Powder-bed additive manufacturing: the effect of layer thickness on powder bed density

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Abstract

The effect of layer thickness (LT) on powder bed density (PBD) was experimentally studied. The effect of LT on PBD was found dependent on both the powder flowability and measurement scenario. In the measurement scenario of fixing the powder bed height, increasing LT decreased PBD of both free-flowing powders and cohesive powders. In the measurement scenario of fixing the number of powder layers, increasing LT did not significantly affect PBD of free-flowing powders but significantly decreased PBD of cohesive powders. These findings shed light on the inconsistent results in the literature and provide guidance on the design of future studies.

Keywords: Additive manufacturing; layer thickness; powder bed density; flowability

1. Introduction

Powder-bed additive manufacturing refers to additive manufacturing technologies that utilize binder or heat source to bond particles in a powder bed [1]. Binder jetting and powder bed fusion, as two common powder-bed additive manufacturing technologies, are attracting increasing interests from different industries [2–10]. In powder-bed additive manufacturing, layer thickness is a critical parameter that could affect powder bed density (packing density of the powder bed on the build platform) [11–15], and thereby, affect density and mechanical properties of final products [16,17]. Therefore, understanding the relationship between layer thickness and powder bed density is essential to controlling density and mechanical properties of final products.

The effect of layer thickness on powder bed density has been studied before but resultant trends are inconsistent. The experimental work by Lee [11] and Budding et al. [12] indicated that powder bed density decreased with increasing layer thickness. On the contrary, the experimental work by Ziaee et al. [13] and Chen et al. [14] showed that powder bed density increased with increasing layer thickness. Different from the aforementioned trends, the experimental work by Cao et al. [15] showed that powder bed density increased first and then decreased with increasing layer thickness.

Using powders of different flowabilities could be one of the possible causes for the inconsistent trends. Lee [11] used alumina powders that had particle sizes of 10 μm and 30 μm, and a stainless steel powder that had a particle size of 30 μm. Budding et al. [12] used a plaster powder with a mean particle size of 46.33 μm. Ziaee et al. [13] used a mixture of a polycaprolactone powder that had a mean particle size of 600 μm and a demineralized bone powder that was around 300 μm wide and 1 mm long. Chen et al. [14] used stainless steel powders of different particle sizes (from 11.6 μm to 96 μm) and their mixtures. Cao et al. [15] used a mixture of two alumina powders and a urea formaldehyde powder with mean particle sizes of 17.38 μm, 3.31 μm, and 0.83 μm, respectively. Because of the different materials and particle sizes, flowabilities of the powders used in these studies could be different. The different flowabilities could have affected the relationship between layer thickness and powder bed density, and thus, led to different trends.

Another possible cause for the inconsistent results could be different scenarios of measuring powder bed density. Lee [11] and Cao et al. [15] measured powder bed density by forming a powder bed with a certain height while Ziaee et al. [13], Chen et al. [14], and Budding et al. [12] formed a powder bed with a certain number of powder layers. When the powder bed height is fixed, different layer thickness values lead to different numbers of powder layers. Similarly, when the number of powder layer is fixed, different layer thickness values lead to different values of powder bed height. It is possible that these different measurement scenarios could have led to different results.

This study aims to reveal the relationship between layer thickness and powder bed density for powders of different flowabilities in different measurement scenarios. The effect of layer thickness was studied by measuring powder bed density achieved at different layer thickness values. To show the effect of powder flowability, five powders of different sizes were used in this study. To reveal the effect of different measurement scenarios, powder bed density was measured in two scenarios, i.e., by forming a powder bed with a certain height and by spreading a certain number of powder layers.

2. Experimental methods

2.1. Powders and powder flowability measurement

To cover powders of different flowabilities, five powders as listed in Table 1 were used in this study. Flowability of these five powders was evaluated by measuring their apparent density following the ASTM B212-17 standard [18] and their tap density following the ASTM B527-15 standard [19]. Apparent density is the packing density of freely settled powder [20]. Tap density is the packing density of a powder that has been tapped, to settle contents, in a container under specified conditions [20]. Then, Hausner ratio of each powder, an empirical metric for powder flowability, was calculated by dividing its tap density by its apparent density [21].

Table 1. Powders used in this study.

Material	Nominal particle size (µm)	Supplier	Item number
Tungsten	23	Inframat Advanced Materials	SP74001545
Alumina	70	Inframat Advanced Materials	26R8S70
Alumina	20	Inframat Advanced Materials	26R8S20
Alumina	0.3	Allied High Tech Products	90187125
Alumina	0.1	Inframat Advanced Materials	26N0811UPA

2.2. Powder spreading experiments

To study the effect of layer thickness on powder bed density in two different measurement scenarios, powder spreading experiments were conducted by varying the layer thickness with either a fixed powder bed height or a fixed number of powder layers, as illustrated in Fig. 1. In the first scenario, the powder bed height was fixed at 10 mm, and thus, the number of powder layers within the formed powder bed was different at each layer thickness value. In the second scenario, the number of powder layers was fixed, and thus, the powder bed height was different at each layer thickness value. Layer thickness was varied across 80, 120, 160, 200, and 240 µm in both scenarios. The corresponding values of powder bed height and number of powder layers are plotted in Fig. 1.

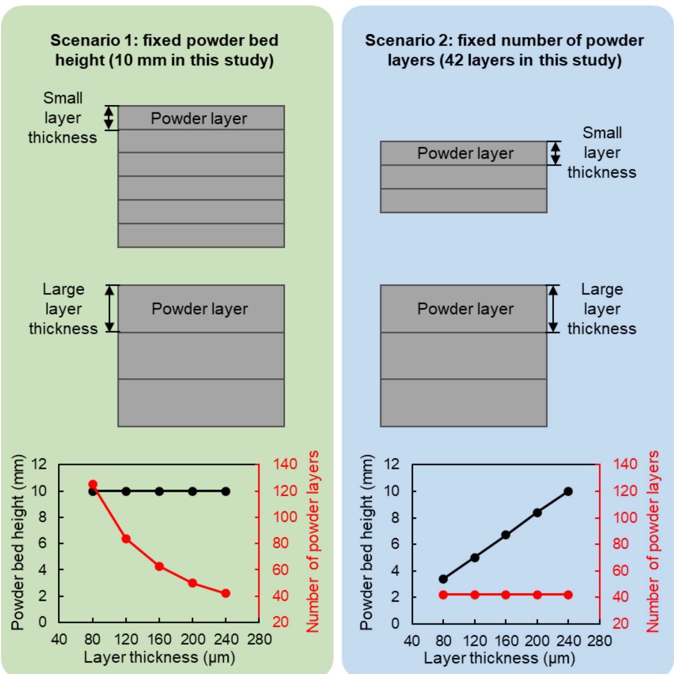

Fig. 1. Two different scenarios of measuring powder bed density at different layer thickness values.

The powder spreading experiments were conducted on a commercially available binder jetting 3D printer (ComeTrue T10, Microjet). The powder in the build box was collected after spreading to measure its weight, and the relative powder bed density ρ'_{pb} is defined as follows:

$$\rho'_{pb} = \frac{m_{pb}}{h_{pb} \cdot A_{pb} \cdot \rho_{th}} \times 100\% \quad (1)$$

where m_{pb} is the weight of collected powder after spreading, h_{pb} is the average height of the powder bed (measured via a calliper at four corners), A_{pb} is the area of the powder bed, and ρ_{th} is the theoretical density for the corresponding tested powder (i.e., 19.30 g/cm^3 [22] and 3.97 g/cm^3 [23] for tungsten and alumina, respectively). Roller traverse speed (30 mm/s), roller rotation speed (500 RPM), and dosing ratio (1.4) were kept the same in all the powder spreading experiments. The powder spreading experiments were replicated three times for each powder. The sequence of conducting these experiments and replications was randomized.

3. Results and discussion

3.1. Powder flowability

The apparent density, tap density, and Hausner ratio of the five powders are plotted in Fig. 2. The tungsten powder had a better flowability than all the alumina powders. For the alumina powders, flowability decreased with decreasing particle size. According to the Hausner ratio, these five powders were divided into two different categories. The tungsten powder and the 70 µm alumina powder had a Hausner ratio smaller than 1.25, and therefore, were categorized as free-flowing powders [24,25]. The other three alumina powders were categorized as cohesive powders.

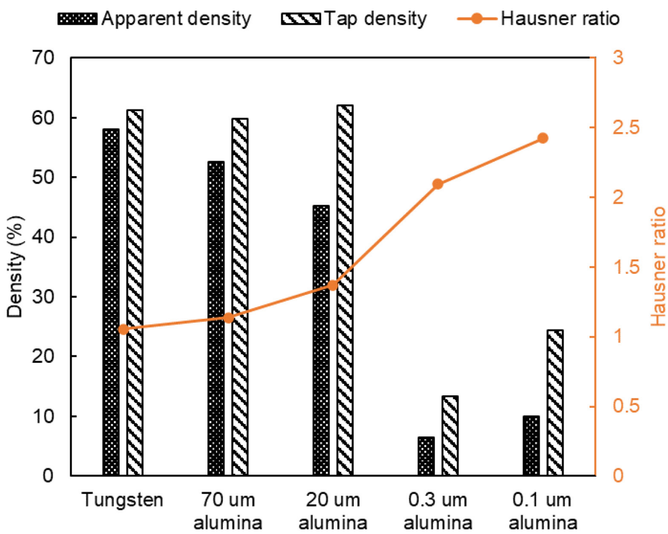

Fig. 2. Apparent density, tap density, and Hausner ratio of the five powders.

3.2. The effect of layer thickness on powder bed density of free-flowing powders

The effect of layer thickness on powder bed density for the two free-flowing powders is discussed in this section. As shown in Fig. 3, when powder bed height was fixed (10 mm), powder bed density decreased with increasing layer thickness for both free-flowing powders. However, when number of powder layers was fixed (42 layers), the trends became unclear for both free-flowing powders. Although powder density seemed to vary with increasing layer thickness, powder bed density was similar at different layer thickness values. Therefore, statistical testing was conducted. Table 2 lists the ANOVA results based on these data. Powder bed density was statistically different at different layer thickness values for the free-flowing powders in the measurement scenario of fixing the powder bed height (i.e., Null Hypotheses 1 and 3 are rejected). However, in the measurement scenario of fixing the number of powder layers, Null Hypotheses 2 and 4 could not be rejected at a significance level of 0.05, meaning powder bed density was statistically same at different layer thickness values.

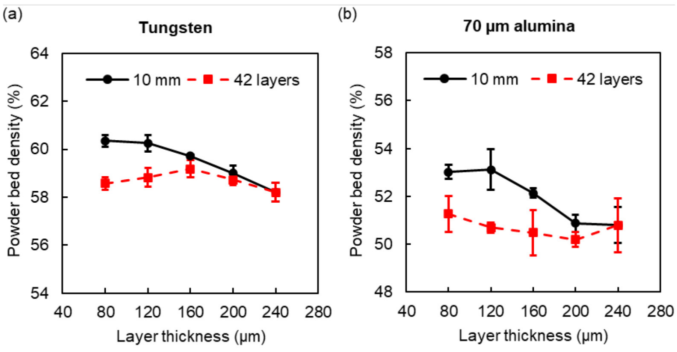

Fig. 3. The effect of layer thickness on powder bed density in two different measurement scenarios (fixed the powder bed height at 10 mm and fixed the number of powder layers at 42, respectively) for two free-flowing powders: (a) Tungsten powder; (b) 70 µm alumina powder.

Table 2. ANOVA of the effect of layer thickness on powder bed density of free-flowing powders in two different measurement scenarios.

Powder	**Null hypothesis**	**p-value**	**Test result**
Tungsten	1. Powder bed density is the same at different layer thickness values in the measurement scenario of fixing the powder bed height	0.000	Rejected
Tungsten	2. Powder bed density is the same at different layer thickness values in the measurement scenario of fixing the number of powder layers	0.052	Not rejected
Alumina (70 µm)	3. Powder bed density is the same at different layer thickness values in the measurement scenario of fixing the powder bed height	0.000	Rejected
Alumina (70 µm)	4. Powder bed density is the same at different layer thickness values in the measurement scenario of fixing the number of powder layers	0.451	Not rejected

Fig. 3 also indicates that powder bed density increased with the increasing number of powder layers at the same layer thickness. For example, at the layer thickness of 80 µm, the powder bed density from both powders achieved by the 10 mm thick powder bed (consisting of 125 powder layers) was higher than that achieved by 42 powder layers. By increasing layer thickness, the number of powder layers in the 10 mm thick powder bed decreased, and thus the powder bed density became closer to what was achieved by 42 powder layers. At the layer thickness of 240 µm, there were 42 powder layers in both scenarios, and therefore, there was no difference in the powder bed density. The increasing powder bed density with increasing number of powder layers could be explained by rearrangement of powder particles [26,27]. In the powder spreading experiments, all the powder layers were spread on the previous layers of loose powder. Spreading more powder layers could improve powder bed density because of more chances for powder particles to rearrange.

3.3. The effect of layer thickness on powder bed density of cohesive powders

Fig. 4 and Table 3 show the effect of layer thickness on powder bed density for the three cohesive powders. For all the three cohesive powders, decreasing layer thickness significantly increased powder bed density in both measurement scenarios (10 mm and 42 layers).

By comparing the powder bed density achieved at different numbers of powder layers (i.e., at the same layer thickness but in different measurement scenarios), it was found that the effect of number of powder layers for the cohesive powders was not as significant as that for the free-flowing powders. This might be because the powder particles could not get rearranged efficiently because of strong cohesion. Therefore, powder bed density did not significantly increase with increasing number of powder layers.

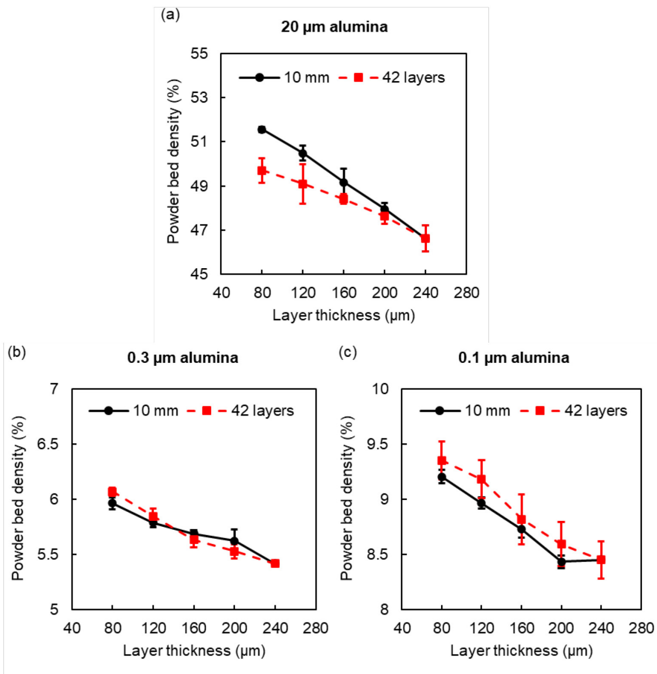

Fig. 4. The effect of layer thickness on powder bed density in two different measurement scenarios (fixed the powder bed height at 10 mm and fixed the number of powder layers at 42, respectively) for three cohesive powders: (a) 20 µm alumina powder; (b) 0.3 µm alumina powder; (c) 0.1 µm alumina powder.

Table 3. ANOVA of the effect of layer thickness on powder bed density of cohesive powders in two different measurement scenarios.

Powder	**Null hypothesis**	**p-value**	**Test result**
Alumina (20 μm)	5. Powder bed density is the same at different layer thickness values in the measurement scenario of fixing the powder bed height	0.000	Rejected
Alumina (20 μm)	6. Powder bed density is the same at different layer thickness values in the measurement scenario of fixing the number of powder layers	0.000	Rejected
Alumina (0.3 μm)	7. Powder bed density is the same at different layer thickness values in the measurement scenario of fixing the powder bed height	0.000	Rejected
Alumina (0.3 μm)	8. Powder bed density is the same at different layer thickness values in the measurement scenario of fixing the number of powder layers	0.000	Rejected
Alumina (0.1 μm)	9. Powder bed density is the same at different layer thickness values in the measurement scenario of fixing the powder bed height	0.000	Rejected
Alumina (0.1 μm)	10. Powder bed density is the same at different layer thickness values in the measurement scenario of fixing the number of powder layers	0.000	Rejected

This work highlights the importance of considering different powder flowabilities and measurement scenarios in studying the effect of layer thickness on powder bed density. Hypothetical explanations are given in this short communication. More work needs to be done to confirm or reject them. Discrete element method simulation and in-situ imaging could be promising ways to investigate the underlying mechanisms.

4. Conclusions

This short communication reports an experimental study on the effect of layer thickness on powder bed density for powders of different flowabilities (free-flowing and cohesive powders) in two different measurement scenarios (fixing powder bed height and fixing number of powder layers). The major conclusions are drawn as follows:

- In the scenario of fixing the powder bed height, increasing layer thickness decreased the powder bed density of free-flowing powders.
- In the scenario of fixing the number of powder layers, layer thickness did not significantly affect the powder bed density of free-flowing powders.
- In the scenario of fixing the powder bed height, increasing layer thickness decreased the powder bed density of cohesive powders.
- In the scenario of fixing the number of powder layers, increasing layer thickness decreased the powder bed density of cohesive powders.

These conclusions indicate that the powder flowability and measurement scenario should be considered in future studies on the effect of layer thickness on powder bed density.

Acknowledgements

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