. In contrast to other AM processes no fusion takes place during this printing. The cured liquid binder simply glues the particles together producing a “green” part. As
the resultant green part usually has relatively low strength, the part is usually post processed by methods such as infiltration or sintering to improve density and part strength [1].

![Diagram of the basic binder jetting process](image)

**Figure 2-1: Illustration of the basic binder jetting process.**

BJ has many potential advantages compared to other AM processes. BJ uses the unbound powder as support structures. This decreases post processing required by other AM methods in removing the support structure and eliminates virtually all material waste. BJ unlike most AM processes can use any powdered material as feedstock including polymers [19], ceramics [20], and metals [18]. The process has a relatively high build rate and large build area by using inkjet technology with many nozzles to dispense the binder. BJ has strong potential to be a low-cost and high-speed AM process.

However, further implementation in industry requires improved mechanical properties, improved dimensional accuracy, and decreased cost. Research has made progress addressing these
challenges. Steps have been taken to improve surface finish and print resolution by using finer powder [21]. Furthermore, bimodal mixtures where fine particle are mixed with coarser particles has improved surface finish and part density [22-24]. Nano particle have been added to binders to improve green strength improving applications of BJ [23]. While there have been significant improvements in appearance and prototype applications, due to relatively poor density and strength post processing by sintering and infiltration has been needed for end use parts. Significant progress has been made in post processing, as many materials can be sintered and infiltrated to near full density [23, 25, 26].

Current methods of identifying printing parameters for BJ are generally a try and fail approach [27-31]. This wastes resources and does not improve predictability for new materials and new machines. Much of the current research is directed to identifying printing parameters for specific materials and specific machines [27-30, 32]. However, an increased understanding of the physics of the fundamental binder/powder interaction will help researchers identify materials and corresponding print parameters independent of machine type and with reduced testing. This increased understanding will allow for improved dimensional tolerances, enhanced material properties, and reduced minimum feature size, as well as decreased cost to develop new machines and material systems.

The fundamental interaction in BJ is the binder/powder interaction. The basic building block of BJ is the deposition of a droplet into a powder bed to form a new region of bound powder. In BJ, 20-60 µm droplets impact powder with velocities ranging 1-10 m/s. The forces involved in the interaction are complex. Both capillary and inertial forces are significant and powder bed rearrangement is common [33]. The individual droplet stitch together to create lines, layers, and multi-layer parts. This fundamental interaction of understanding influences on the stitching
between droplets and droplet-powder impact is crucial to the advancement of BJ. This thesis will advance understanding of this critical area.

### 2.2.2 Saturation

A primary measurement for the binder/powder interaction is saturation. Saturation is defined as the amount of void space within the powder bed that is filled with binder. In BJ, the saturation must be sufficient to form a continuous network of binder for the green part to have sufficient strength. However, both lower and higher saturation will introduce part defects in printing. If the saturation is too high, a defect called “bleeding” will occur. Bleeding happens when hydrostatic pressure grows and exceeds capillary forces which causes the binder to spread past the desired dimensions of the part, negatively impacting dimensional accuracy [34, 35]. If the saturation is too low, the part will have insufficient bonding between the powder particles resulting in a low green strength [36]. Critical BJ development is improving selection of saturation levels.

Prior to printing, the user selects a target print saturation. This setting determines the amount of binder to print into the powder and is calculated based on the anticipated void space within the powder bed. Print saturation is

\[
S_p = \frac{V_b}{(1 - P_f)tA}
\]  

(2-1)

where \(V_b\) is the volume of binder deposited, \(P_f\) is the packing fraction or the ratio of the powder bed density to true density of the material, \(t\) is the thickness of the part, and \(A\) is the area where binder is deposited. This assumes the binder will remain in a pre-determined volume, however, environmental conditions and interaction with previously-printed regions can cause the binder to bond more or less powder than anticipated, causing the effective saturation to be different from the target print saturation [37, 38].
During BJ, droplets impact the powder bed surface and penetrate a short distance. Inertial forces dominate at short times while capillary pressure is the primary force acting on the fluid in the powder over longer time periods [11]. Capillary pressure ($P_c$) is the difference in pressure across a curved interface between two immiscible fluids. Capillary pressure drives fluid from saturated to unsaturated regions. The max saturation is reached when pressure is equilibrated across all surfaces. This causes some areas to imbibe or drain and due to the hysteresis between the imbibition and drainage curves there are different saturation levels at equilibrium [21]. The max saturation is the limit where binder will remain stable and stop further migration. This limit is complex and is dependent on various environmental conditions, print parameters, and binder and powder properties [38].

As the max saturation can vary in parts and highly dependent on other factors, an effective saturation can be reported from a part mass by

$$S_{eff} = \frac{m_b \rho_{pb}}{m_p \rho_b \ast (1 - P_f)}$$

(2-2)

where $m_b$ is the mass of the deposited binder, $\rho_b$ is binder density, $m_p$ is the mass of the bound powder, $\rho_{pb}$ is powder bed density, and $P_f$ is the packing fraction. The importance of understanding effective saturation has led to a search for predictive measures. Bai et al. [39] explored effective saturation levels from primitives formed by millimeter-scale sessile drops as a relatively quick predictive measure. It was found that in millimeter-scale drops as the dynamic contact angle increased the saturation level increased and binder penetration depth decreased.

Miyanagi et al. [14] proposed the first physics-based model to predict the effective saturation. The model is based on measured capillary pressure and assumes a single equivalent pore size to describe the powder bed. The predicted max saturation level was compared to experimental effective saturation for three geometries (single line, single layer, and multilayer...
parts). The effective saturation varied significantly with geometry and no one geometry fit the predicted max saturation [40]. Possible source of error was the models disregard to process parameters in BJ. The lack of theoretical models and inaccuracy with current ones may be caused by the misunderstood and underappreciated impact of printing parameters in BJ.

The specific printing process has a significant impact on effective saturation because it is path dependent. However, it is commonly treated as only dependent on powder and binder properties. Understanding the influence of print parameters on effective saturation will help optimize the printing process and improve properties in BJ parts.

2.2.3 Capillary Rise

Imbibition of binder into a powder bed depends on particle size, density, and surface chemistry. A simple model for powder beds is a bundle of cylindrical tubes based on an effective pore size [41]. By assuming capillary tubes, powder beds can be related to the capillary rise. The capillary rise can be simplified and separated into three major regimes, inertial, Washburn’s, and late viscous as illustrated in Figure 2-2. Depending on the fluid and powder properties the transition times between the regimes may be different, but all follow the general shape shown in Figure 2-2.

As the droplet impacts the powder bed the inertial regime begins. It is short but can be explained by a constant known as the Quéré velocity \( V_q \)

\[
V_q = \frac{2 \gamma}{r_{eff} \rho_b}
\]

(2-3)

where \( \gamma \) is surface tension, \( r_{eff} \) is the effective pore size, and \( \rho_b \) is the liquid or binder density [43]. This model breaks down as the fluid continues to infiltrate. In the inertial segment, the mass increases linearly with time, but it only lasts milliseconds for many fluid/powder combinations [43, 44].
As the fluid continues to infiltrate it transitions to the Washburn regime in which the mass gained, or height infiltrated squared is proportional to time as shown in Figure 2-2. This regime lasts for longer periods of time than the inertial regime and dominates many porous infiltration problems. Thus, measurement of this regime is relatively simple and is commonly done using the Washburn Capillary rise method which relates the flow of fluid in powder to fluid and powder properties [42].

The Washburn regime transitions to the late viscous regime when the capillary pressure approaches equilibrium. Eventually, the change in mass or height with time becomes zero. The capillary rise helps in modeling in BJ by understanding the binder and powder properties through relatively simple measurements and calculations.

Figure 2-2: An illustration of the capillary rise. The three major regimes are shown as a function of mass squared and time. Mass squared can substituted for height squared. Adapted from [42].
2.2.4 Inkjet

Inkjet printing utilizes ejection and propulsion of picoliter-sized droplets from an orifice onto a substrate. Inkjet technology is one of the most widely used printing technologies available today. In recent years, manufacturing emerged as a new application for the technology. Inkjet printing has proven successful in various applications including conductive inks [45], additive manufacturing [1, 16] and drug delivery [46].

Inkjet technology can be divided largely between two major groups, continuous and drop-on-demand (DOD) [47, 48]. Continuous inkjet printing involves a continuous stream of droplets from an orifice. The droplets are then selectively deposited onto a substrate or discarded to a recycling reservoir. The control of droplet placement is usually done by electrically charging selective droplets which are then deflected by an electrode directing them to the substrate [49, 50].

DOD print heads, unlike continuous inkjet print heads, only eject droplets when signaled. The two most common instruments used to eject droplets in DOD are piezoelectric and thermal transducers [50]. Piezoelectric transducers contract and expand based on the voltage waveform they receive from the drive electronics. When the transducer contracts, droplets are ejected. Contrastingly, thermal transducers operate by heating a small plate in the fluid which creates a vapor bubble causing a temporary increase in pressure which ejects the droplet [45-49]. Piezoelectric transducers are used more in manufacturing settings because they avoid the potential thermal degradation of the liquid caused by thermal transducers. They can also print a wider range of materials [14]. DOD droplets emerge elongated as shown in Figure 2-3. These droplets have long tails that tend to break up and produce satellite droplets. These satellite droplets are common in many printing systems and often the effects are ignored due to the relatively small size of the satellite drop.
Inks are designed/selection based on their fluid properties such as density, viscosity, and surface tension. These properties dictate the “jettability” of inks including droplet size, shape, and surface impact [48, 49]. Surface tension must be low enough to eject a droplet but high enough not to continuously drip. Viscosity must be low enough to refill near the orifice after the ejection of the droplet. Fluid properties can be quickly assessed by dimensionless numbers: Reynolds (Re), Weber (We), and Ohnesorge (Oh). The Reynolds number relates inertial forces to viscous forces and is defined by

\[ Re = \frac{\rho VL}{\eta} \]  

(2-4)

where \( \rho \) is fluid density, \( V \) is droplet velocity, \( L \) is nozzle diameter, and \( \eta \) is dynamic viscosity. The Weber number is the ratio of inertial forces to surface tension forces defined by
Where $\gamma$ is surface tension. The Ohnesorge number is the ratio of viscous force to surface and inertial forces, defined by

$$Oh = \frac{\sqrt{We}}{Re} = \frac{\eta}{\rho L \sigma}$$

This has led to the identification of a parameter, $Z$, to characterize conditions for acceptable printing of stable droplets [51, 52]. $Z$ is the reciprocal of the Ohnesorge number. Previous work has shown stability in printing when the $Z$ value is between 1-10 [51, 52]. The Weber and Reynolds number provide additional boundaries for stable inkjet printing as depicted in Figure 2-4.

![Figure 2-4: Ideal inkjet printing fluid properties illustrated. The Weber and Reynolds number can help define a printable region, in addition to the range of $Z$ values. Adapted from [48].](image-url)
Outside of desktop printing, inkjet technology has been successfully applied to printing a wide range of materials. Nanoparticle inks are a common material deposited using inkjet technology. Nanoparticle inks consist of nanoparticles dispersed in fluid which then can be printed. The large surface area of the nanoparticles allows for low sintering temperatures so that they can be cured on a low temperature substrate such as plastics. These are commonly used in printed electronics [45, 53, 54]. Metals with lower melting temperatures such as solder are also deposited with inkjet printing [55]. There is interest in combining inkjet-printed medicines with BJ fabrication to create customized pills with personalized combinations and special does release rates [46].

Inkjet technology is a fundamental part of BJ systems. The technology is a crucial aspect of the binder/powder interaction as it directly alters droplet size, shape, velocity, and inter-arrival time. Improvement in selection of BJ printing parameters and system design, improved understanding of impact of these parameters is needed. Details of the apparatus and inkjet system used in this work is explained in detail in the following chapter.

2.3 Effects of Printing Parameters

The BJ process may appear relatively simple and straight forward, however, there are many factors which contribute to the end part’s properties and features. There are print parameters selected by the user or manufacturer that can have significant impact on the part. The impact of these parameters can be seen in the droplet/powder interaction. The following subsections describes the impact of various printing parameters on BJ parts.
2.3.1 Inkjet Printing Parameters

In BJ, individual droplets must coalesce within and between layers to form continuous features. However, fluids minimize their energy by forming spheres. BJ features successfully form when binder infiltrates into the powder before enough pools on the surface that surface energy minimization drives it to form bulges or pinch off into separate balls (balling). Line formation is the ability of droplets to coalesce to form a line defects such as balling prevent that. Successful line formation is another measurement of the binder/powder interaction.

Understanding binder/powder interaction is critical to improving the selection of print parameters. The target print saturation selected by the user is related to other printing parameters by

\[ S = \frac{\pi D_d^3}{6 \Delta x \Delta y \Delta z (1 - P_f)} \]  

(2-7)

where \( D_d \) is the droplet diameter, \( \Delta x \) is the droplet spacing, \( \Delta y \) is the line spacing, and \( \Delta z \) is the layer thickness. The relation of inkjet parameters to saturation and line formation is not well known in BJ.

2.3.1.1 Droplet Spacing and Size

BJ shares some principles in common with 2D inkjet printing on solid surfaces. For example, coalescence of individual droplets into lines of uniform width without bulges or necking is important to good 2D print quality. Line formation is known to depend on droplet size, droplet spacing, droplet velocity, and contact angle [37, 56, 57]. When printing on glass, smaller droplet spacings lead to bulging while larger spacings did not coalesce to a single line, a droplet spacing to droplet radius between 1.35 and 1.6 produced uniform lines [56]. While these 2D observations are helpful, relatively little is known about the conditions required for line formation in BJ where
droplets impact powder rather than a solid surface. Understanding how the droplet spacing and size can influence line formation and primitive size in BJ will aid improvements in print quality and productivity.

In BJ, droplet size, droplet spacing, and layer thickness determine the overlap between successive droplet primitives. Primitive overlap will result in increased green strength [58] but too much binder will decrease geometric accuracy [38]. Droplet overlap in powder also impacts build time and formation of defects such as balling [59].

### 2.3.1.2 Droplet Interarrival Time

The interaction between droplets and line formation on solid surfaces has been shown to depend on a droplet inter-arrival time [60]. Droplets deposited on a glass with a shorter inter-arrival period created a more uniform line than those printed at longer intervals [57]. However, the dynamics in BJ are more complex than 2D printing on solid surfaces as droplets can both spread over and penetrate the pores between powder particles.

In BJ, it is known that generally a short inter-arrival time is detrimental in line formation [61]. Baker [62] used a continuous jet printhead with large 90-100 μm droplets at frequencies of 40.67 to 40 kHz to study printing and reported line formation and balling being connected to droplet spacing and inter-arrival time. However, the reported frequencies were significantly higher and droplets much larger than in the scope of current BJ systems. Additionally, the results were qualitative. A new look is needed.

### 2.3.1.3 Droplet Velocity

Primitive formation is dependent on impact velocity. While little work has been done with BJ conditions (inkjet-sized droplets and tightly packed powder beds), granule (primitive)
formation has been studied using millimeter-scale droplets on loose powder beds. Emady et al. [63] developed a map to identify conditions for granulation that identifies formation mode regimes based on bond number and bed porosity. The different modes are differentiated based on the vertical aspect ratio of the primitive. Impact velocity directly determined whether spreading or cratering regime was exhibited by the droplet. The formation modes were also correlated with powder size, powder shape, binder composition, and porosity [64, 65]. These studies, though insightful, use droplet sizes orders of magnitude larger than droplets in BJ. The studies also did not include effects of interaction with adjacent wetted powder which has been shown to significantly impact the wetting regimes [66]. In BJ, the interaction with adjacent moist regions is critical to creating 3D geometry from individual primitives.

Studies using in-situ high-speed optical and x-ray imaging have observed deformation of the powder bed during primitive formation [33, 61]. These studies visually show that the droplet transfers kinetic energy to the particles upon impact by ejecting powder, creating pores in some regions and compacting others. Droplet velocity in fine powders has also been shown to impact the feasibility of printing itself. In fine (<15 µm) 17-4 PH steel powders, balling was observed at droplet velocities of approximately 12 m/s, while parts were successfully printed at 14 m/s [59]. Figure 2-5 is an example balling during line printing. Droplet velocity clearly impacts BJ

Figure 2-5: Balling seen during line printing in fine 316 stainless steel powder.
outcomes, but limited experimental assessment has been performed, and no models currently include its effect on printing outcomes.

2.3.2 Layer Thickness

Layer thickness as discussed earlier is related to saturation, droplet spacing, and line spacing. Layer thickness also directly effects the parts resolution and surface finish. Thinner layers will mitigate the stair stepping defect and for most materials the properties improve as well [29, 62, 67]. In addition, layer thickness impacts green part density. Where thinner layers increased green part density [68]. It also directly affects the print time as layer spreading tends to be a time intensive process.

2.3.3 In-process Drying

In the BJ process, a heat lamp will pass over the surface following the printing of a layer to partially dry the binder. Part of the user setting is controlling the intensity and time duration of the heat source. Limited knowledge exists in literature on this subject. However, one study has shown a direct connection between in-process drying and part effective saturation. Crane [38] showed that drying is critical in maintaining accuracy in multilayer parts. Drying decreased sensitivity of print parameters in thicker parts, part size remained constant with drying conditions as print saturation increased. Further studies are needed to improve understanding, however, the impact of in-process drying is significant in part dimensional accuracy and effective saturation.
2.3.4 Powder Properties

Various powder properties influence the printing process in BJ. Including surface chemistry [62], flowability [69], and size distribution. These properties have wide ranging impacts from how the powder is dispensed to the density of the part.

Particle size distribution has received much attention in literature. The particle size and size distribution of the powder impact the packing density of the powder bed and final part density. For monosized spherical powders the theoretical max density is 60% of the true material density [62]. Higher density has been found with powders using a bimodal mixture of coarse and fine particles [23, 70].

Finer particles have an increased surface area to mass ratio and are more influenced by environmental conditions affecting the interparticle forces while gravitational forces are less significant. All these factors reduce flowability. This can cause challenges in the powder deposition process including nonuniform powder bed density [71]. However, finer particles are desirable for increased resolution and thinner layers [72]. Finer powders also create challenges in printing causing balling and other defects. This has been overcome by high droplet velocity, low droplet frequency, or additional powder treatments [59, 62]. Powder properties can influence the various factors of binder jetting including the binder/powder interaction.

2.4 Summary

BJ is an AM process with many potential advantages for widespread use in industry. Current limitations on this potential are primarily due to a lack of understanding of the fundamental physics within the printing process. Predictive methods to this point need improvement and methods for determining print parameters are inefficient. The binder/powder interaction is the
building block in BJ. Improved understanding will decrease cost, decrease print time, improve part mechanical properties, and improve predictive models.
3. EXPERIMENTAL APPARATUS

3.1 Overview

Understanding the binder/powder interaction is crucial to further BJ development. Safeguards and proprietary technology complicate modifications to commercial machines to be retrofitted for greater control of printing parameters and optical observation. A custom apparatus was needed for greater motion and printhead control while allowing optical observations. For experiments in this work, relatively simple geometry was required, however, planned following studies required flexibility in design for later additions such as high-speed video.

Several possible ideas were thoroughly explored, the experimental apparatus nicknamed the “T-Rent 2.0” was developed. It consisted of three subsystems named: motion control, printhead setup, and powder spreader. The three subsystems worked together using various triggers from a master LabVIEW VI in connection with a C-Rio dock. The T-Rent 2.0 allowed for single line, single layer, and multilayer printing while maintaining the ability to readily add needed functions such as high-speed video and a second inkjet nozzle. The T-Rent has a total build space of 3.15 inches by 3.15 inches by 1.18 inches. A max translational velocity of 60 mm/s. Figure 3-1 shows the apparatus.
3.2 Motion Control

![Image of the binder jetting apparatus built for this work. Nicknamed the T-Rent 2.0 it uses a MicroFab inkjet system, CNC router, and a custom powder spreader while a LabVIEW VI operates the complete system.](image)

The motion control system is built off a retrofitted CNC router machine, the Techno ISEL Stepper DaVinci. An updated controller was installed (Gecko G540) which would allow for future flexibility of software choice. For the purpose of this work LabVIEW was chosen as the software to control the systems. Figure 3-2 illustrates the motion system and the connections. The modified CNC reached max translational velocity of 60 mm/s with a step size and repeatability of 2 µm. Translational space of 10 inches x-axis, 12 inches y-axis and 5 inches on the z axis. The powder spreader mounted to the y-axis limited the range in the y-direction.

In order to maintain high accuracy in triggering motion and printhead at the correct moment, a NI cRIO dock was needed for its Field-Programmable Gate Array (FPGA) capabilities. The FPGA allowed for calculations such as triggering the printhead based on location without
communication with the PC. This removes a significant time delay found with other hardware. NI 9401 module was used for triggering the motion by sending TTL and direction signals to the Gecko G540 which would control the stepper motors. NI 9263 controlled signaling for the printhead. TTL signals were created for drop frequency, the signal would trigger once the x-axis had reached the desired velocity and position. NI 9263 was also used for preliminary high-speed video triggering. Additional NI modules can be added for future capability.

3.3 Powder Spreader

The powder setup imaged in Figure 3-1 utilized two vertical translational stages driven by stepper motors as the powder supply and build pistons. A separate stepper motor moved the spreader roller across the powder and build pistons to level the bed. A DC motor turned the roller...
(0.75 in diameter) counterclockwise to reduce powder bed roughness and increase packing density. An Arduino microcontroller controls the layer spreading system. The program allows the user control over each vertical piston in addition to a master operation that would spread a layer of powder at the desired thickness. The aluminum frame was bolted to the CNC y-axis. Spreading parameters were: rotational speed – 80 rpm, spreading speed – 1 mm/s, and layer thickness varied – (0.35, 0.50, and 0.65 µm).

3.4 Printhead Setup

A basic MicroFab Inkjet setup was used for dispensing binder illustrated in Figure 3-3. The setup used a MicroFab MJ-AB single nozzle printhead (40 or 30 µm), Jetdrive III (piezoelectric drive electronics), and pneumatics console. MicroFab Jet server software was used to set the voltage waveform, detailed in subsection 3.4.1. As illustrated in Figure 3-3 the printhead was connected to a pressure-controlled binder reservoir. For proper droplet ejection, a constant orifice

![Diagram of printhead setup](image)

**Figure 3-3:** Diagram depicting the basic inkjet system used in the T-Rent 2.0. Integration with other systems is shown.
pressure must be maintained. From testing, the ideal pressure was discovered to be -10kPa. Pressure was controlled by the pneumatics console which also allowed for purging for printhead priming. Jetting frequencies are recommended to be below 1kHz, however, ranges tested were 100 Hz to 1.5 kHz [73]. Jetserver software controlled triggering of the printhead. Once the waveform was selected Jetdrive III would wait for an internal or external trigger for each individual droplet waveform generation.

### 3.4.1 Waveform and Droplet Formation

Drop formation in inkjet printing can be controlled by the waveform generation. As discussed in section 2.2.3 DOD print systems use either a piezoelectric or thermal transducer. In the set up presented in this work a piezoelectric printhead was used, the Microfab MJ-AB or MJ-ABP with 30 and 40 µm orifices. The printhead’s piezoelectric element inside will expand and contract depending on the voltage waveform sent by the Jetdrive III. The waveform controls the droplet velocity, size, and shape.

A basic waveform for drop formation is shown in Figure 3-4. This shape is essentially on/off switch for the device. The pulse width is directly related to the droplet volume and velocity [74]. There exists an optimal point where velocity and volume are largest for a given voltage amplitude, a short or long pulse width will result in lower volume and velocity or no drop formation [74, 75]. The voltage amplitude in the waveform directly affects the droplet velocity and size. Figure 3-5 shows the relationship between droplet velocity and size during testing.
Complex waveforms help improve inkjet stability and can significantly decrease the droplet size. A bipolar waveform depicted in Figure 3-6 helps increase stability in jetting. By expanding a simple waveform to go negative to the same voltage amplitude this can cancel some of the acoustic residual waves in the printhead [74]. The timing for wave pressure propagation in

Figure 3-4: Simple waveform for inkjet drop generation. Adapted from [74].

Figure 3-5: Droplet size and velocity relationship is linear. Data points taken from experimental procedures.
bipolar waveforms depends on the speed of sound in the fluid. This delay is doubled in wave canceling fluid expansion, the negative value of the wave. More complex waveforms can alter droplet size to a quarter of the orifice size in diameter [76]. For this work bipolar waveforms were used for increased stability and droplet velocity was altered by changing peak voltages in the bipolar waveform. MicroFab recommends voltages not to exceed positive 70 volts [73]. Wave form parameters used in testing are summarized in Table 3-1. The specific values were determined through trial and error.

![Bipolar waveform for inkjet drop generation. Adapted from [74].](image)

3.5 LabVIEW VI and Connectivity

A LabVIEW VI controlled the triggering of the printhead and motion of the CNC. However, the powder spreader worked independently but did have the future capability of integrating with the VI. Pauses were programmed into LabVIEW to allow for manual control of the powder spreader and inspecting of the part. Purging of the printhead was also performed during
this time to improve printhead performance. In summary the T-Rent 2.0 fulfilled the requirements of a system with its capability of printhead control, precision in movement, and capability for future adjustments and additions.

<table>
<thead>
<tr>
<th>Orifice size (µm) – Droplet Velocity (m/s)</th>
<th>Droplet Size (µm)</th>
<th>Voltage Peaks (V)</th>
<th>Wave Propagation Delay (µs)</th>
<th>Wave Cancelation Delay (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 – 2.6</td>
<td>56</td>
<td>20</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>30 – 4.9</td>
<td>62</td>
<td>25</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>30 – 9.1</td>
<td>70</td>
<td>30</td>
<td>20</td>
<td>40</td>
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<td>74</td>
<td>40</td>
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</tr>
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<td>40 – 9.1</td>
<td>46</td>
<td>30</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>40 – 11.1</td>
<td>50</td>
<td>40</td>
<td>20</td>
<td>40</td>
</tr>
</tbody>
</table>
4. INFLUENCE OF DROPLET VELOCITY, SPACING, AND INTER-ARRIVAL TIME ON LINE FORMATION AND SATURATION IN BINDER JET ADDITIVE MANUFACTURING

4.1 Introduction

Binder Jetting (BJ) is a low-cost additive manufacturing (AM) process that combines a powder bed with inkjet printing technology. In this process, powder is spread in thin layers and an inkjet printhead deposits droplets to bind powder in the region of the desired cross-section. A new layer of powder is spread on top, and this process is repeated layer-by-layer [1]. A drying or heating process is often included between layers. BJ uses powder from lower layers as a support for upper layers. The lack of large thermal heating to cause a phase change and the use of inkjet technology enables faster printing speeds than most competing technologies. The resulting “green” part can be post-processed by sintering or infiltration to improve part properties such as strength and density [1, 77]. A major advantage of BJ over other AM processes is its ability to utilize almost any powdered material including polymers [78], ceramics [20], and metal [18]. Interest has grown as techniques for sintering homogenous materials to full density have been refined [26, 79-81].

As early BJ patents expire and overall AM demand grows, interest in BJ has increased. However, further BJ implementation in industry depends on improving dimensional accuracy, mechanical properties, and cost effectiveness. Much of the current research in BJ focuses on
developing printing parameters for specific machines and specific materials [27-30, 32]. However, an increased understanding of the physics of the binder/powder interaction will help researchers identify materials and corresponding print parameters independent of machine type and with reduced testing. Current modeling practices disregard the influence of printing parameters such as droplet velocity, droplet inter-arrival time, and heating/drying even though these parameters have shown to affect printing in BJ or related fields [31, 37, 38, 56, 82]. Improved understanding of these print parameters in BJ will allow for improved dimensional tolerances, enhanced material properties, and reduced minimum feature size, as well as decreased cost to develop new machines and material systems.

While BJ performance is affected by many factors including powder selection, printing parameters, and post processing, the key to BJ is the interaction of binder droplets with the powder bed to form a new region of bound powder. This agglomeration of powder bound by a single droplet (large or small) is referred to as a primitive. In BJ, many droplets are deposited in close proximity to form lines, layers, and 3D parts. Droplets 20-60 µm in diameter impact powder with velocities ranging from 1-10 m/s. The forces involved in the droplet/powder interaction are complex. Both capillary and inertial forces are significant and powder bed rearrangement is common [33]. While experiments have shown the impact of print parameters on part-level properties such as dimensional accuracy, porosity, and strength [23, 58], the impact of print parameters (droplet velocity, droplet size, droplet inter-arrival time, and droplet spacing) on the basic binder/powder interaction itself has not been reported.

During BJ, droplets impact the powder bed surface and begin to infiltrate into the pore space. Inertial forces dominate at short times while capillary pressure is the primary force acting on the fluid over longer time periods [83]. Capillary pressure varies with saturation and often has
significant hysteresis (Figure 4-1). Binder will migrate through voids in powder bed until the pressure across the binder-air interface balances the wetting forces. Upon impact, droplets temporarily create fully saturated region on the surface—where the void space between powder particles is filled with binder. Surrounding unsaturated regions absorb binder as capillary pressure drives flow from saturated regions until equilibrium is reached. Due to powder packing variation and the hysteresis between the imbibition and drainage curves the saturation level can vary throughout the wetted region.

Miyanaji, et al. [40] proposed a physics-based model to predict the equilibrium saturation level from the measured capillary pressure based on a single equivalent pore size. It excluded the impact of in-process drying, droplet size, and droplet velocity. Unfortunately, the limited experimental data did not show consistent correlation between model predictions and part-level

![Diagram](image_url)

**Figure 4-1:** General trend of saturation for drainage and imbibition curves with capillary pressure (Pc). There is generally significant hysteresis between the imbibition and drainage curves. $S_{WR}$ indicates the irreducible wetting saturation level. Adapted from [84].
measurements [40]. Drying and droplet size have since been shown to have a significant impact on saturation levels [38].

Bai, et al. [39] explored saturation levels in primitives formed by millimeter-scale sessile drops. The study calculated the dynamic contact angle from measured imbibition times of sessile drops and attempted to correlate these measurements to saturation level [39]. It was found that as the dynamic contact angle increased the saturation level increased and binder penetration depth decreased.

Another printing parameter is saturation, the percentage of pore space filled by binder. Saturation is a function of the binder, powder (size, shape), packing fraction, and the distribution of pore sizes in the powder bed [35]. While saturation in BJ is typically taken as a single parameter, there is actually a range of equilibrium values due to hysteresis between the imbibition and drainage curves [35] (Figure 4-1). This range of potential values make it path dependent rather than a state variable. Thus, the effective saturation is likely to vary with the printing parameters. In this study, the binder/powder interaction is characterized in terms of a part’s effective binder saturation ($S_{\text{eff}}$) by measuring the mass of powder bound by a known quantity of binder deposited using the equation:

$$S_{\text{eff}} = \frac{m_b \rho_{pb}}{m_p \rho_b \cdot (1 - P_f)}$$

where $m_b$ is the mass of the deposited binder, $\rho_b$ is binder density, $m_p$ is the mass of the bound powder, $\rho_{pb}$ is powder bed density, and $P_f$ is the packing fraction.

As droplets are printed adjacent to prior droplets, the bound regions merge into lines. The characteristics of line formation provide insight into the binder/powder interaction. Because nozzle pitch is larger than droplet diameters, most areas are formed by printing individual lines that are
later joined. Line formation is particularly important to fine feature development. While minor defects in larger features may not be critical to part function, these defects in small features are critical to part structure. Understanding the formation of lines can help select printing parameters for improved speed or feature resolution.

Successful line formation is the ability to print uniform width lines without defects such as balling. Line formation as a measurement is used in 2D printing on solid surfaces [37, 56, 57, 85] but has been limited in application in 3D powder bed surfaces. Binder droplets seek a minimum energy state which can result in breakup into individual balls, bulges, or other defects in the line. While [86] looked at the impact of printing frequency (droplet inter-arrival time) and spacing on line formation, the parameter range was too small to provide insight into the nature of the relationship.

Effective printing also requires the printed binder is sufficient to fully bind the powder within the part without spreading beyond it. A target print saturation is generally set by the user to determine how much binder is deposited per volume of the part. However, environmental conditions and interactions with previously printed regions can alter the quantity of bound powder per volume binder so that the effective saturation of the part may differ from the target saturation [38]. To continuously bind the powder together, the saturation must be sufficient to form a continuous network of fluid. If it is continuous, pressure is equilibrated throughout the network. As successive layers are deposited, hydrostatic pressure grows and may exceed capillary forces causing a defect commonly called “bleeding” in which the binder migrates beyond the desired part boundaries, decreasing dimensional and form accuracy [38, 67].

This paper focuses on the effects that varying key printing parameters in BJ (droplet velocity, size, spacing, and inter-arrival time) on line formation and effective saturation. Line
formation can be a measurement of defects in BJ and assist in improving printing fine features. Effective saturation may differ from the target print saturation specified by the user. The difference may be due to inaccuracies in modeling by disregarding certain print parameters. Both line formation and saturation impact the accuracy and quality of printed parts. The relationships were analyzed by optical imaging and mass measurements of printed lines. These results are compared to single drop primitives from millimeter-scale droplets. This study builds upon previous work [87], with additional materials, a broader range of printing conditions, and an expanded analysis and discussion. The following section provide an overview of the effects of printing parameters on BJ-printed parts.

4.2 Key Printing Parameters

In BJ, individual droplets must coalesce within and between layers to form continuous features. However, fluids minimize their energy by forming spheres. BJ features successfully form when binder infiltrates into the powder before enough pools on the surface that surface energy minimization drives it to form bulges or pinch off into separate spheres (balling). The total quantity of binder deposited must also be controlled so that the effective saturation matches the printed saturation. Too little saturation weakens the green part while too high of saturation causes bleeding as binder moves beyond the printed regions. The line formation and saturation depend on print parameters.

The basic study of saturation and formation of a printed lines in a porous powder medium has received little attention. Most BJ studies focus on full parts while droplet studies utilize single millimeter-scale droplets. Interactions with adjacent droplets are known to have a significant impact but have not been evaluated [88]. Understanding the impact of printing parameters on effective saturation will guide future modeling on saturation. Line formation can lead to improved
fine feature development. Understanding the impact of printing conditions on line formation and effective saturation will improve accuracy and quality of printed parts and reduce the time and resources needed to evaluate new powders, binders, and machines. The key printing parameters are defined below.

### 4.2.1 Droplet Spacing and Size

BJ shares some principles in common with 2D inkjet printing on solid surfaces. For example, coalescence of individual droplets into lines of uniform width without bulges or necking is important to good 2D print quality. Line formation is known to depend on droplet size, droplet spacing, droplet velocity, and contact angle [37, 56, 57]. When printing on glass, smaller droplet spacing led to bulging while larger spacing did not coalesce to a single line [56]. While these 2D observations are helpful, relatively little is known about the conditions required for line formation in BJ. In BJ, droplet size, droplet spacing, and layer thickness determine the overlap between successive droplet primitives. Primitive overlap will result in increased green strength [58] but too much binder will decrease geometric accuracy [38]. Droplet overlap in powder also impacts build time and formation of defects such as balling [59].

### 4.2.2 Droplet Inter-arrival Time

The interaction between droplets and line formation on solid surfaces depends on droplet inter-arrival time [60]. Droplets deposited on a glass with a shorter inter-arrival period created a more uniform line than those printed at longer intervals [57]. However, the dynamics in BJ are more complex than 2D printing on solid surfaces as droplets can both spread over and penetrate into the pores between powder particles. In BJ, a short inter-arrival time is often detrimental to line formation [61]. Baker [86] using a continuous jet printhead with large 90-100 μm droplets at
frequencies of 6.7 to 40 kHz reported line formation and balling being connected to droplet spacing and inter-arrival time. However, the reported frequencies were significantly higher and droplets much larger than characteristic of current BJ systems.

4.2.3 Droplet Velocity

Primitive formation also depends on droplet velocity at impact. Emady et al. [63] developed a map to identify conditions for granulation in millimeter scale droplets that delineates granule regimes with different vertical aspect ratios based on bond number and bed porosity. The regimes were correlated with impact velocity, powder size, powder shape, binder composition, and porosity [64, 65]. These studies, though insightful, use droplet sizes orders of magnitude larger than droplets in BJ. The studies also did not include effects of interaction with adjacent wetted powder which has been shown to significantly impact the wetting regimes [66]. In BJ, the interaction with adjacent moist regions is critical to creating 3D geometry from individual primitives.

Studies using in-situ high-speed optical and x-ray imaging have observed deformation of the powder bed during primitive formation [33, 61]. These studies visually show that the droplet transfers kinetic energy to the particles upon impact by ejecting powder, creating pores in some regions and compacting others. Droplet velocity in fine powders has also been shown to impact the feasibility of printing. In fine (<15 µm) 17-4 PH steel powders, balling was observed at droplet velocities of approximately 12 m/s, while parts were successfully printed at 14 m/s [59]. Droplet velocity clearly impacts BJ outcomes, but limited experimental assessment has been performed, and current models do not include its effect on printing outcomes.
4.3 Materials

Droplet primitives and lines were printed with ExOne solvent binder with properties provided by the manufacturer (density 1.05 g/cc, viscosity 4.6 cps, surface tension 32 dynes/cm). Binder was printed into three different powders: ExOne stainless steel 420 SS, ExOne stainless steel 316 SS, and alumina abrasive 320 grit. The powders were chosen to evaluate the impact of printing parameters with powder differences. Powder size distribution was measured by NSL Analytical using laser diffraction (ISO 13320). Particle shapes were observed with images from scanning electron microscopy (Apreo C SEM). Resultant distributions and powder images are shown in Figure 4-2. As seen in Table 4-1 and Figure 4-2, the three powders have different particle size distributions, shapes, contact angles, packing fractions, and powder bed densities.

Figure 4-2: (Left) Particle size distribution of the test powders and (Right) SEM images of the powder morphology: A) 420 stainless steel, B) 316 stainless steel, C) Alumina.
Contact angles of solvent binder on polished, dense samples of each material were measured using a goniometer. Rods of 420 SS and 316 SS were polished up to 1200F sandpaper prior to angle measurements. A sapphire window was used as an ideal alumina sample. Images were analyzed using ImageJ for contact angle measurements (Table 4-1).

Table 4-1: Properties of powder materials used in the experiments.

<table>
<thead>
<tr>
<th></th>
<th>Sauter Mean Diameter, D(3,2) (µm)</th>
<th>Contact Angle on polished Block</th>
<th>Powder Bed Density (g/cm³) – Packing Fraction</th>
<th>Tapped Density (g/cm³)</th>
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<tbody>
<tr>
<td>420 Stainless Steel 316</td>
<td>45.5</td>
<td>33°</td>
<td>4.48 – 58%</td>
<td>4.95</td>
</tr>
<tr>
<td>316 Stainless Steel</td>
<td>7.58</td>
<td>40°</td>
<td>4.24 – 53%</td>
<td>4.64</td>
</tr>
<tr>
<td>Alumina</td>
<td>36.2</td>
<td>31°</td>
<td>2.01 – 51%</td>
<td>2.29</td>
</tr>
</tbody>
</table>

4.4 Methods

The binder/powder interactions were studied with three experimental methods (1) primitive formation from millimeter-scale droplets released from varying heights, (2) Washburn capillary rise measurement of binder/powder wetting, and (3) line printing with picoliter inkjet droplets with varied droplet velocity, spacing, and inter-arrival time.

For all tests, a uniform powder bed was created by filling shallow aluminum containers, tapping them for improved density, and leveling with an aluminum straight edge. Average density was calculated by measuring mass of the prepared powder beds and dividing by the container volume. All powder beds prepared were within ±1% packing fraction of the average reported in
Table. Powder beds were prepared in this manner for all experiments. Washburn capillary rise used a glass tube packed to the same density as powder beds prepared with aluminum containers. Powder size, packing fraction, and powder bed density are reported in Table 4-1.

4.5 Millimeter-scale Droplets

Effective saturation in millimeter-scale droplets was measured by dropping millimeter-scale droplets (2-14.5 microliters) into a powder bed from varied heights (0, 10, and 20 cm; approximately 0, 1.4, and 2 m/s impact velocity respectively) as illustrated in Figure 4-3. ExOne solvent binder was dispensed from a micropipette at the desired heights. The powder bed was placed on a scale (Ohaus AX224, 0.1 mg resolution) to measure the mass of each droplet similar to [65]. Immediately following deposition, the powder bed was cured at 180°C for 2 hours. After curing, the primitive formed by the droplet was extracted. The mass of each droplet primitive was measured individually, and effective saturation calculated using Equation (4-1).

![Figure 4-3: Illustration of the experimental procedure for millimeter-scale droplet primitives.](image)
4.6 Washburn Capillary Rise

Washburn capillary rise method describes the wetting between binder and powder and can be used to estimate effective pore size of the powders [42, 89, 90]. In this method, a hydrophilic fabric is used to close one end of a tube. The tube is then filled with powder and tapped to increase density to the target level. The hydrophilic plug is placed on the surface of the liquid and the mass gained of the powder measured over time. The capillary rise has three regimes inertial, Washburn’s, and late viscous. The ratio $\frac{m^2}{t}$ is constant in the Washburn regime, where $m$ is binder mass gained and $t$ is time in seconds. Each powder was tested three times using glass tubes 6 mm diameter and 150 mm in length. The binder absorbed over time was quantified by measuring the mass lost from the reservoir as illustrated in Figure 4-4.

Prior to the Washburn regime, infiltration velocity (Quéré velocity) is constant for a short period [43, 44, 91]. Early inertial regime of the capillary rise lasts just milliseconds and was unobservable with the setup. However, the Quéré velocity that characterizes this regime can be

![Figure 4-4: Left, diagram of the Washburn rise method. Right, 420 SS powder in contact with solvent binder measuring the Washburn rise.](image-url)
calculated. The effective pore size was estimated using the Kozeny approach using laser particle
diffraction particle size measurements. The effective pore size is

$$r_{eff} = \frac{\phi \ d_{32} \ \epsilon}{3 \ (1 - \epsilon)}$$  \hspace{1cm} (4-2)

where $\epsilon$ is powder bed porosity, $S_o$ is specific surface area of the powder, $\rho_s$ is the density of the
powder, $\phi$ is a shape correction factor and $d_{32}$ is the Sauter mean diameter powder property
reported in Table [41]. The Sauter mean diameter is measured from laser particle diffraction. The
shape correction factor is unity for spherical steel powders while the angular alumina is assumed
to have cubic particles with a shape factor of 1.91. The Quéré velocity is given by

$$V_q = \frac{2 \ \gamma}{r_{eff} \ \rho_b}$$  \hspace{1cm} (4-3)

Quéré velocity and effective pore sizes are reported in Table 4-2. To analyze data in the printing
experiments described below, a dimensionless velocity ratio $V_r$ was used where

$$V_r = \frac{V_d}{V_q}$$  \hspace{1cm} (4-4)

and $V_d$ is the droplet velocity.

4.7 Line Printing

A custom BJ apparatus was utilized to print lines of binder into powder with controlled droplet
volume, velocity, spacing, and inter-arrival time. Each line was 20 mm in length. The apparatus
consisted of a MicroFab MJ-AB-01 (40 and 30-micron orifice) print setup triggered in unison with
three motorized linear stages as illustrated in Figure 4-5. The single nozzle print setup utilizes a
pressure control system, binder reservoir, drive electronics (MicroFab Jet Drive III), and a single
The pressure control maintained a vacuum on the print reservoir of -10 kPa during testing. The reservoir was maintained at the same height as the printhead. Figure 4-5 shows the integration of the systems. Images produced from IDS UI-3370CP-M-GL camera at 2.5x

MicroFab printhead. The pressure control maintained a vacuum on the print reservoir of -10 kPa during testing. The reservoir was maintained at the same height as the printhead. Figure 4-5 shows the integration of the systems. Images produced from IDS UI-3370CP-M-GL camera at 2.5x

Table 4-2: Powder properties of Washburn Capillary rise, effective pore size from Laser Diffraction, and Quéré velocities.

<table>
<thead>
<tr>
<th>Material</th>
<th>Washburn Slope (mg²/s)</th>
<th>Effective Pore Size (µm)</th>
<th>Quéré Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>420 Stainless Steel</td>
<td>2.4</td>
<td>10.98</td>
<td>5.55</td>
</tr>
<tr>
<td>316 Stainless Steel</td>
<td>0.80</td>
<td>2.24</td>
<td>27.21</td>
</tr>
<tr>
<td>Alumina</td>
<td>2.1</td>
<td>22.03</td>
<td>2.77</td>
</tr>
</tbody>
</table>

Figure 4-5: A diagram of the experimental apparatus and connectivity between units. The Newport linear stages controlled in unison with triggering the JetDrive III to actuate the printhead and deposit lines with controlled droplet spacing. The inkjet properties (droplet velocity, droplet size) were varied using the JetDrive III waveform controls.
magnification and a strobing LED behind the droplets were used to measure droplet velocity. The
velocity was calculated by measuring the distance between droplet images from successive strobe
flashes.

Line formation experiments were conducted with a range of printing parameters. From
these results, a parameter map identifying conditions under which lines could be extracted for mass
measurements was created for each powder for a range of droplet spacing and inter-arrival times
(Table 4-3). A successful print constituted at least 50% of lines successfully extracted from the
powder bed. At least 8-12 lines were printed for each condition. The various values of droplet
spacing and frequency were all tested using the print head with a 30-µm orifice at a constant droplet
velocity (2.6 m/s). Lines printed in 316 SS powder were analyzed before extraction using a
microscope. Lines that exhibited balling were recorded and an aspect ratio of the length to width
(l/w) of the ball segments were measured.

<table>
<thead>
<tr>
<th>Powder Type</th>
<th>Droplet Velocities (m/s)</th>
<th>Droplet Spacing (µm)</th>
<th>Inter-arrival Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Formation (30 µm orifice)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>420 SS</td>
<td>2.6</td>
<td>5 - 15</td>
<td>0.4 - 2</td>
</tr>
<tr>
<td>316 SS</td>
<td>2.6</td>
<td>2.5 - 40</td>
<td>0.4 - 2</td>
</tr>
<tr>
<td>Alumina</td>
<td>2.6</td>
<td>5 - 35</td>
<td>0.4 - 2</td>
</tr>
<tr>
<td>Saturation (30 and 40 µm orifice)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>420 SS</td>
<td>2.6 - 11.1</td>
<td>5 - 12.5</td>
<td>1</td>
</tr>
<tr>
<td>316 SS</td>
<td>2.6 - 11.1</td>
<td>5 - 12.5</td>
<td>1</td>
</tr>
<tr>
<td>Alumina</td>
<td>2.6 - 11.1</td>
<td>5 - 12.5</td>
<td>1</td>
</tr>
</tbody>
</table>
In the line saturation studies, droplet printing frequency was maintained constant while the impact of varying saturation, droplet velocity and spacing was measured. Droplet velocity was altered by changing peak voltages sent to the printhead. This also causes droplet size to change as indicated in Figure 4-6.

After printing, powder beds were heated in a convection oven at 180°C for 30 minutes to cure the binder. The printed lines were removed, and the mass of each line measured individually. Effective saturation of the lines was calculated using Equation (4-1). The mass of binder was measured by printing the equivalent of 20 lines into a container to be weighed. This method of capture included the mass of satellite droplets where present. Satellite droplets increased in volume with higher droplet velocity but were estimated to be less than 10% of the total printed volume.

![Figure 4-6: As droplet velocity increases the droplet size increases. The trend is linear and in both 30 and 40 μm orifice sizes.](image)
The printing parameters were summarized using dimensionless parameters. Droplet spacing was nondimensionalized as the droplet overlap ratio:

\[ O_r = \frac{D_d}{l} \]  

(4-5)

where \( D_d \) is the droplet diameter and \( l \) is the spacing between droplets. A mass ratio \( M_r \) was defined as:

\[ M_r = \frac{M_b}{M_p} \]  

(4-6)

where \( M_b \) is the mass of a single binder droplet, and \( M_p \) is the mass of an average particle size in the powder bed, assuming spherical shape at bulk density. Range of printing parameters tested, are summarized in Table 4. Bond (Bo), Reynolds (Re), and Weber (We) numbers are included and calculated as follows:

\[ Bo = \frac{\rho g L^2}{\gamma} \]  

(4-7)

where \( \mu \) is the dynamic viscosity of the binder, \( \theta \) is the contact angle for binder and material, and \( L \) is the diameter of the droplet (Table ).

\[ Re = \frac{D_d V_d \rho_b}{\mu} \]  

(4-8)
Table 4-4: Parameter and property ranges in line printing experiments.

<table>
<thead>
<tr>
<th>Dimensionless Parameter</th>
<th>Value Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translational Velocity</td>
<td>5 – 12.5 mm/s</td>
</tr>
<tr>
<td>Droplet Velocity</td>
<td>2.6 – 11.1 m/s</td>
</tr>
<tr>
<td>Droplet Frequency (constant)</td>
<td>1000 HZ</td>
</tr>
<tr>
<td>Droplet Size</td>
<td>38 – 74 µm</td>
</tr>
<tr>
<td>$V_r$ (Eqn. (4-4))</td>
<td>67.4 – 558</td>
</tr>
<tr>
<td>$O_r$ (Eqn. (4-5))</td>
<td>3.28 – 14.8</td>
</tr>
<tr>
<td>$M_r$ (Eqn. (4-6))</td>
<td>0.089 – 53.86</td>
</tr>
<tr>
<td>Bond Number ($Bo$ Eqn. (4-7) – Line Printing)</td>
<td>0.0004 – 0.0018</td>
</tr>
<tr>
<td>Bond Number ($Bo$ Eqn. (4-7) – mm Droplet)</td>
<td>1.85 – 3.09</td>
</tr>
<tr>
<td>Reynolds Number ($Re$ Eqn. (4-8) – Line Printing)</td>
<td>22.6 – 187</td>
</tr>
<tr>
<td>Reynolds Number ($Re$ Eqn. (4-8) – mm Droplet)</td>
<td>0 – 1415</td>
</tr>
<tr>
<td>Weber Number ($We$ Eqn. (4-9) – Line Printing)</td>
<td>8.4 – 299</td>
</tr>
<tr>
<td>Weber Number ($We$ Eqn. (4-9) – mm Droplet)</td>
<td>0 – 406</td>
</tr>
</tbody>
</table>

4.8 Results and Discussion

The experiments provided insight into the impact of printing parameters on both effective saturation levels in lines and conditions for successful line formation as summarized below.

4.8.1 Saturation

In BJ, a target saturation value is generally selected based solely on the combination of binder and powder. However, a range of values are possible depending on the imbibition and drainage curves because the actual effective saturation is process dependent. In this work, the
effective saturation is calculated to provide insight into the appropriate target saturation values and how they differ with printing parameters.

The average effective saturation from millimeter-scaled droplets is shown in Figure 4-7 as a function of droplet velocity. Over the range studied, the drop velocity had no significant impact on the effective saturation of the droplet primitives. Alumina and 420 SS powders had similar sessile drop saturation levels, while the finer 316 SS powder had a significantly lower saturation level. The average effective saturation of the sessile drop (0 cm drop height) is used as a comparison to the effective saturation of the inkjet-printed lines.

![Figure 4-7: Millimeter-scaled droplets at various heights for equilibrium saturation calculation and comparison to line printing.](image)

As seen in Figure 4-8, the lines had lower effective saturation than the sessile drops for all powders and printing conditions. It is possible that the sessile drop saturation will provide an upper-bound for the printed cases, but the sessile drop saturation is not an effective predictor of effective saturation in single lines. With the larger droplets from the 40 μm orifice, the effective
saturation approached (but never exceeded) the sessile droplet saturation as droplet velocity decreased and overlap ratio increased.

Overlap ratio is a measure of the relative spacing of the droplets. The nondimensionalization compensates for the changing of droplet size with droplet velocity. Overlap ratio increases as droplet spacing decreases. Increasing overlap ratio generally causes a small increase in the effective line saturation for each orifice/material combination (Figure 4-8). Effective saturation is most sensitive to overlap ratio with the larger droplets (40-μm orifice) and the larger 420 SS and alumina powders. For each droplet velocity, increasing overlap ratio increased saturation in the 420 SS and alumina powders. This suggests that the moistened powder acts to reduce the spread of the new droplets. Hapgood et. al. [92] observed that in millimeter-scale droplets, increased overlap decreased penetration time and increased saturation as well. Both the overlap ratio and droplet velocity had a much smaller effect with the smaller droplets from the 30 μm orifice. These results suggest that the trend of BJ towards smaller droplet sizes will decrease the sensitivity of effective saturation to the printing parameters. Thus, smaller droplet sizes will allow for greater decoupling of saturation from other printing parameters.

The finer 316 SS powder has a lower effective saturation for mm-scale sessile droplets than the course 420 SS and alumina powders. The smaller pores likely promote capillary binder infiltration compared to the larger powders—decreasing saturation. Using finer powders may also reduce the sensitivity to other printing parameters. The effective saturation of the 316 SS lines was much less sensitive to the droplet size, velocity, and overlap ratio than the coarser powders. While there is some evidence of the same trends observed in the other powders, the variation largely lies within a single standard deviation. The reduced sensitivity is a positive for the finer 316 SS powder,
Figure 4-8: Plot of equilibrium saturation measured for each material (316 SS, 420 SS, Alumina) and orifice combination (40 µm orifice (left), 30 µm orifice (right)). A general trend of higher velocities and smaller overlap (larger droplet spacing) corresponds to a lower saturation levels in each of the materials with 40 µm orifice. The effective saturation of lines printed with 30 µm orifice is less sensitive to the printing parameters.
but the parameter space that successfully formed a line is more limited for the 316 SS powder as shown in the line formation study.

A statistical linear regression analysis was conducted with four nondimensional numbers to evaluate the significance of four parameters (overlap ratio ($O_r$), velocity ratio ($V_r$), mass ratio ($M_r$), and contact angle) on the effective saturation of the lines. A p-value below 0.05 indicates that the parameter is statistically significant. Linear regression was done on the 40-µm orifice and 30-µm orifice separately and then on the combined dataset as reported in Table 4-5.

All of the printing parameters have a significant impact on effective saturation in at least one dataset as seen in Table 4-5. Droplet overlap ratio was statistically significant in all of the models. Significance of the overlap ratio confirms that droplets infiltrate powder differently when adjusting the amount of overlap with pre-moistened powder and/or pools of binder remaining on the surface. The velocity ratio was found significant for the combined and 40-µm datasets. The remaining parameters had variation between the different models. These results confirm that droplet spacing (overlap ratio), droplet velocity (velocity ratio) and size (mass ratio) are critical to determining the effective saturation. An understanding of how the effective saturation varies with printing parameters is particularly critical to creating fine features with high accuracy.

The regression analysis reported a significantly higher $r^2$ value for the 40-µm orifice, 0.78, than the 30-µm orifice and combined datasets, 0.47 and 0.52 respectively. Thus, the variation in the 40-µm orifice data can be largely explained by these changing printing parameters. The lower correlation coefficients for the 30-µm orifice is partially due to the increased variation in the measurements due to the uncertainty introduced by the smaller sample masses from the smaller droplets produced from the 30-µm orifice. However, the smaller droplets also appear to decrease the sensitivity of the saturation to the printing parameters.
Table 4-5: Results from the linear regression analysis. Each parameter had a coefficient and an exponent. The p-values are reported.

<table>
<thead>
<tr>
<th>Orifice Size (µm)</th>
<th>$r^2$</th>
<th>Nondimensional Number</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.78</td>
<td>Overlap Ratio</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity Ratio</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass Ratio</td>
<td>0.752</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contact Angle</td>
<td>0.010</td>
</tr>
<tr>
<td>30</td>
<td>0.47</td>
<td>Overlap Ratio</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity Ratio</td>
<td>0.429</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass Ratio</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contact Angle</td>
<td>0.003</td>
</tr>
<tr>
<td>Combined</td>
<td>0.52</td>
<td>Overlap Ratio</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity Ratio</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mass Ratio</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Contact Angle</td>
<td>0.143</td>
</tr>
</tbody>
</table>

4.8.2 Line Formation

The success of line formation is also sensitive to printing parameters. For example, at 9.1 m/s, all powders formed successful lines with both the 40- and 30-µm orifices. However, in the 316 SS, droplets from the 40-µm orifices did not coalesce to from a line at 5.4 m/s droplet velocities as seen in Figure 4-9. The inability of droplets to coalesce as a line in 316 powder with larger droplets at lower droplet velocities is evidence both of different wetting characteristics in the finer powder and for the influence of kinetic energy on line formation. Lines printed at lower velocities (5.4-2.6 m/s) with larger droplets were not included in saturation analysis in Figure 4-8 because they were often unrecoverable. Lines that were unrecoverable, broke primarily due to balling. Images of a broken and fully coalesced lines are shown in Figure 4-9. Similar observations were found in [59], where higher droplet velocities were needed to successfully print in fine powder. Though droplet velocity did not significantly impact line saturation with smaller droplets (30-µm orifice), droplet velocity did still affect the feasible print range. The ability to tune a machine by
altering the droplet velocity could lead to less defects in parts without altering other printing parameters such as layer thickness or saturation.

These observations led to a study of line formation at low droplet velocity (2.6 m/s) as a function of droplet spacing and inter-arrival time (droplet frequency) using all three powders. Sixteen lines were printed at each droplet spacing/inter-arrival time combination. A print condition was deemed successful if at least 50% of the lines were removed intact. For the 316 SS powder, optical imaging allowed clear observation of the aspect ratio of printed features from 1:1 (balls) to full lines. This provides a richer dataset that illustrates the transition from immediate balling to successful line formation. Figure 4-10 shows that the aspect ratio of the features in 316 SS lines increases as it approaches the success/fail boundary below which lines are successfully created. The formation of the lines depends on the relationship between the droplet spacing and inter-arrival time.

In the coarser powders (alumina, 420 SS) lines were indistinguishable from the rest of the powder bed in visual inspection prior to extraction. Therefore, a length to width ratio could not be

Figure 4-9: Lines printed in 316 SS powder (40-μm orifice). Top) 9.1 m/s droplet velocity, recoverable. Bottom) 5.4 m/s droplet velocity, unrecoverable.
calculated for failed lines. Instead, lines were calculated as success/fail based on the extraction criteria. Figure 4-11 shows the success/failure map of alumina and 420 SS powders. Alumina shows a similar trend that was seen in 316 SS powder. The results for the 420 SS were unclear because lines printed with 420 SS powder at larger droplet spacing broke. It appeared that with the small size of the droplets relative to the powder, insufficient powder particles were bonded together to form a line with sufficient handling strength.

While imbibition of the droplets is difficult to observe, the relationship between droplet spacing and droplet inter-arrival times parameters that form successful lines provides insight into the binder imbibition process. When printing a line, droplets arrive in quick succession—often faster than they absorb into the power bed. This creates an elongated pool of liquid on the surface.
Observations have shown that under some circumstances, this pool will break-up into individual segments or spherical balls [24, 35, 61]. Similar challenges are observed in melt pools of powder-bed fusion processes [93]. Break-up is energetically favorable when the aspect ratio of the pool increases above a threshold level. The length of the fluid pool is related the ratio of the time for a droplet to imbibe into the powder to the printing velocity (droplet spacing/inter-arrival time) and the extent of droplet spreading. Prior work has suggested that an aspect ratio of 3.13 will cause breakup of free streams [94], but in BJ, the trailing edge of the pool is wetted into the powder bed and so the critical aspect ratio of powder is expected to deviate from the free stream value.

While the exact aspect ratio at which lines would breakup into droplets is unknown, the aspect ratio (l/w) of the pool should be related to the ratio of the line printing speed to the infiltration velocity. Thus, the aspect ratio should be proportional to:

![Figure 4-11: Success/failure regions for alumina and 420 SS powders. A power law fit to the data points on the success/fail boundary produced a relationship, to the 0.4712 power, of droplet spacing and inter-arrival time. All lines printed at 2.6 m/s droplet velocity.](image)
\[ \frac{l}{w} \propto \frac{\Delta x}{\Delta t v_i} \]  

(4-10)

where \(\Delta x\) is the droplet spacing, \(\Delta t\) is the droplet inter-arrival time, and \(v_i\) is the fluid infiltration velocity. Assuming that the maximum stable aspect ratio of the pool is a constant, the maximum droplet spacing for stable line formation (\(\Delta x_{\text{max}}\)) would be proportional to

\[ \Delta x_{\text{max}} \propto \Delta t^n v_i \]  

(4-11)

where the value of \(n\) depends on the variation of infiltration rate with time. It is expected to be 0.5 for Washburn and 1.0 for Quéré infiltration. The relationship between droplet spacing and inter-arrival time thus provides insight into the fluid infiltration velocity and how it varies with time. To estimate this boundary, a power law curve was fit to the nearest data points on both sides of the boundary of successful line formation.

Both alumina and 316 SS have exponents (n) near 0.5 with 0.4712 for alumina and 0.414 for 316 SS. The data suggest the droplets are largely absorbed in the Washburn regime. The higher Washburn slopes for the alumina (Table 4-2: alumina: 2.1, 316 SS: 0.8), correlates with the ability to form lines when printing at higher droplet frequencies (shorter inter-arrival time). The smaller Washburn slopes in 316 SS may also contribute to the decreased sensitivity of the 316 SS line saturation to the printing parameters. Baker [86] previously showed an interaction between inter-arrival time and droplet spacing on the successful formation of a line with a kilohertz printhead at kilohertz frequencies, but without sufficient resolution to characterize the relationship.

BJ Printing speeds can be optimized by trading between droplet spacing and inter-arrival time to improve overall print quality and build rate. However, the finer 316 SS powder clearly
requires longer droplet inter-arrival time at the same droplet spacing—potentially slowing printing in the finer powders. Further study is needed to see how much this can be addressed by increasing the droplet velocity at impact or by altering the printing pattern.

This study of single lines does not represent printing of a full part, but these results are applicable to layer printing in BJ. While layer formation introduces additional factors, the layers start as a series of lines because nozzle spacing in commercial systems is significantly wider than the droplet size. Therefore, in the first phase of printing, individual lines are typically printed by each nozzle in the printhead. Subsequent passes fill in the spaces between the lines to create continuous layers. Defects such as balling could lead to large pores in the green bodies within or between layers. They may also contribute to other defects that are commonly observed in BJ parts. Line printing could also be used as a simple test to determine appropriate droplet spacing and droplet inter-arrival time.

4.9 Conclusion

This work studied the impact of droplet velocity, spacing, and inter-arrival time on the effective saturation of printed lines and the success of line formation. Current models disregard the kinetic energy from droplets and assume quasi-static conditions. These assumptions predict a single saturation value for all printing parameters. However, this work shows that effective saturation depends on droplet size, velocity, and spacing. As improved saturation models develop, the influence of droplet velocity and spacing should be included. The results show that lines will have less variation in saturation when using smaller droplets and smaller powder particles. Additional work is needed to study how these variables impact the formation of printed layers.

Line formation is well-studied in 2D inkjet printing on solid surfaces but has yet to be understood in BJ. This work shows that the boundary for stable line formation is influenced by the
powder properties, droplet spacing, and droplet inter-arrival time. For a given powder and droplet velocity, larger droplet spacing and/or shorter inter-arrival time leads to instability in line formation. The maximum droplet spacing for successful line formation has been shown to vary with approximately the square root of the droplet inter-arrival time in the 316 SS and alumina powders which is consistent with the Washburn infiltration mode. Line formation is likely influenced by droplet velocity and volume as well though these variables were not studied in this work.

This work demonstrates that the binder/powder interaction is complex and depends on many printing parameters that are often overlooked. Many BJ studies do not report these key parameters. Increased understanding of the underlying physics will speed development of new materials and improve allocation of development resources, print quality, and process utilization in industry. However, the extension of effects seen in lines to layers and full parts is unknown and needs further study. Such studies will provide valuable insight into the impact of part geometry on the range of feasible print parameters. This understanding is critical to maximizing printing speeds, improving part accuracy, and reducing internal defects.
5. IMPACT OF PRINTING CONDITIONS ON FORMATION OF 2D AND 3D BINDER JETTING GEOMETRIES

5.1 Introduction

Binder jetting (BJ) is an additive manufacturing (AM) process that uses inkjet technology to deposit a binding agent on thin layers of powder to bind together the cross section of each layer. Following binder deposition, the surface is often heated to partially dry the binder. This process is repeated layer-by-layer until the full part is built. The resultant “green” part consists of powder held together with binder. Green parts are fragile and are usually post processed by sintering and/or infiltration to improve mechanical properties [1, 2].

As demand for AM continues to grow and early BJ patents expire, interest in BJ has increased in both academia and industry [9]. BJ offers many potential advantages over other AM processes for low-cost manufacturing. Unlike AM processes that require high energy input for fusion (i.e., direct energy deposition, laser powder bed fusion) relatively little heat is applied in BJ. This eliminates the risk of potential flaws caused by heating. In addition, no additional structures are required for support or heat dissipation. These support structures can be labor intensive and expensive to remove after printing. In BJ, the use of inkjet technology allows for high-volume, low-cost production. BJ can also print any powder material including ceramics [20], metals [95], and polymers [96].
This flexibility has allowed its adoption into many industries such as biomedical, foundry, automotive, and aerospace [78]. However, compared to other additive manufacturing process, its adoption in industry has been slower. This is due to limitations in part properties which stem from challenges in eliminating porosity in parts. Post-processing has been improved significantly with increased use of liquid phase sintering [97-99]. However, there remains challenges in eliminating large pores that originate in the printing process. The printing process must be better understood to identify the source of these large pores and find methods to reduce their formation.

Current methods for determining printing parameters in BJ are inefficient and are primarily determined through trial and error. Significant experimentation has been conducted to determine optimal printing parameters based on specific materials and machines [27-29, 31, 100]. General trends for some parameters have been found to impact print quality such as printing speed [31], in-process drying [38, 101] and layer thickness [86, 102]. However, these trends still require significant testing to identify parameters with new printing conditions and materials. Improved process fundamentals will lead to efficient methods for determining printing parameters to increase the rate of adoption in industry.

During printing, picoliter-scale droplets of binder impact the powder bed to form the geometry. This is the fundamental interaction in BJ, but it is difficult to observe because it is highly dynamic. Studies using high speed optical and x-ray imaging showed that the interaction exhibits particle ejection and powder bed deformation which create pockets of densified powder and pores [33, 61]. Observations are limited to single droplets or single lines and optical imaging is limited to above-surface interactions, while x-ray imaging can only see particle movement below the surface - not binder flow. Significant research exists with microliter droplets interacting with powder [63-65]. However, these studies incorporate droplets orders of magnitude larger than those
typically used in BJ, which makes connecting the phenomena challenging. In addition, these studies do not include interaction between droplets and pre-wetted powders which significantly changes the wetting behavior of the powder [66].

Aside from these optical observations, others have studied the process artifacts to understand parameter selection. Line printing has also been used to observe the binder/powder interaction in BJ. Increased droplet velocity alters part saturation and line formation, these effects are reduced with droplet size [59, 87]. Line formation (the ability for droplets to coalesce in a lines) forms a relationship dependent on droplet size/spacing and droplet inter-arrival time (frequency) [24, 86, 87]. The prior chapter concluded that larger droplet overlap helped in forming lines. This high overlap is not seen in commercial systems. Instead droplet spacing is commonly comparable to the droplet size.

While these general trends in line formation studies are helpful, no reported connection exists between the effects of these parameters in printed lines compared to in full parts. Most commercial machines do not permit these parameters to be changed nor do they alter the parameters based on the print saturation value selected by the user parameters. Connections between results of lines to implications for layers and full parts has not been reported.

Environmental conditions (i.e. ambient temperature and humidity) are factors that have largely been disregarded in BJ. However, as fine powders are becoming more common in printing for increased resolution and surface finish, the increased surface area of the finer particles makes it more susceptible to changes in environmental conditions [26]. This has largely been viewed as a hindrance in spreading of the powder as high humidity levels decrease flowability [27]. However, the effect of ambient humidity on the binder/powder interaction in BJ has not been reported.
In order to improve the implementation of BJ in industry the fundamental binder/powder interaction must be understood further. The focus of this paper is to address the impact that traditional parameters in line formation — droplet spacing, droplet inter-arrival time, and layer thickness — in the relationship of saturation and defects between single- and multi-layer parts. In addition, the impact of ambient humidity in part saturation and part defects is evaluated.

5.2 Saturation

One parameter that represents key aspects of the binder/powder interaction is binder saturation, the percentage of void space in a porous medium filled with binder. In BJ, a “print saturation” is a target value set by the user. If binder remains in the intended region, the print saturation is given by

\[ S_p = \frac{\pi D_d^3}{6 \Delta x \Delta y \Delta z (1 - P_f)} \]  (5-1)

where \( S_p \) is print saturation, \( D_d \) is the diameter of the binder droplet, \( \Delta x \) is droplet spacing, \( \Delta y \) is line spacing, \( \Delta z \) is layer thickness, and \( P_f \) is packing fraction of the powder bed. Packing fraction is the ratio of powder bed density to true material density. In commercial systems, the user typically inputs the packing fraction (\( P_f \)) specifies the print saturation (\( S_p \)) and layer thickness (\( \Delta z \)). The machine software then selects the droplet and line spacing based on proprietary algorithms.

In BJ, saturation must be sufficient for the binder to form a continuous network in order for the green part to have sufficient strength for extraction and handling. If saturation is insufficient the green part will not bond sufficiently. If saturation is too high and exceeds the stable limits, binder will migrate outside the predetermined space producing a defect commonly known as “bleeding.” Bleeding negatively impacts part dimensional accuracy. Therefore, the placement of
the binder droplets on the surface and binder migration into the powder bed are crucial in BJ to avoid bleeding defects. Though a user selects a single print saturation, the printing process usually creates a range of saturation values in the part that varies both spatially and temporally due to hysteresis in the imbibition and drainage curves [84]. As droplets impact the surface it creates a fully saturated region which is then driven by capillary pressure to the surrounding unsaturated regions until equilibrium is reached. Due to powder packing variation, nonlinearities in the flow of binder with saturation level, and the hysteresis between drainage and imbibition curves, saturation values vary throughout the wetted region. However, only the target print saturation is typically reported.

Equilibrium saturation is the maximum print saturation where the binder will not flow past the desired boundaries. Methods of predicting equilibrium saturation levels have been proposed. Miyanaji, et.al [40] developed the first physics based equilibrium saturation model based on a single equivalent pore size. Unfortunately, limited experimental data did not correlate with predicted values. Since, dynamic contact angle [39], in-process drying [38], droplet velocity and size [87] have been shown to alter part saturation values suggesting that even this quantity is a function of the process parameters. This paper reports the impact of ambient humidity levels on saturation levels in BJ parts. The relative impact of moisture level during powder storage to printing conditions is compared. Results show that saturation is not only a binder/powder property but rather dependent on various factors one of which can be ambient humidity. Future saturation modeling and testing need to control ambient humidity levels to improve predictability.
5.3 Methods

5.3.1 Materials

ExOne solvent binder was used in each of the experiments conducted, the following properties were provided by the manufacturer (density 1.05 g/cc, viscosity 4.6 cps, surface tension 32 dyns/cm). All experiments used ExOne 316 stainless steel powder ($D_{50} = 10 \mu m$). Particle size distribution was measured using laser diffraction by NSL analytical (ISO 13320). Particle shapes were observed using scanning electron microscope (Apreao C SEM). Particle distributions and SEM images are shown in Figure 5-1.

Figure 5-1: Particle size distribution and SEM images for the 316 powder used in experiments.

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5.3.2 Part Fabrication and Experimental Apparatus

All experiments were printed using a custom-built binder jetting apparatus at 21°C. The apparatus consisted of a basic MicroFab MJ-AB printhead (30 µm orifice), Techno DaVinci CNC router modified with a Gecko G540 controller, and a custom powder spreader. All were controlled
using a LabVIEW VI and a NI cRio device. The apparatus was enclosed in a chamber with humidifiers controlled with an Inkbird IHC-200 humidity controller. Humidity levels were logged with an additional humidity sensor (Omega OM-HL-SP-TH).

Test parts were fabricated as 10 mm x 7.5 mm rectangles with varying thicknesses. Thicknesses were based on the number of layers printed (1, 2, 3, 5, 8). Layer thickness was varied (35, 50, 65 µm). In addition, droplet spacing and droplet frequency were varied in the experiments with values of 40, 50, 60 µm and 500 and 1000 Hz respectively. Line spacing was equal to droplet spacing. Droplet velocity remained constant for all prints at 4.9 m/s. Images produced from IDS UI-3370CP-M-GL camera at 2.5x magnification and a strobing LED behind the droplets were used to measure droplet velocity. Each data point is the average of six samples.

Following printing each set of parts, the powder bed was heated at 180°C for 1 hour. After air cooling surface roughness was measured on the printed surface of 2-3 parts using a 3D profilometer (Zeta 20). Parts were then extracted and cleaned using pressurized air through an 18-gauge needle. The part weight was used to calculate the effective saturation by

\[
S_{eff} = \frac{m_b \rho_{pb}}{m_p \rho_p * (1 - P_f)}
\]

(5-2)

where \(m_b\) is the mass of the deposited binder, \(\rho_b\)is binder density, \(m_p\) is the mass of the bound powder, \(\rho_{pb}\) is powder bed density, and \(P_f\)is the packing fraction.

### 5.3.3 Powder Conditioning Procedures

Moisture can impact the binder jetting process in two phases. First, moisture absorption during storage from the ambient environment would tend to decrease the packing density by increasing the cohesion of the powder bed. Secondly, the moisture in the powder during printing is expected to increase the rate of binder imbibition. The relative impact of each was evaluated.
The evaluation of ambient humidity on the printing process was tested by comparing parts printed with powder exposed to prolonged ambient humidity (≈30%) to dried powder exposed to humidity during the spreading and printing itself. Four powder conditions were used. Ambient moisture printed at ambient conditions (Amb-Amb), dried powder printed at 80% humidity (Dry-80%), dried powder printed at 40% humidity (Dry-40%), and dried powder stream treated prior to printing (Dry-Steam). This helps provide insight into the relative impact of powder conditioning before printing (dry or ambient humidity exposure) to the impact of humidity exposure during the layer spreading and printing process itself.

Ambient moisture is where powder was exposed to ambient humidity (≈30%) for 48 hours before printing. Powder was then spread, and tests were printed as normal. Dry Powder was prepared by heating for 8 hours at 180° C prior to use and stored in airtight containers. A small amount was removed to be spread for each layer. Humidity tests (Dry-80%, Dry-40%) used dry powder which was spread into layers then exposed for 10 minutes to ambient humidity prior to printing to evaluate the effect of humidity in the printing process.

A household steamer was used with an attachment that diffused and lowered the pressure of the steam. This was used to imitate an extreme exposure to a humid environment. After dried powder was spread, the steamer attachment was held about 18 inches from the powder bed surface to not disturb the bed and steamed for 10 seconds at each layer prior to printing. Steam tests were conducted inside the humidity chamber at 80% saturation to reduce possible evaporation of the powder bed after steam application.

5.3.4 Droplet Volume and Powder Bed Density Measurements

The droplet volume measurements were conducted by running the MicroFab nozzle at the same frequency for two minutes, droplets were captured and weighed. This was repeated daily at
least three times. An average droplet volume was then calculated. Powder bed density was measured by using the plug method in which a sample of powder is extracted by inserting a cylindrical plug of a known size (2.8 cm diameter) into the powder bed and weighing the powder [25]. Powder bed density was measured to 4.35 g/cm³ (55% packing fraction). Repeated measures fell to within 1% of the packing fraction for all powder conditions.

5.3.5 Part Cross-sectioning

Selected parts printed in 316 SS were infiltrated with cyanoacrylate adhesive to increase strength and then with low viscosity clear epoxy under vacuum for 8 hours. This improved infiltration and decreased porosity in the epoxy. Parts were mounted in polishing epoxy parts following infiltration. Surfaces were then polished and imaged using an Olympus GX51 microscope.

5.4 Results and Discussion

5.4.1 Layer Printing under Line Printing Conditions

Line printing and line formation have often been used as a method in understanding the binder/powder interaction. These studies have been used to draw general connections between print parameters (i.e., droplet velocity, droplet spacing, line spacing) and their impact on the BJ printing process. However, no connection to single-layer and multi-layer parts exists.

In the previous chapter, successful line formation in fine 316 stainless steel powder was shown to depend on a relationship between droplet spacing and droplet inter-arrival time (frequency). Smaller droplet spacing and longer inter-arrival period lead to improved line formation. To test the applicability of these conditions to layer printing, single layers were printed
using a raster pattern at a droplet frequency of 1 kHz, droplet velocity of 4.9 m/s, and using a range of droplet spacing values (5, 7.5, 10 µm) determined from the previous chapter to form lines successfully. In total 24 tests with varying droplet spacings and line spacings (110-440) µm were conducted in ambient moisture exposed powder and ambient conditions (Amb-Amb). Lines spacing values were selected based on Figure 2-2. The line printed can be assumed cylindrical \cite{61}, and have a diameter approximately 120 µm. This determined a potential line spacing where lines would overlap to create a layer.

Of the tests conducted, two trends emerged. First when the line spacing was similar to the diameter of the printed line, the layers had uneven thicknesses. The first line in the raster pattern was much thicker than the last lines. This was observed in 316 SS but can be seen more clearly in alumina powder as presented in Figure 5-3 where line spacing was set to 110 µm. Imaging of the alumina powder bed shows the printed layer slightly darker on the same edge of the first line in the raster (Figure 5-3b. The darker and thicker edge of the first line printed suggests significant

Figure 5-2: A single 316 SS line shown printed at 10 µm droplet spacing, 1 kHz droplet frequency, and 45 picoliter droplet volume. Thickness is approximately 120 µm, thickness value found by mass measurements verified with this image each square represents 100 µm.
binder migration from later lines into the moist powder of the previously printed lines. This transport phenomena has been recorded in millimeter-scaled droplets as well [92].

Figure 5-3: A) An illustration of the line printing and spacing to make a full layer, compare Figure 5-4. B) Layer printing with 10 µm droplet spacing and 50 µm line spacing, image is of the top prior to extraction in the powder bed. C) is an image of the bottom of the printed layer after extraction from the powder bed. Binder migrated from following lines to the earlier printed region.

Figure 5-4: A) an illustration of the line printing and spacing compare to Figure 5-3. B) Layer print attempted with print parameters determined from successful line formation, 10 µm droplet spacing and 400 µm line spacing. Only individual lines were formed from the parameters selected based on line formation data.
Second, at larger line spacing values lines would remain separate rather than merge together as a layer. An extreme case of this behavior is presented in Figure 5-4 with a line spacing of 400 µm. Using print parameters from lines can possibly be an approach for making larger or thicker layer features which may be desirable for coarse powders or large objects like sand casting molds. However, the effects of binder migration between lines would need to be solved. The droplet spacing of 10 µm was the largest spacing to print lines in 316 SS at 1 kHz droplet frequency. This was done because of the observation from the previous chapter that lines did not form at 12.5 µm droplet spacing. The lines printed were 120 µm diameter which would in theory be the thinnest layer size. Many commercial systems look to print sub 50 µm in layer thickness. Line printing parameters produce thicker layers that will result in reduced resolution and limit the ability to produce fine features to the size of the line. Using line formation as a tool is challenging in addition is not suitable for thin layer or fine features formation.

5.4.2 Layer Formation under Equiaxed Spacing

Line printing parameters may not be suitable for layer printing in most BJ scenarios. However, the same parameters that effect line printing must influence layer printing as well. In many BJ systems, a print saturation and layer thickness are selected by the user and line/droplet spacing is determined by the software. In general, dimensions such as droplet spacing, line spacing,

![Figure 5-5: Balling seen in 316 SS line printing. Print parameters were 1 kHz droplet frequency, 4.9 m/s droplet velocity, and 50 µm droplet spacing.](image)

70
and layer thickness are of similar values as this produces the finest features. Under these droplet spacing values, individual lines did not form successfully at practical droplet frequencies. Balling was often observed as shown in Figure 5-5. However, commercial printing systems often print with droplet spacing and line spacing values comparable to the droplet diameter. To this point, the binder/powder interaction has been studied through line formation and effective saturation of printed lines. In layers the interaction will be observed by the effective saturation. Surface roughness will be used to measure how layers are forming and provide indication of the quality of the part.

An evaluation of droplet frequency values (500 and 1000 Hz), droplet spacing (40, 50, 60 µm), and layer thickness (35, 50 65 µm) was conducted by measuring surface roughness of the printed layer and effective saturation. Samples were printed using powder with ambient moisture levels. A desired layer thickness was chosen and equal droplet and line spacing values were chosen to reach the print saturation using the relationship in Equation (5-1).

### 5.4.2.1 Surface Roughness

Visual observation of layers was conducted by measuring surface roughness. The change in surface roughness between a bare powder bed, one-, and three-layer parts was obvious as the breakup of the surface into separate spherical agglomerates is clearly seen in Figure 5-6. Surface roughness measurements (Figure 5-8) show that printing a first layer increases roughness significantly compared to the spread powder bed before printing. For all conditions, printing the first layer significantly disturbed the powder bed. However, with additional printed layers, the surface roughness decreases until the printed layers are smoother than the spread powder bed. This typically takes three to five layers.
This surface roughness phenomenon appears to be due to change in the droplet imbibition process when printing over moist powder. Since the number of layers plays a larger role in determining roughness than droplet spacing or frequency, the interaction between layers must play a greater role in affecting BJ parts than the interaction between droplets of the same layer. While the samples are all rougher after printing the first layer, the variation in the magnitude of roughness does not have a clear trend with the droplet/line spacing. Larger droplet spacings (60 µm) appear to result in rougher surfaces for the first four layers, but the differences disappear by the fifth layer. Meanwhile, smaller droplet spacings (40 and 50 µm) tended to smooth out as soon as the third layer.

The surface roughness seen on the first layers could be a source of defects as layers are stacked and bonded together to form a part. Parts were cross sectioned to investigate the prevalence of porosity between the first two layers. Of the samples sectioned many had large pores just above the first layer seen in Figure 5-7. Furthermore, no such defects were found near the last layers of the parts that were sectioned. Surface roughness between layers may be a factor in created pores.
Figure 5-7: Cross section of a 5 layer part. Large porosity seen between first and second layer.

Figure 5-8: Surface roughness values of single- and multi-layer parts printed in ambient moisture powder. Each condition was sample two times. Legend depicts print parameters in order: sample number, droplet frequency, droplet spacing (µm), layer thickness (µm), and print saturation.
directly by preventing powder spread into the crevices or indirectly by reducing bonding between layers. Further testing is needed to see if these large pores are caused by the surface roughness of the first parts.

5.4.2.2 Effective Saturation

Effective saturation results of single-and multi-layer parts are presented in Figure 5-9. It should be noted that most BJ systems print saturation is between 60-80% with in-process drying. Without drying as shown here, the mass increases linearly with binder content (Figure 5-9) creating a natural saturation limit that is dependent on layer thickness. This phenomena is seen in this work [38] where samples printed with different layer thickness but similar droplet/line spacing values had similar saturation levels. However, the effective saturation values were consistently below the target values. This suggests that the parts were thicker than expected.

Two groups emerge in the data that are separated primarily due to droplet spacing. Data groups a, b, and e (Figure 5-9) have essentially the same effective saturation. All have a droplet spacing of 40 or 50 μm. A notable difference in effective saturation is seen between these data groups and data group c even though the print saturation was determined to be the same (≈90%). The effective saturation of data group c, instead, followed closely with that of data group d even though the print saturations of these two groups differs by a factor of two. However, data groups c and d have the same droplet spacing of 60 μm. Droplet spacing appears to have an impact on the effective saturation of layers just as it had with line printing [86, 87]. However, this dependency on droplet spacing appears to reach a limit. There was no difference between 40 and 50 μm spacing but a large gap at 60 μm. Since droplets were measured as being 46 μm in diameter, it is probable that the droplets interact with each other possible during impact at droplet spacings of 50 μm or less. This interaction is decreased significantly past a certain point. In this case, that point is most
likely between 50 and 60 µm. Print settings could be optimized to capitalize on this connection. One improvement could be to use thinner layers for increased resolution at a “max” droplet spacing where a closer spacing will have no increased saturation. Alternatively, droplet spacing values could be reduced to increase layer thickness and improve print time with no impact in effective saturation.

5.4.3 Layer Formation with Different Environmental Conditions

The separate impact of powder conditioning and environmental conditions during printing was evaluated through comparison of surface roughness and saturation at four conditions which are ambient moisture (Amb-Amb), dry powder 80% printing (Dry-80%), dry powder 40% printing
(Dry-40%), and steamed (Dry-Steam). Powder conditioning is detailed in the methods section (5.3.3).

5.4.3.1 Effective Saturation

In Figure 5-10(a, b, c) effective saturation is plotted against number of layers under the various conditions. The same linear trend of increasing saturation with increasing thickness is seen in each condition as discussed earlier, except for the steamed powder. However, the increase is small. Each layer is adding only a few percentage points in saturation. The effective saturation is linearly dependent on the thickness of the part.

In each of the plots in Figure 5-10(a, b, c) there is a separation between the Dry-Steam and the rest of the conditions. Moisture absorbed into the powder during the steaming treatment significantly affects the flow of the binder. These parts were significantly larger than the others (Figure 5-11) suggesting a continuous liquid network in the powder from the condensed steam formed before the binder was printed. During printing, the binder spread quickly along these networks without the constraints of wetting boundaries. These parts bled significantly past the intended print volume and resultant parts were fragile due to the low saturation (≈15%). Treating the powder with steam or other liquid source, offers potential advantages such as reduced binder required to fill a desired area and the ability to print thicker layers. This capability can be applied in large area printing and could decrease the number of passes or increase the spacing between nozzles on a printhead leading to a significant increase the printing speed. Pretreatment with moisture could also be used to enhance printing in certain powder/binder combinations that show poor wetting. However, research into controlling the binder spread for the creation of fine features and geometric accuracy is needed.
Figure 5-10: (a, b, c) Saturation values for various printing conditions. (f, e, d) surface roughness values for printing conditions tested. Titles represent droplet frequency (Hz) – droplet spacing (µm) – layer thickness (µm). Ambient moisture (Amb-Amb), dry powder 80% humidity printing (Dry-80%), dry powder 40% humidity printing (Dry-40%), and dry powder steamed printing (Dry-Steam) environments. Each effective saturation data point is an average of six parts. Plots a, b, d, and e had a print saturation at approximately 90%, the plots c and f had a print saturation of 48%. (f, e, d)
In Figure 5-10(a, b) only droplet frequency changes as plot b is lower. Chapter 4 showed that line printing was dependent on droplet frequency. However, in layers there is no change in effective saturation with this decrease in droplet frequency. This was done with only two frequencies; a more inclusive study will draw stronger conclusions on the impact of droplet frequency.

Droplet spacing has an impact on the effective saturation of thin parts as seen as effective saturation in Figure 5-10(c) is below the others. Steam appears to remove the impact as it is approximately the same value as the other steam condition in Figure 5-10(a) at ≈15%. Effective saturation in the steam conditioned powder remains relatively constant with increasing layers unlike the other powder conditionings.

The difference between the average effective saturation of the Amb-Amb and the Dry-80% or 40% is relatively small for all conditions. While it appears that moisture absorbed during the 48 hours has negligible impact on effective saturation, it did increase the variation between the parts. In Figure 5-10(a) the Amb-Amb has more variation compared to Dry-80% and 40%. This variation

Figure 5-11: Both parts shown printed at 50 µm droplet/line spacing and layer thickness with a droplet velocity of 1000 Hz. (Left) Three-layer part printed with steam powder conditioning. (Right) Three-layer part printed with ambient moisture powder conditioning.
cannot be explained by the increase in number of layers, it is likely due to the variation of moisture in the powder bed as uncertainty exists during its preparation. It is interesting that Dry-80% and 40% are virtually identical in their measurements. The ten-minute exposure to humid air after spreading had negligible impact on the flow of the binder, it is assumed that the powder was essentially dry.

It is known that moisture in powder effects the flow of fluid in the powder. However, even with 10 minutes of exposure to a humid environment before printing, insufficient moisture is absorbed to impact the effective saturation. To assess the exposure time required to impact the saturation, single layers were printed on dry powder exposed to 80% humidity for varying times before printing. Figure 5-12 shows that for humidity exposures under 60 minutes, there was no

Figure 5-12: Single layer part effective saturation printed plotted against time exposed for a single layer to 80% humidity prior to printing. Error bars depict the standard deviation of the parts. Layers of powder exposed to humidity <60 minutes exhibited no real change in mass, however prolonged exposure to the ambient humidity significantly changes the imbibition. Error bars depict the standard deviation in the samples.
significant impact on the effective saturation. Only after 11 hours of exposure to humid air did the effective saturation change beyond the standard deviation of the samples. It is important to note that most BJ system will not have powder exposed for prolonged periods of time. This makes exposure to ambient humidity negligible during printing. Pretreatment to dry powder and dry storage will produce repeatable and predictable results in printing regardless of ambient humidity. These results show that humidity control of the printing apparatus itself is probably not necessary.

5.4.3.2 Surface Roughness

Figure 5-10(d, e, f) presents the data for surface roughness values plotted against number of layers. Spread powder represents the surface roughness of the powder bed as spread prior to printing. Measurements of spread powder at each powder conditioning were approximately equal. The surface roughness decreases with increasing number of layers for all conditions. The interaction between layers becomes the primary driver in determining surface roughness rather than interaction between other droplets in the same layer. It was expected that steam treatment would decrease the surface roughness as it already has a continuous network of fluid in the powder. However, the surface roughness of the steamed layers was comparable to Amb-Amb powder conditioning. The steam treatment does appear to lower the surface roughness compared to Dry-80% at larger droplet spacings. Further investigation can help draw a stronger conclusion, but preliminary results show promising reduction in surface roughness by treating the powder bed with steam prior to printing.

Dry-80% powder has the highest surface roughness on the first layer in Figure 5-10(d, e, f). It expected that this high roughness is due to the dry powder. Furthermore, the larger droplet spacing used with the dry powder appear to contribute to this increase. Droplet frequency appears to have no major impact.
5.4.3.3 Linear Regression

Table 5-1: Effective saturation p-values from linear regression model.

<table>
<thead>
<tr>
<th></th>
<th>Number of Layers</th>
<th>Droplet Frequency</th>
<th>Droplet Spacing</th>
<th>Layer Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amb-Amb</td>
<td>0.017</td>
<td>0.050</td>
<td>0.002</td>
<td>0.518</td>
</tr>
<tr>
<td>Dry-80%, 40%</td>
<td>&lt;0.001</td>
<td>0.851</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dry-Steam</td>
<td>0.510</td>
<td>NA</td>
<td>0.999</td>
<td>0.480</td>
</tr>
</tbody>
</table>

Linear regression models were used to analyze the influence of the number of layers, droplet frequency, droplet spacing, and layer thickness on surface roughness and effective saturation for each of the powder conditions. Table 5-1 summarizes the p-values for effective saturation. Number of layers was found significant in Amb-Amb and Dry-80%, 40% but not in Dry-Steam. This helps verify the changes of fluid flow with steam as effective saturation no longer is dependent on the number of layers. Droplet frequency was insignificant in all cases. Droplet spacing was significant in Amb-Amb and Dry-80%, 40% but insignificant with Dry-Steam. This confirms the analysis on droplet spacing and its impact on effective saturation. Layer thickness was only significant with Dry-80% and Dry-40% conditioning. Dry-Steam was not influenced by any of the printing parameters. This reduction of sensitivity to printing parameters may help improve printing speed and efficiency if the spread can be controlled to maintain dimensional accuracy.
Table 5-2 summarizes the linear regression model for surface roughness. As discussed earlier, number of layers is significant in this regression and is a driving factor in determining surface roughness. Using Amb-Amb powder conditioning, each parameter was found to be significant in determining roughness. In this way, the Amb-Amb condition is similar to line printing where droplet spacing and droplet frequency are the main factors in determining if a line prints. Only droplet spacing influenced the surface roughness of the Dry-80% powder. Dry-Steam treatment is not influenced by droplet spacing or layer thickness only by number of layers. This implies that the connected network of moisture in the powder changes the imbibition of the binder significantly. There are potential benefits as discussed earlier but the overall outcome may be better controlled if the moisture level were reduced. A controlled partial prewetting of the powder in future studies could help identify an optimal tradeoff in reduction to sensitivity of printing parameters and loss of dimensional accuracy.

Table 5-2: Surface roughness p-values from linear regression model.

<table>
<thead>
<tr>
<th></th>
<th>Number of Layers</th>
<th>Droplet Frequency</th>
<th>Droplet Spacing</th>
<th>Layer Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amb-Amb</td>
<td>&lt;0.001</td>
<td>0.013</td>
<td>0.016</td>
<td>0.012</td>
</tr>
<tr>
<td>Dry-80%</td>
<td>&lt;0.001</td>
<td>0.965</td>
<td>0.014</td>
<td>0.171</td>
</tr>
<tr>
<td>Dry-Steam</td>
<td>0.002</td>
<td>NA</td>
<td>0.999</td>
<td>0.100</td>
</tr>
</tbody>
</table>

**5.5 Conclusion**

This work studied the connection of line printing to single- and multi-layer printing by measuring surface roughness and effective saturation. Parameters used for line printing are not
ideal in printing single- or multi-layer parts. However, similar relationships exist in printing parameters between single lines and single- and multi-layer parts. This work found droplet spacing, droplet frequency, and number of layers to be significant in affecting surface roughness and effective saturation levels under normal printing conditions. Layer thickness was also found to be significant in affecting surface roughness. Cross sections of printed parts show a prevalence of large voids between the first and second layers. This could be caused by the roughness of the printed part, but more data is needed to verify this connection.

Surface roughness was a measure used to observe the formation of layers during printing. Surface roughness decreased as the number of layers increased. The first layer was always the roughest and had the most variation. It was also the most sensitive to printing parameters. Surface roughness of all printing conditions eventually converged with increasing layers to approximately the roughness of the bare powder bed suggesting a less dynamic binder/powder interaction. Lower frequencies tend to produce less roughness in layers similar to results in line formation. As powder began to be pretreated with overnight heating, the dryer powder created rougher surfaces on the first layer. These trends suggest that the binder/powder interaction reacts differently depending on the layer. It also implies that the interaction with the previous layer is more significant than the droplets on the layer being printed. This alludes to altering process parameters on the first layers to reduce the dynamic interaction while increasing parameters such as print speed and frequency with successive layers to decreasing the overall print time while maintaining part quality.

Effective saturation increased linearly with the number of layers printed. Results show droplet frequency and layer thickness as significant parameters in determining effective saturation. As droplet spacing increased and layer thickness decreased effective saturation levels dropped. Under normal printing conditions, ambient humidity will have little to no effect on the print quality.
as long as the powder has been properly conditioned and stored. Parts built with ambient humidity at 40% and 80% show effective saturation was equivalent. However, under long exposure (>60 minutes) the moisture absorbed in the powder begins to effect saturation levels. Steamed powder had significantly different wetting dynamics as effective saturation levels dropped significantly compared to other powder conditioning, binder spread further outside the predetermined volume.

This study demonstrates that line printing as a tool for determining print parameters cannot be used directly. Rather the effects of specific print parameters, once understood in the context of single-and multi-layer printing can be useful in determining print parameters for full builds. As successive layers are printed these effects become less significant in surface roughness and effective saturation. Further studies connecting surface roughness to possible defects and identifying methods of controlling binder spread in moist powder will provide greater insight into parameter selection and print time reduction.
6. CONCLUSION

6.1 Summary

Chapter 1 provides a brief background and motivation for the research. The thesis outline and objective are stated.

Chapter 2 is a literature review on BJ and topics related to it. Saturation is defined and its many uses in BJ are explained. An overview of the capillary rise as a model in fluid flow in powder is discussed. The fundamental physics of inkjet technology is presented including its applications and how it relates to BJ.

Chapter 3 presents the experimental apparatus built for these studies. This discusses the decisions made and the reasons behind them. The design allowed for additional capability to be readily built in to allow for its use in future studies. Specific waveform parameters for droplet generation are discussed.

In Chapter 4, a study is presented evaluating the impact of various printing parameters (droplet velocity, droplet spacing, droplet size, and droplet inter-arrival time) on line formation and effective saturation. Effective saturation was studied by printing lines using two printheads with different orifice sizes at various droplet velocities and spacings. Line formation was studied by printing at one droplet velocity at various droplet spacings and inter-arrival times. Several potential relationships to improve printing are discussed.
Chapter 5 presents a study connecting parameters determined from line printing to single- and multi-layer parts. In addition, the impact of ambient humidity and powder conditions is reported. Printing parameters determined in Chapter 3 are applied to full layers and evaluated. Surface roughness and effective saturation of single- and multi-layer parts is measured. Surface roughness is identified as a source of a potential defect. The measurements are correlated with powder conditioning and printing parameters.

6.2 Conclusions

Several outcomes of this research include:

- **Most in literature incorrectly assume that effective saturation is dependent only on binder and powder properties.** This research demonstrated that several printing parameters impact the effective saturation in addition to the binder and powder properties. Increased droplet velocity and decreased droplet spacing decreased effective saturation. Methods for predicting effective saturation should look to include these parameters in modeling. This will improve accuracy and help use adapt print parameters across different machines.

- **The impact of printing parameters on the binder/powder interaction decreases with droplet size.** Lines printed with the 30 μm orifice had less variation using different print parameters than lines printed using the 40 μm orifice. As industry trends to smaller droplet sizes the sensitivity to printing parameters will decrease.

- **Line formation is dependent on droplet inter-arrival time and droplet spacing.** This relationship varied approximately to the square root of the droplet inter-arrival time in 316 SS and alumina powders. This is related to the Washburn infiltration as mass absorbed is
related to the square root of time. The Washburn infiltration can be used as a method to help determine optimal printing parameters.

- **Optimal parameters determined using line printing are not necessarily ideal for layer printing.** Most BJ systems print thinner layers than what is possible using parameters from line printing. These parameters produced thicker layers – which under certain circumstances can be advantageous – and included significant binder migration from later lines into the first printed region. To use these conditions for printing thicker layers, binder migration issues would need to be solved.

- **Surface roughness between printed layers was identified as a possible source of defects.** Surface roughness decreased with successive printed layers suggesting the interaction becomes less dynamic with increasing number of printed layers.

- **Powder conditioning is more impactful than ambient humidity during printing.** Dried powder exposed to 40% and 80% humidity during printing exhibited no difference in effective saturation while powder exposed to ambient humidity for 48 hours had significantly larger variation. Consistent powder conditioning will produce consistent printing results independent of ambient humidity. If powder conditioning is consistent print parameters identified can be applied across all regions.

- **Premoistened powder will react independent of printing parameters.** Dried powder conditioned with steam statistically showed to have no reaction to altering printing parameters. Effective saturation was the same at all layers. Steamed powder can be used to improve print quality and speed as it remains independent of individual parameters.

- **Premoistened powder decreased surface roughness.** Surface roughness of the premoistened powder was lower than other conditions. This can possibly be connected to
a reduction in printing defects as binder migrates further and with less disturbance on the powder bed.

6.3 Recommendations for Future Work

This thesis lays the foundation for further exploration which should include the following:

- **Tests to identify a connection between line printing and layer printing parameters.** Simple tests are needed to help identify printing parameters. Printing lines can be this test if a connection between parameters to layer printing is found. This can help reduce overall testing that is required.

- **X-ray and high-speed optical observations of the binder/powder interaction as droplets interact with each other and with other layers.** Understanding how print parameters and layers change this interaction. These observations will help select printing parameters that could reduce pores.

- **Increased studies of surface roughness and connecting it to defects in the first layers of BJ printed parts.** Pores affect mechanical properties, if surface roughness can be confirmed as a potential cause of pores steps can be taken to reduce surface roughness to improve end use BJ parts.

- **Develop methods of controlling binder spread using premoistened powder.** The reduced sensitivity to print parameters allows for decreased printing time. This can be applied to large print areas if the bleeding can be controlled.

- **Further research in understanding the changes in the binder/powder interaction caused by premoistening the powder.** This includes the identification of an optimal moisture content that balances tradeoffs in spreading with reduced sensitivity to printing
parameters. This will allow for machine and process tuning to decrease print time and improve part quality.

- **Identification of print parameters or print patterns to reduce surface roughness on the first layer in BJ.** If surface roughness is confirmed to cause pores in BJ parts. Then managing and decreasing the first layer surface roughness will improve part use.
A. APPENDIX – UNCERTAINTY ANALYSIS

Each measurement in experimental setup has a level of uncertainty. This appendix provides estimates of the uncertainty in the key measurement types used in this thesis. Reported values of effective saturation and droplet velocity have an overall uncertainty. Uncertainty propagation through mathematical operations for an overall uncertainty can be calculated by

\[
\delta q = \sqrt{\left(\frac{\partial q}{\partial x} \delta x\right)^2 + \cdots + \left(\frac{\partial q}{\partial z} \delta z\right)^2}
\] (A-1)

where \(\frac{\partial q}{\partial x}\) is partial derivatives of the function with respect to the measured variable, and \(\delta x\) is the uncertainty of the measurement device. The following sections summarize the uncertainty in the key measurements used in this thesis.

A.1. Line Printing

In line printing uncertainty exists in the reported effective saturation values and droplet velocity. Effective saturation broken down to measurements in the experimental setup is

\[
S_{eff} = \frac{m_b m_{pb}}{m_p \rho_b V_{pb} \left(1 - \left(\frac{m_{pb}}{V_{pb} \rho_{true}}\right)\right)}
\] (A-2)

where \(m_b\) is the binder mass, \(m_{pb}\) is the mass of the powder in the powder bed, \(m_p\) is the mass of the line primitive, \(\rho_b\) is the density of the binder, \(V_{pb}\) is the volume of the powder bed, and \(\rho_{true}\) is the true density of the powdered material. The uncertainty of each measurement under the range
of values tested is reported in Table 6-1. Uncertainty values for weight measurements were taken from the scales manufacturer specifications (Ohaus). Powder beds cavities were manufactured using a CNC and it was estimated that the volume has an uncertainty of 1% of the designed volume. The highest saturation uncertainty seen is due to the alumina powder at large droplet spacings due to the small mass of the lines. If alumina is removed from the data set uncertainty for effective saturation decreases to a max value of 1.97%, significantly lower than reported. Alumina has a much lower density than the stainless steel powders causing lines formed to be significantly lower in weight.

<table>
<thead>
<tr>
<th></th>
<th>Uncertainty</th>
<th>Relative Uncertainty</th>
<th>420 SS</th>
<th>316 SS</th>
<th>Alumina</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_b )</td>
<td>0.0001 g</td>
<td>0.57-2.51%</td>
<td>0.57-1.72%</td>
<td>0.57-3.70%</td>
<td></td>
</tr>
<tr>
<td>( m_{pb} )</td>
<td>0.01 g</td>
<td>&lt;0.01%</td>
<td>&lt;0.01%</td>
<td>&lt;0.01%</td>
<td></td>
</tr>
<tr>
<td>( m_p )</td>
<td>0.0001 g</td>
<td>0.59-1.99%</td>
<td>0.49-1.22%</td>
<td>1.53-9.17%</td>
<td></td>
</tr>
<tr>
<td>( V_{pb} )</td>
<td>0.6853 cm³</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
<td></td>
</tr>
<tr>
<td><strong>Overall Effective Saturation Uncertainty</strong></td>
<td></td>
<td></td>
<td>0.37-1.09%</td>
<td>0.26-1.97%</td>
<td>1.95-10.84%</td>
</tr>
</tbody>
</table>

Droplet velocity was also measured in the line printing experiments using a camera and a strobe. Images taken with the camera determined the velocity once calibrated. Each pixel was calibrated to 1.4 microns with an uncertainty of 1 pixel as droplet velocity was averaged over five images. The strobe reported by the manufacturer (MicroFab) has an uncertainty of 1 µs. The uncertainty analysis is summarized in Table 6-2.
Layer printing used a different experimental setup and has a different uncertainty associated with it than the line printing. Only 316 SS powder was used. Powder bed density found using the plug method alters the effective saturation equation to be

\[ S_{eff} = \frac{m_b m_{pb}}{m_p \rho_b \pi r^2 l \left( 1 - \frac{m_{pb}}{\pi r^2 l \rho_{true}} \right)} \]  

(A-3)

where \( r \) is the radius of the plug and \( l \) is the depth of the powder bed. The uncertainty analysis is summarized in Table 6-3. Uncertainty values for weight measurements were taken from the scale manufacturer specifications (Ohous) and distance measurements were limited by the uncertainty of the calipers.

### Table 6-2: Summary of uncertainty analysis of droplet velocity measurements.

<table>
<thead>
<tr>
<th></th>
<th>Uncertainty</th>
<th>Relative Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance Traveled</td>
<td>2.8 µm</td>
<td>0.21-0.86%</td>
</tr>
<tr>
<td>Total Time</td>
<td>2 µs</td>
<td>0.80-2.67%</td>
</tr>
<tr>
<td><strong>Overall Droplet Velocity Uncertainty</strong></td>
<td></td>
<td>0.05-0.19 m/s</td>
</tr>
</tbody>
</table>
Table 6-3: Summary of the uncertainty analysis for the layer printing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty</th>
<th>Relative Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_b$</td>
<td>0.0001 g</td>
<td>0.07-3.11%</td>
</tr>
<tr>
<td>$m_{pb}$</td>
<td>0.0001 g</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>$m_p$</td>
<td>0.0001 g</td>
<td>0.03-0.31%</td>
</tr>
<tr>
<td>$r$</td>
<td>0.02 mm</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>$l$</td>
<td>0.02 mm</td>
<td>&lt;0.01%</td>
</tr>
</tbody>
</table>

**Overall Effective Saturation Uncertainty** 0.13-3.15%
REFERENCES


