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A new physics-based model for equilibrium saturation determination in binder jetting additive manufacturing process

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ABSTRACT

In binder jetting additive manufacturing (BJ-AM) process, the features are created through the interaction between droplets of the liquid binding agent and the layered powder bed. The amount of binder, which is termed binder saturation, depends strongly on the liquid binder and powder bed interaction including the spreading (i.e. lateral migration) and penetration (vertical migration) of the binder in powder bed, and is of crucial importance for determining the accuracy and strength of the printed parts. In the present study, a new physics-based model is developed to predict the optimal saturation levels for the green part printing, which is realized via capillary pressure estimation that is based on the binder and powder bed interactions in the equilibrium state. The proposed model was evaluated by both the Ti-6Al-4V and 420 stainless steel powders that exhibit different powder characteristics and packing densities. In order to estimate the equilibrium saturation using the proposed model, the physical characteristics such as average contact angle between the binder and powder material, specific surface area of powder particles, saturation and capillary pressure characterization curve were determined. Features with various degrees of dimensions (1-D, 2-D, 3-D) were printed out using M-Lab ExOne printer for determining the equilibrium saturation. Good agreement was observed between the theoretical predictions and experimentally measured saturation levels for the Ti-6Al-4V powder. On the other hand, the model underestimated the optimal saturation level for the 420 stainless steel powder, which was likely caused by the micro-surface areas from powder particle surface that do not contribute to the binder-powder bed interactions.

1. Introduction

The binder jetting additive manufacturing (BJ-AM) process is one of the additive manufacturing (AM) processes that has been broadly adopted for various applications. Due to the use of the binders for the geometry creation at room temperatures, the BJ-AM possesses various advantages over other AM processes, such as the elimination of thermally induced defects (e.g. distortion, unwanted grain growth, etc.) and wide compatibility with various materials. Some of the exotic materials such as Inconel 718 [2], copper [3], zirconia [4], silicon carbide [5], barium titanite [6], calcium phosphate [7,8] and hydroxyapatite [9] have been used by the BJ-AM processes, which can be challenging even for some of the other AM processes. In BJ-AM process, droplets of the liquid binder are delivered to the designated surface area of the spread powder bed through a print-head. After the deposition of the binder, the entire surface of the powder bed is exposed to certain amounts of thermal energy commonly by means of heating lamps in order to introduce adequate mechanical strength into the printed structures to withstand the shearing and gravitational forces involved in the consequent printing processes. These steps are repeated for each layer until the entire samples are completed. The geometrical qualities and the structural integrity of the green parts strongly rely upon both the quantity of the deposited binders and the characteristics of the binder-powder bed interactions [10].

In the BJ-AM process, once the liquid droplets are deposited on the desired locations, the droplets will start to migrate into the powder pores under the influence of both capillary attraction and the surface tension-induced pressure gradient across the binder droplet meniscus formed between the binder and air as schematically shown in Fig. 1 [11–16]. The surface tension-induced pressure gradient decreases as the binder penetrates further into powder bed, and eventually disappears when there is no binder left on the powder bed surface. Therefore, during the binder permeation process the primary driving mechanism for the binder movement inside the powder bed is the capillary pressure. The state when the binder stops migration within the powder bed due to the balance of the capillary pressure (P_c) across all binder-air interfaces (meniscus) establishes the equilibrium state of the process

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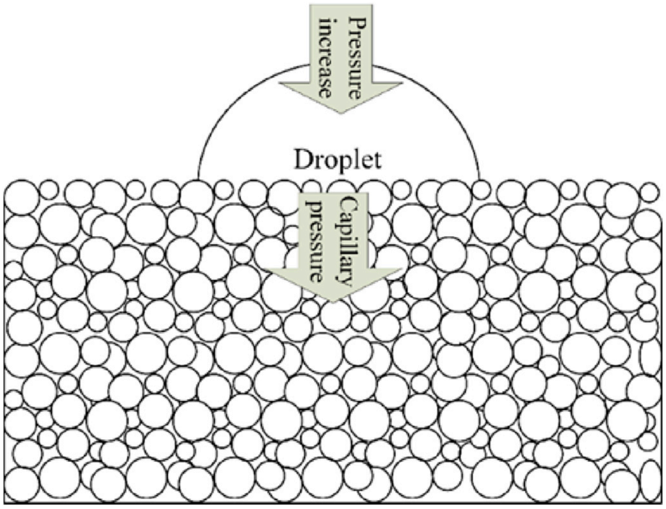

Fig. 1. Schematic presentation of a binder droplet on the powder surface.

(Fig. 2) [11,12].

Under the equilibrium conditions, the binder saturation level, which is defined as the ratio of binder volume to the pore volume in a predefined envelope of powder bed, is of significant importance in the BJ-AM process. This equilibrium saturation determines the optimal saturation level required for the successful creation of green parts [17,18]. If the saturation imposed by the printer control settings is much greater than the equilibrium saturation, the excess liquid binder tends to migrate out of the designated boundaries of the feature to be printed. On the other hand, in the opposite case, the printed part won't have sufficient mechanical strength due to the lack of sufficient binder phase, which results in weak bonding between the particles as well as between successive layers. Several works have experimentally demonstrated that the binder level plays a key role in determining the part dimensional accuracy and mechanical performance in BJ-AM process [6,16,19,20]. Therefore, precise estimation about the equilibrium saturation for a given powder bed and liquid binder is highly desired for the design of the BJ-AM process and the optimization of the qualities of the printed parts. Currently, the selection of the binder saturation levels in the BJ-AM process is largely based on trial and error approach, and very limited attempts have been reported for the prediction of the equilibrium saturation levels. In Ref. [18], the equilibrium saturation estimations from the model that was developed based on previously proposed imbibition-drainage characterization does not appear to be in good agreement with the experimental results, which was suggested to be attributed to several potential factors such as the hysteresis between the drainage and imbibition characteristics [17]. In order to understand the interactions between liquid binder and the porous powder bed effectively, a fundamental model that describes the behaviors of a fluid in a porous medium for the BJ-AM process is needed.

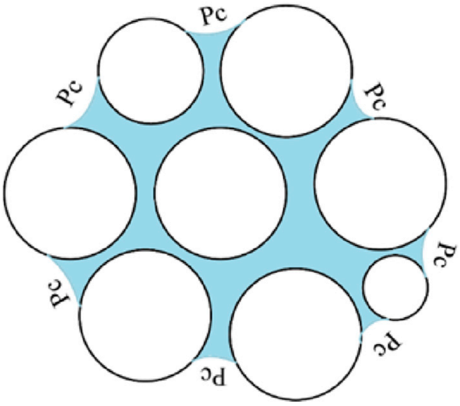

Fig. 2. Equilibrium state in the pore scale (*Pc*: capillary pressure).

There exist relevant application areas where displacement of a fluid by another fluid in the presence of porous structures is considered, such as oil recovery [21], water infiltration into the soil [22] and 2-D inkjet printing [23]. Within these areas, an abundance of literature covers various subjects including displacement patterns and computer simulations [24], displacement mechanisms in the pore (micro) scale and macro scale [25], spreading (lateral displacement) and penetration (vertical diffusion) rates [13,26], wettability and its effect on fluid migration [27], simulation of fluid migration inside porous medium [28], and saturation dependence on the capillary pressure [18]. While many of these works provide useful references to the understanding of the BJ-AM process, the equilibrium saturation levels of a finite-volume fluid body in the presence of another fluid inside a porous medium has not been dealt with in much details in the context of the BJ-AM process.

In the present work, a physics-based model is established to estimate the average capillary pressure in the equilibrium state. The model can be employed to predict the average saturation levels with the calibration of the experimental saturation-capillary pressure characterization curve. The accuracy of the model was evaluated through experimentation, and the results were discussed in detail.

2. Modeling of binder saturation

During the BJ-AM process, the binder droplets are delivered from individual nozzles in the printhead and subsequently deposited on the powder bed surfaces. Upon impact on to the powder bed surfaces, the droplets experience some turbulences due to inertial forces [23]. Depending on the velocity, density, surface tension, and volume of the droplet, splashing might occur upon the impact. In Ref. [29], it was demonstrated that the splashing phenomenon is more likely to occur when the Weber (We) number is > 50. For BJ-AM process, The We number can be calculated from:

$$\mathrm{We} = \rho r v^2 / \gamma \tag{1}$$

where ρ is the density of the binder material, r and v are the radius and velocity of the droplet, respectively, and γ the surface tension of the liquid binder. From the printer specifications and binder physical characteristics used in the present study, the We number is calculated to be less than the threshold amount $(\mathrm{We} \approx 50)$ for splashing. Therefore, although initial disturbance and wave-like curvature might be present on the droplet surface after impact [23,30], no splashing is expected to occur. Furthermore, the momentum will be dissipated very quickly (10^{-4}s), and capillary force is expected to be the only dominant driving force thereafter (after 10^{-3}s) [18,26].

In order to establish the equilibrium model that properly represents the physical reality of the binder-powder bed interaction, the binder penetration pattern must be evaluated first, as it could significantly influence the uniformity of the saturation levels within the permeated regions. From the literature, fluid-fluid displacement in the presence of a solid surface can be categorized into two types as either drainage or imbibition based upon the system's wettability [27,31]. While drainage is described as the fluid migration mechanism in which the penetrating fluid is less wetting to the solid surface than the displaced fluid, imbibition refers to the opposite case in which the penetrating fluid is more wetting. It is obvious that imbibition is more representative for the description of the binder permeation process in BJ-AM, since the displacing fluid (liquid binder) is more wetting than the fluid being displaced (air). The most critical factors that determine the displacement patterns are the viscosity ratio *M* and the capillary number *Ca*, which are two dimensionless factors that indicate the relative viscosity and relative viscous force respectively [31–33]. The definitions for *M* and *Ca* are given in Eq. (2) and Eq. (3), respectively.