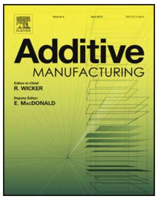
Additive Manufacturing 20 (2018) 1–10

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma



Effect of printing speed on quality of printed parts in Binder Jetting Process

Hadi Miyanaji[a], Niknam Momenzadeh[b], Li Yang[a,*]

[a] Department of Industrial Engineering, University of Louisville, Louisville, KY, 40292, USA
[b] Department of Mechanical Engineering, University of Louisville, Louisville, KY, 40292, USA

ARTICLE INFO

Article history:
Received 4 November 2017
Received in revised form 6 December 2017
Accepted 22 December 2017
Available online 26 December 2017

Keyword:
Additive manufacturing
Binder jetting
Printing speed
Droplet

ABSTRACT

Binder Jetting Process is an Additive Manufacturing technique (AM) in which a liquid binder is employed for establishing the initial strength and fabricating the geometry of components. In this process, the delivery of the binding agent is accomplished through a drop-on-demand (DOD) printhead by deposition of picoliter-sized droplets of the liquid binder. The velocity of the droplets impinging the powder bed surface might have significant effect on droplet spreading and absorption dynamics, which can be manifested in quality and integrity of the fabricated parts. In the present study, the effect of the printing speed on dimensional accuracy and equilibrium saturation level of printed samples is experimentally investigated and the observed trends are discussed in detail.

1. Introduction

Binder jetting additive manufacturing process (BJ-AM) is an additive manufacturing process in which a part geometry is fabricated by applying liquid binder to the selective areas of a spread layer of powder material. In this process, small droplets with diameters less than 100 μm are successively deposited onto the powder bed surface through a drop-on-demand (DOD) printhead in a pattern of raster scanning. After deposition of the liquid binder, the entire surface of the powder bed, including saturated and unsaturated areas, is exposed to a fixed amount of heat commonly by means of a heat lamp. This in-process heating is to establish appropriate mechanical strength via partially cured binder within the already generated layer to withstand the shear and gravitational compressive forces involved in the spreading and printing of subsequent layers. These steps are repeated for each layer until the whole feature is completed [1]. The quality and integrity of the components printed via BJ-AM process might be significantly affected by the physical properties of the liquid binder, powder material, powder bed characteristics and process parameters. Some of these process control parameters, including saturation level, heating power intensity, liquid binder curing time, feed-to-powder ratio, and spreading speed, have been experimentally investigated for their effect on the dimensional accuracy and mechanical strength of the printed features [2–8]. The saturation level, binder amount used for part printing, coupled with binder curing parameters (power intensity and curing time) has been shown to play a key role in determining the quality of the fabricated parts [8–11].While the excessive binding agent would result in dimensional inaccuracies, insufficient usage of binder would deteriorate the mechanical performance of the printed components [12]. In [13], the authors have developed a physics-based model to predict the optimal saturation amount which ensures the structural integrity and dimensional accuracy of the printed features. The quality of the fabricated parts may also be influenced by the powder spreading speed and the feed-to-powder ratio (thickness of feed layer to layer thickness that is attributed to the change in powder packing characteristics and spreading uniformity [2,14]. The effect of layer thickness has also been evaluated by different researchers [3,4,12]. The layer thickness which is used for binder saturation calculations might remarkably affect the dimensional accuracy and mechanical strength of the printed features [8,11,12]. With a fixed binder saturation and droplet volume, thicker layers would require further deposition of binder in the already pre-wetted area which might consequently influence the binder flow dynamics. It is suggested that for the desirable spreading of powders in BJ-AM process, the layer thickness should be at least thicker than the largest particle and preferably three times of particle size [15]. On the other hand, the printing speed, which corresponds to the forward travel rate of the printhead (in Y direction as shown in Fig. 1), has received little

---

[*] Corresponding author at: J.B. Speed Bldg., Room 311, Department of Industrial Engineering, University of Louisville, Louisville, KY 40292, USA.
E-mail addresses: h0miya02@louisville.edu (H. Miyanaji), n0mome01@louisville.edu (N. Momenzadeh), li.yang.1@louisville.edu (L. Yang).

https://doi.org/10.1016/j.addma.2017.12.008
2214-8604/© 2017 Published by Elsevier B.V.

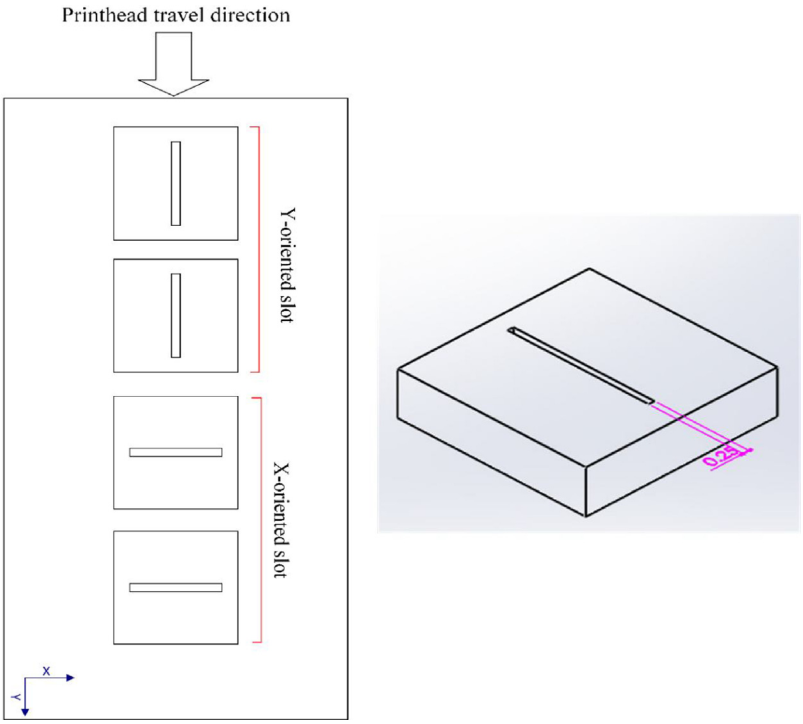


Fig. 1. The designed geometry for printing samples and part configuration in the powder bed.

attention in the literature. While it is generally perceived that for AM higher printing speed would correspond to reduced geometrical accuracy of the printed parts, the driving mechanisms differ among processes. For example, in powder bed fusion the printing speed could be conveniently interpreted as the moving speed of the melting pool, which impacts the printing quality by imposing different spatiotemporal thermal characteristics [16,17]. Similarly, in vat photopolymerization the printing speed affects the curing characteristics of the parts, which in turn affects the dimensional accuracy of the parts [18,19]. For the material extrusion systems, the printing speed is closely associated with the kinetics of the motion platform and the extruded materials, which is similar to the issues encountered by BJ-AM and in turn could significantly impact the part quality [20,21]. However, for BJ-AM technology such fundamental understanding of mechanisms and their impacts on quality of the fabricated components have not been widely studied.

Similar to the interaction of a droplet with an impermeable surface, three phenomena, spreading, bouncing (i.e. rebounding of impinging droplets on a solid surface) or splashing, might take place upon impact of a droplet on a porous surface. Such behaviors between an impinging droplet and a permeable surface depend on many factors including the physical properties of the droplet and the target surface, compact conditions (impact velocity and droplet size), porous structure characteristics, and the wettability of the porous material to the droplet [22–24]. One of the key parameters determining the droplet interaction with the any surface is the velocity of the impinging droplet [24–26]. It has been shown both experimentally and analytically that the velocity of the droplets upon impact has a significant influence on droplet flow dynamics in porous media due to effect of the inertia forces [23,24,27–31]. While spreading dominates the interaction of the impinging droplet and the surface at low velocities, bouncing and/or splashing are the dominant mechanisms in the interaction at high impact velocities. In BJ-AM process, as the formation of green parts is closely associated with the binder permeation characteristics in the porous powder bed, occurrence of each of these phenomena primarily due aracteristics and binder liquid characteristics could significantly impact not only the to the factors such as initial droplet shape and velocity vector, powder bed pore chequilibrium binder saturation conditions but also the geometry of the binder-wetted area. Spreading due to the droplet impact would increase the initial contact area between the droplet and powder bed and as a result would influence the subsequent droplet penetration and saturated area. On the other hand, if bouncing phenomenon occurs, the impinging droplets would rebound from the powder bed surface upon initial contact, which could potentially result in offset of permeation zone along the Y direction from the initial location and introduce dimensional inaccuracies to the printed structures. Also, splashing in which the impinging droplet disintegrates in two or more secondary smaller droplets after impact might contribute to loss of integrity and accuracy of parts by decreasing the droplet permeation area. Therefore, it is expected that the printing speed as the horizontal component of the overall binder droplet velocity (Fig. 6) could significantly affect the geometrical accuracy and saturation characteristics of the green parts, which was experimentally investigated in the present study.

2. Methodology

To assess the effect of printing speed on components fabricated via BJ-AM process, cuboid samples with 8 × 8 × 2 mm dimensions which contain narrow slots with width of 0.25 mm were fabricated using ExOne M-Lab printer. As shown in Fig. 1. The designed geometry for printing samples and part configuration in the powder beda set of such samples was fabricated in such a way that slots were aligned with the printing direction (Y direction). For fabrication of the second group of these structures, parts were oriented along with X direction (perpendicular to printing direction). The narrow slots in the design as shown in Fig. 1 were designed to capture the effect of the printhead speed on dimensional accuracy in Y and X directions. A broad range of printing speeds from 15 mm/sec to 1000 mm/s were applied for the fabrication of the parts.