A Literature Review on Powder Spreading in Additive Manufacturing

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Abstract

Powder-bed additive manufacturing, including powder bed fusion and binder jetting, has a wide range of applications in various industries. Powder spreading is a critical step of powder-bed additive manufacturing and has a determinative impact on powder bed quality and thus final part quality. This paper provides a literature review on powder spreading, focusing on the effects of influencing factors on powder bed quality. Three groups of influencing factors are discussed: spreaders, spreading parameters, and feedstock powder properties. Besides the effects of individual factors, the interaction effects between these factors are also discussed where applicable. Powder bed quality is discussed in terms of powder bed density and powder bed surface condition. Furthermore, knowledge gaps and research opportunities are presented as concluding remarks.

Keywords

Powder spreading, powder bed fusion, binder jetting

1. Introduction

Powder-bed additive manufacturing, including powder bed fusion and binder jetting, utilizes a heat source or binder to selectively bond particles in a powder bed. Two commonly used powder-bed additive manufacturing systems (i.e., piston-based system and hopper-based system) are shown in Figure 1. For the piston-based system, powder-bed additive manufacturing starts with raising the feedstock platform to provide a certain amount of powder to be spread and lowering the build platform to get ready for receiving the new powder. Then, a spreader carries the powder from the feedstock platform to the build platform and generates a new layer of powder on the powder bed. Finally, the heat source or binder is applied to selectively bond particles on the powder bed. For the hopper-based system, the powder is directly dispensed by a hopper. Then, a spreader moves across the powder bed to spread the powder. Finally, similar to the piston-based system, the heat source or binder is applied to bond particles. In these two systems, although the methods to supply powder to the powder bed are different, the spreading process (i.e., the process that the spreader moves across the powder bed to form a new layer) is similar.

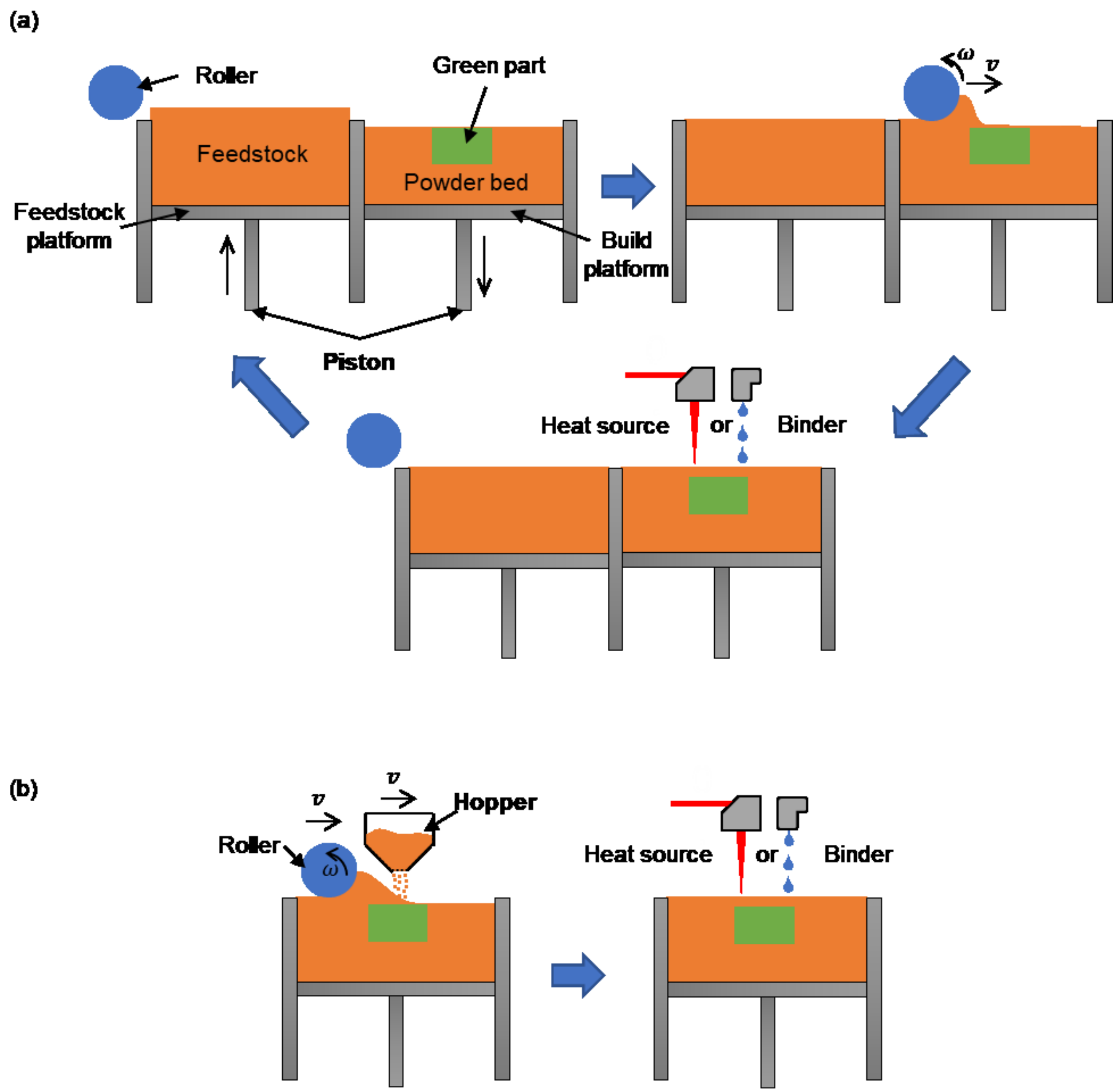

Figure 1. Schematic illustration of two different powder-bed additive manufacturing systems: (a) piston-based system and (b) hopper-based system

Powder spreading has a determinative impact on final part quality because defects (e.g., pores) that occur during powder spreading could affect the subsequent processes. For example, the size, location, and distribution of the defects may affect energy absorption in powder bed fusion [1-5], interaction between binder and powder in binder jetting [6, 7], and densification (e.g., fusion, sintering, and infiltration) in both powder bed fusion and binder jetting [8-11]. Therefore, in order to fabricate high-quality parts by powder-bed additive manufacturing, it is necessary to understand the effects of the influencing factors in powder spreading on powder bed quality.

Several review papers on powder bed fusion [12-17] and binder jetting [18-22] are available in the literature, and some brief discussion of powder spreading has been included in some of these papers. Mostafaei et al. [18], Du et al. [19], Li et al. [20], and Ziaee et al. [21] pointed out that feedstock powder properties (e.g., particle size and morphology) and spreaders (e.g., wiper, counter-rotating roller, and forward-rotating roller) were important factors in powder spreading. Hebert et al. [12] pointed out that layer thickness and spreader traverse speed also affected part quality. However, none of these review papers had powder spreading as its focus. Besides all the aforementioned papers, there is a review paper on methods for achieving high powder bed density [23]. It reviewed the effects of feedstock powder properties and spreaders on powder spreading. However, it did not include the effects of spreading parameters or the interaction effects among feedstock powder properties, spreaders, and spreading parameters. In addition, the different methods for evaluating powder bed density (e.g., with multiple layers or a single layer) could lead to different trends, which has not been discussed in the existing review papers.

This paper will fill these gaps in the literature by presenting a detailed review on powder spreading. It reviews the effects of three groups of influencing factors (spreaders, spreading parameters, and feedstock powder properties) on powder bed quality (powder bed density and powder bed surface condition), and the interactions between these influencing factors. The reported results are tabulated or plotted in an easily digestible form. In addition, this paper discusses knowledge gaps and potential research opportunities.

This review only covers the knowledge about powder spreading that is applicable to both powder bed fusion and binder jetting. It does not include studies on the downstream processes such as melt pool dynamics and binder-powder interaction. These aspects are covered by other review papers [12-22].

2. Evaluation of powder bed quality

In reported studies, powder bed quality has been evaluated in terms of density and surface condition. This section presents their definitions and evaluation methods.

2.1 Powder bed density

2.1.1 Definition

Powder bed density is defined as the packing density of the powder that has been spread on a build platform [19].

2.1.2 Evaluation methods of powder bed density

Powder bed density has been evaluated with either multiple layers of powder [6, 24-44] or a single layer of powder [45-59]. Multi-layer powder bed density is mostly investigated in experimental studies reported in the literature, probably because it is difficult to measure single-layer powder bed density accurately through experiments, especially when layer thickness is very small. Single-layer powder bed density is mostly investigated in numerical studies reported in the literature, probably because the computational cost is high to numerically simulate multiple layers of powder bed.

Table 1 lists several experimental measurement methods for powder bed density. The most straightforward method is to spread multiple layers of powder on a build platform, and then measure the mass and bulk volume of the whole powder bed [24-27].

Table 1. Reported experimental measurement methods for powder bed density

Measurement method	Reference
Measuring the mass and bulk volume of the entire powder bed	[24-27]
Measuring the mass and bulk volume of a fraction of the powder bed:	
• Printed cups or fences	[6, 38-43, 45, 46]
• Inserted tubes	[34-37]
• CT scan of immobilized powder bed (with photopolymer)	[28]
• Reduced build volume	[29-32]
Ex situ measurement with customized spreading setup	[33, 44]

Powder bed density can also be estimated by measuring the mass and bulk volume of a fraction of a powder bed. One such method is printing cups or fences within a powder bed (Figure 2 (a)) [6, 38-43, 45, 46]. In this method, the powder enclosed by the cups or fences can be easily collected. Then, powder bed density can be calculated from the mass and volume of the enclosed powder. This method has also been used to measure single-layer powder bed density by printing fences whose height is equal to layer thickness [46].

Another method is inserting cylindrical or square tubes into a powder bed from the top of the powder bed after it is formed (Figure 2 (b)) [34-37]. After removing powder around the inserted tubes, the powder inside the tubes can be collected. Powder bed density can be calculated from the mass of the powder inside the tubes and the internal volume of the tubes. To minimize their disturbance to the powder bed and therefore achieve high measurement accuracy, the tubes usually have thin walls and sharp edges.

Photopolymerization is another method [28]. By dispensing the liquid photopolymer resin onto an area of a powder bed and curing the photopolymer with light, the portion of the powder bed is immobilized (Figure 2 (c)). By scanning the immobilized powder bed with computed tomography (CT), powder bed density can be calculated using image processing software. Disturbance caused by the resin droplets can be reduced by carefully adjusting the properties (for example, viscosity) of the resin and introducing the resin as close to the powder bed as possible.

Reducing build volume by adding customized feedstock platform and build platform to a printer can simplify powder bed density measurement (Figure 2 (d)) [29-32]. By installing a smaller build platform and feedstock platform on a printer, the amount of powder needed for spreading is reduced, and collecting the powder becomes faster and easier.

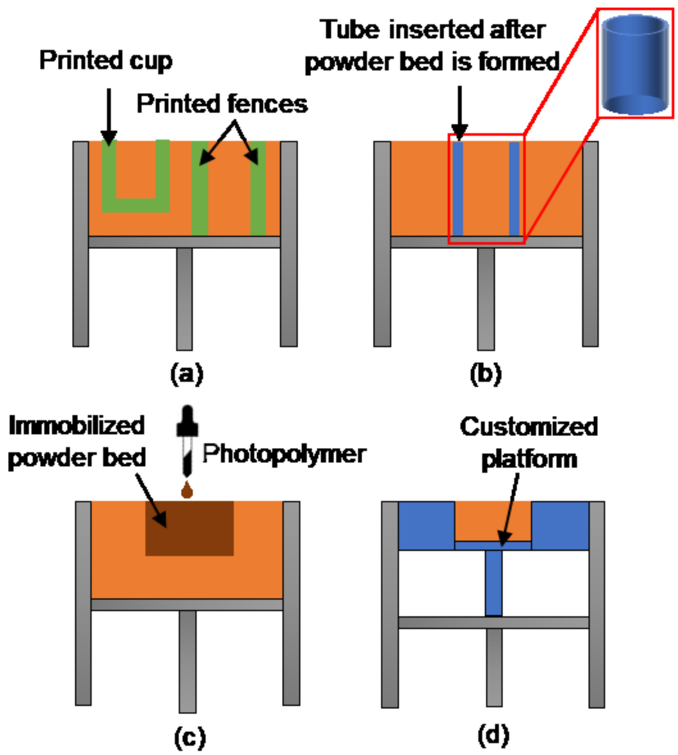

Figure 2. Different powder bed density measurement methods involving a fraction of a powder bed: (a) printing cups or fences, (b) inserting tubes, (c) immobilizing powder bed with photopolymer, and (d) reducing build volume

The aforementioned methods are performed on a printer. Alternatively, a customized powder spreading setup can be used to measure powder bed density ex situ [33, 44]. The customized setup works similarly to a printer but has a much smaller size. Given the dimensions of the build platform, the depth of the powder bed, and the mass of the spread powder, powder bed density can be calculated.

Other than experimentation, powder bed density has also been studied through discrete element method (DEM) simulation. DEM simulation tracks the movement of each individual particle by solving Newton’s equations of translational and rotational motions simultaneously [60]. This way, the location of each particle can be outputted after simulation. Given this information, powder bed density can be calculated [45-59].

2.2 Powder bed surface condition

2.2.1 Definition

In reported studies [36, 38, 45-54, 61-64], powder bed surface condition is evaluated in terms of surface roughness and area of defects. Here, surface roughness is the deviations of powder bed surface from its ideal form along the direction normal to the surface. Area of defects is defined as the area of identifiable defects (e.g., craters and unfilled regions) on the powder bed surface.

2.2.2 Evaluation methods of powder bed surface condition

Surface roughness and area of defects of powder bed can be measured either ex situ or in situ. Table 2 lists characterization instruments used in reported studies [36, 38, 45, 61-64].

Table 2. Characterization instruments for powder bed surface condition

Characterization instrument	Application	Reference
Confocal microscope	Ex situ	[62-64]
CT	Ex situ	[62]
High-speed laser profiler	In situ	[45]
Camera	In situ	[36, 38, 61]

Ex situ measurements are usually carried out using confocal microscope or CT [62-64]. After a powder bed is formed, the build platform is detached from the printer and moved to the measuring instruments (confocal microscope or CT). The surface profile measured with confocal microscope and CT are shown in Figure 3 (a) and Figure 3 (b), respectively.

In situ measurements are conducted directly on a printer, and therefore have minimum disturbance to the powder bed. Additionally, by conducting measurements during the printing, surface condition of each layer can be continuously monitored. A high-speed laser profiler can be used to measure powder bed surface roughness. By mounting the profiler to the spreader, the profiler can scan each layer and generate a series of roughness data as shown in Figure 3 (c) [45]. Cameras have also been used to capture defects on a powder bed surface [36, 38, 61]. One example of the powder bed surface captured with camera is shown in Figure 3 (d) [36]. One drawback of these in situ characterization instruments is that their resolution is usually lower than that of ex situ ones [14].

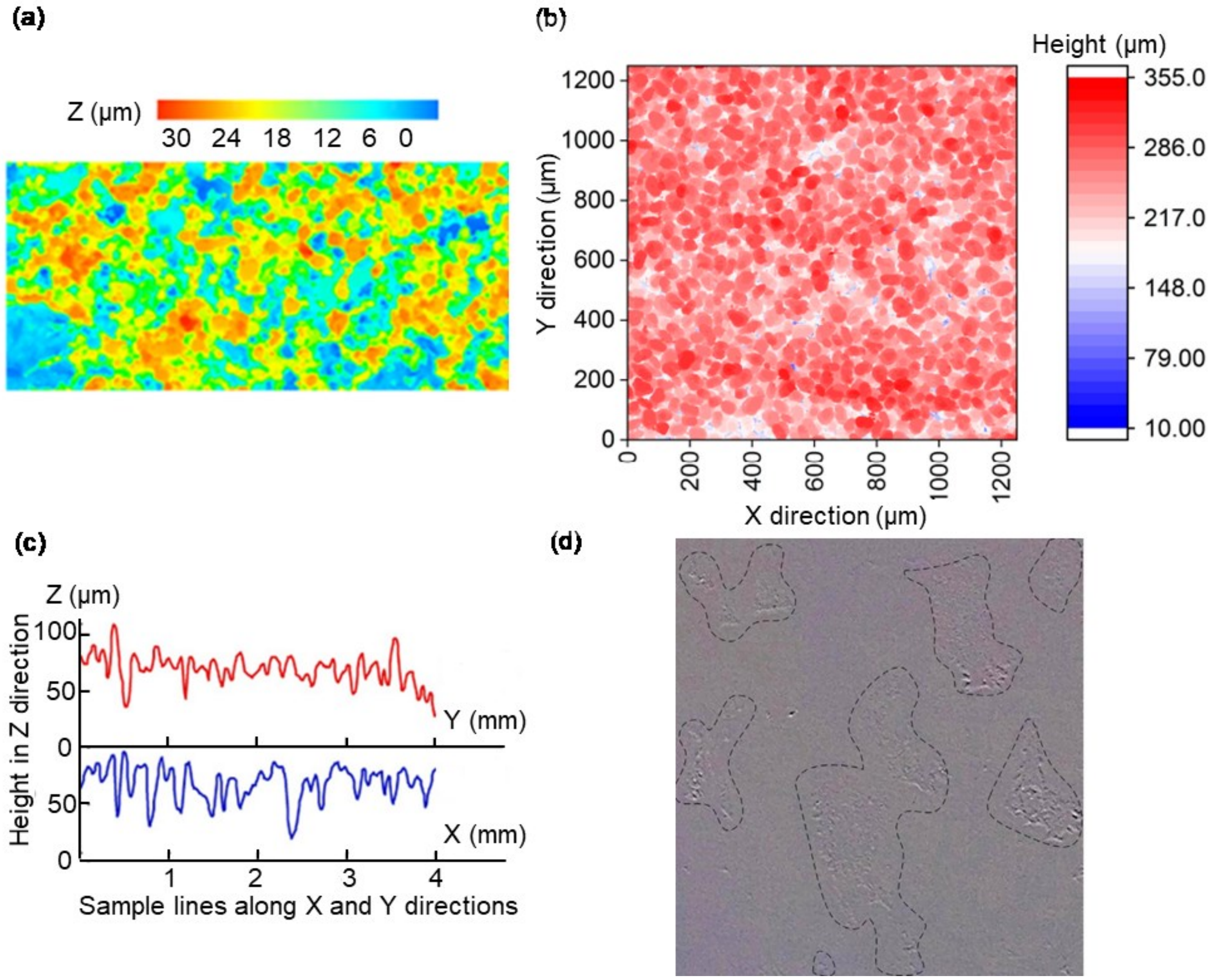

Figure 3. Surface profiles characterized with different instruments: (a) confocal microscope [44], (b) CT [62], (c) high-speed laser profiler [45], and (d) camera [36]

DEM simulation can also be used to study powder bed surface condition. Given the coordinates of each particle, surface roughness can be calculated [49-51]. Similarly, defects (for example, craters and unfilled regions) can be easily caught by simulation [46-49, 52-54].

3. Effects of spreaders

Different types of spreaders have been studied and reported in the literature. Four types of spreaders are discussed in this section, including wiper (sometimes called blade, especially that with a sharp edge), counter-rotating roller, forward-rotating roller, and vibrating spreader.

3.1 Wiper

Figure 4 shows several wiper profiles discussed in the literature [38, 47, 52, 57, 59, 62]. Their effects on powder bed quality have been studied through both experimentation and simulation.

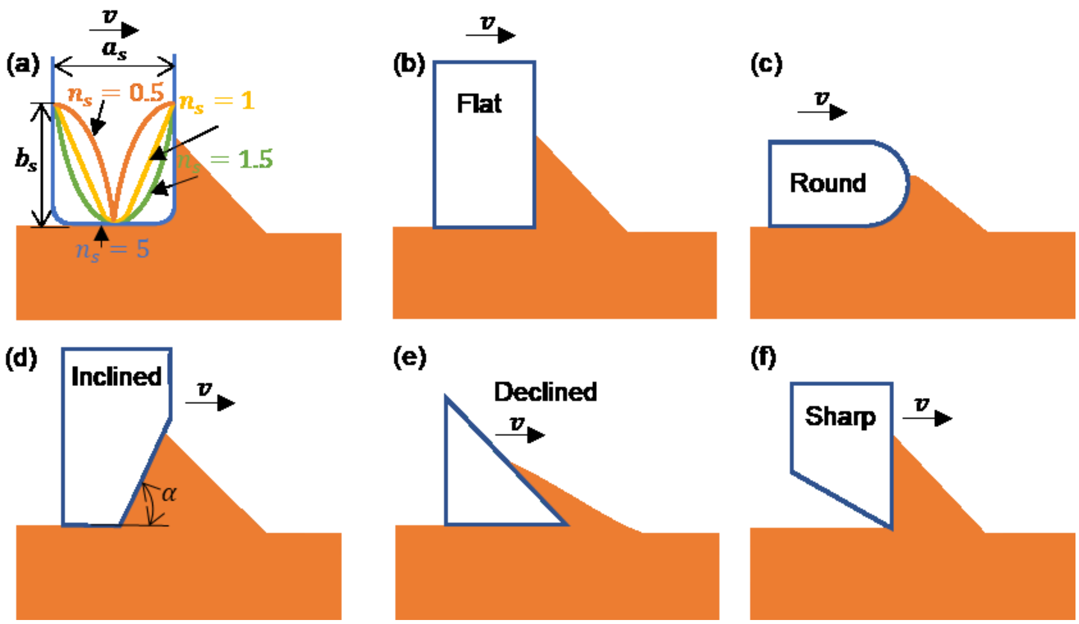

Figure 4. Wipers of different profiles [38, 47, 52, 59, 62]

Haeri et al. [59] conducted a systematic simulation study on the effects of wiper profile. In their study, the wiper profile was governed by the following equation:

$$\left|\frac{x}{a_s}\right|^{n_s} + \left|\frac{z}{b_s}\right|^{n_s} = 1 \quad (1)$$

where x and z are the coordinates of the wiper along the spreading and building directions, respectively. By varying the parameters in the equation (i.e., a_s, b_s, and n_s), a wiper was given different profiles as illustrated in Figure 4 (a). Their simulation results indicated that powder bed density was maximized at n_s of 5 at various a_s and b_s [59].

The experimental comparison between flat (Figure 4 (b)) and round wipers (Figure 4 (c)) by Meyer et al. [38] showed that a round wiper was preferable to a flat wiper to achieve a higher density and a smaller density variation between prints. The higher density achieved with the round wiper was also observed in the simulation work by Wang et al. [52]. Besides the round and flat wipers, they also compared the inclined (Figure 4 (d)) and declined wipers (Figure 4 (e)): The round wiper achieved the highest density, the inclined one achieved a density higher than the flat one, and the flat one had similar performance to the declined one.

As for the effects of wiper profile on powder bed surface roughness, the experimental work by Beitz et al. [62] showed that a flat wiper was more favorable to decrease surface roughness than a sharp wiper (Figure 4 (f)) and a wiper with round tip (Figure 4 (a) at n_s of 1.5). This was because the greater contact zone between the flat wiper and the powder provided more time for the particles to rearrange.

Besides its profile, dimensions of a wiper also affect powder bed quality. The simulation by Haeri et al. [59] demonstrated that a wider (i.e., larger a_s) and shorter (i.e., smaller b_s) wiper (Figure 4 (a)) generated higher powder bed density. However, according to the simulation by Maximenko et al. [57], a wide wiper produced much more disturbance in the powder bed than a narrow wiper, and distorted the printed layers. The simulation work by Yao et al. [47] showed that the performance of an inclined wiper was related to the wiper angle (α in Figure 4 (d)): the powder bed density increased as the wiper angle increased to 15° and then decreased as the wiper angle increased beyond 15°.

It is worth noting that the wiper type could have interaction effects with other parameters, for example, traverse speed. According to the experimental work by Meyer et al. [38], at a low traverse speed, the round wipers achieved a more uniform powder bed surface than flat ones. However, at a high traverse speed, the effects of the wiper type (round versus flat) were the opposite, i.e., the flat ones achieved a more uniform powder bed surface.

The above-reviewed studies on wiper spreading are summarized in Table 3.

Table 3. Summary of reported studies on wiper spreading

Conclusion	Material	Reference
In terms of improving powder bed density, the efficiency of the wipers of different profiles followed the following order: round > inclined > flat ≈ declined	Polyamide and nickel alloy	[38, 52]
In terms of improving powder bed surface condition, a flat wiper was better than a sharp wiper and a wiper with round tip (Figure 4 (a) at n_s of 1.5)	Polyamide	[62]
A wider and shorter wiper generated higher powder bed density	Polyether ether ketone (PEEK)	[59]
For inclined wiper, highest powder bed density was achieved at the wiper angle (α in Figure 4 (d)) of 15°	Stainless steel	[47]
Wiper type could have interaction effects with other parameters	Polyamide	[38]

3.2 Counter-rotating roller

The simulation studies by Haeri et al. [50], Wang et al. [51], and Shaheen et al. [53] compared a counter-rotating roller (illustrated in Figure 5) with a wiper (illustrated in Figure 4) and concluded that a counter-rotating roller outperformed a wiper in terms of powder bed density. This was mainly because the counter-rotating motion of the roller could facilitate the movement of particles. A simulation study by Nan et al. [48] showed that, when being spread with a counter-rotating roller, some particles were lifted by the roller before being incorporated into the powder bed. This way, particles were circulating in the heap region (illustrated in Figure 5), and thus, had more time to get rearranged, resulting in higher powder bed density.

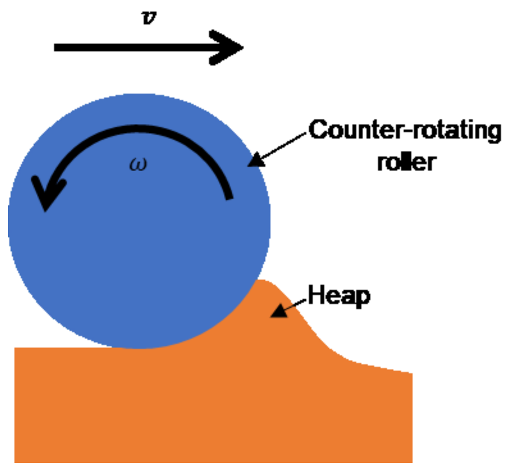

Figure 5. Counter-rotating roller

The design of the roller has been proved to be able to affect powder bed density. The simulation work by Zhang et al. [54] showed that the diameter of a roller affected powder bed density. By increasing the roller diameter, a higher powder bed density was achieved. The experimental study by Oropeza et al. [44] showed that surface texture of a counter-rotating roller also affected powder bed density. In this study, roller with different surface textures were used for powder spreading, and the smooth roller resulted in the highest powder bed density while the roller with diamond knurl resulted in the lowest powder bed density under the same spreading condition.

According to the simulation work by Wang et al. [52], spreader type (a counter-rotating roller versus an inclined wiper) and layer thickness had interaction effects on powder bed density. At a relatively small layer thickness (70 μm), the powder bed density achieved by the counter-rotating roller was lower than that achieved by the inclined wiper. However, at a larger layer thickness (90 μm), the powder bed density achieved by the counter-rotating roller was higher than that achieved by the inclined wiper.

The above-reviewed studies on counter-rotating roller spreading are summarized in Table 4.

Table 4. Summary of reported studies on counter-rotating roller spreading

Conclusion	Material	Reference
In terms of improving powder bed density, a counter-rotating roller outperformed a wiper	PEEK, nickel alloy, and titanium alloy	[50, 51, 53]
Roller with larger diameter led to higher powder bed density	Alumina	[54]
Smooth roller led to higher powder bed density than textured roller	Alumina	[44]
Spreader type (a counter-rotating roller versus an inclined wiper) and layer thickness had interaction effects on powder bed density	Nickel alloy	[52]

3.3 Forward-rotating roller

A forward-rotating roller (Figure 6) rotates in the opposite direction to a counter-rotating roller (Figure 5). According to the experimental studies in the literature [24, 26, 33, 37, 42, 65], compared with a counter-rotating roller or wiper, a forward-rotating roller significantly improved the powder bed density. This was because the forward-rotating motion of the roller griped and dragged powder into the powder bed and thus increased the powder bed density [42]. The powder bed density improvement achieved by using a forward-rotating roller was found to be related to other parameters, for example, powder flowability. According to the experimental study by Yoo et al. [65], a forward-rotating roller only improved the powder bed density of the finest powder they used. In addition, according to the experimental study by Ziaee et al. [37], compared with a wiper, a forward-rotating roller was able to create thinner layers and better align the asymmetric particles.

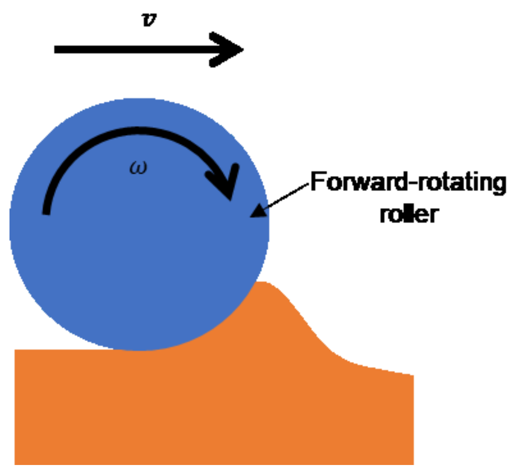

Figure 6. Forward-rotating roller

Although using a forward-rotating roller can improve powder bed density, it can also negatively affect powder spreading. Firstly, after the roller passes over, the powder bed may spring back due to the release of the elastic energy stored in the powder bed [37]. This phenomenon can result in an uneven surface and an inaccurate layer thickness. Secondly, due to the large shear force from a forward-rotating roller, the powder bed surface may be deteriorated [66] and the printed parts beneath the new layer can be shifted [42]. Thirdly, due to the large compaction force, some particles tend to adhere to the roller, which can result in craters on the powder bed surface [42].

These undesired phenomena can be alleviated or avoided by reducing the amount of powder in front of the forward-rotating roller during spreading [42]. This can be realized by adding a pre-spreading step with a wiper or counter-rotating roller before the final spreading step with the forward-rotating roller [26, 33, 42, 65]. Pre-spreading and final spreading can be done either in separate traverses or within a single traverse. As shown in Figure 7 (a), when pre-spreading and final spreading are performed in separate traverses, the amount of powder in front of the forward-rotating roller can be controlled by adjusting the height of the build platform after pre-spreading and before final spreading. Instead of performing pre-spreading and final spreading in separate traverses, by installing a wiper or counter-rotating roller ahead of the forward-rotating roller (shown in Figure 7 (b)), both pre-spreading and final spreading can be finished within a single traverse. This way, the amount of powder in front of the forward-rotating roller can be controlled by adjusting the height of the wiper or counter-rotating roller.

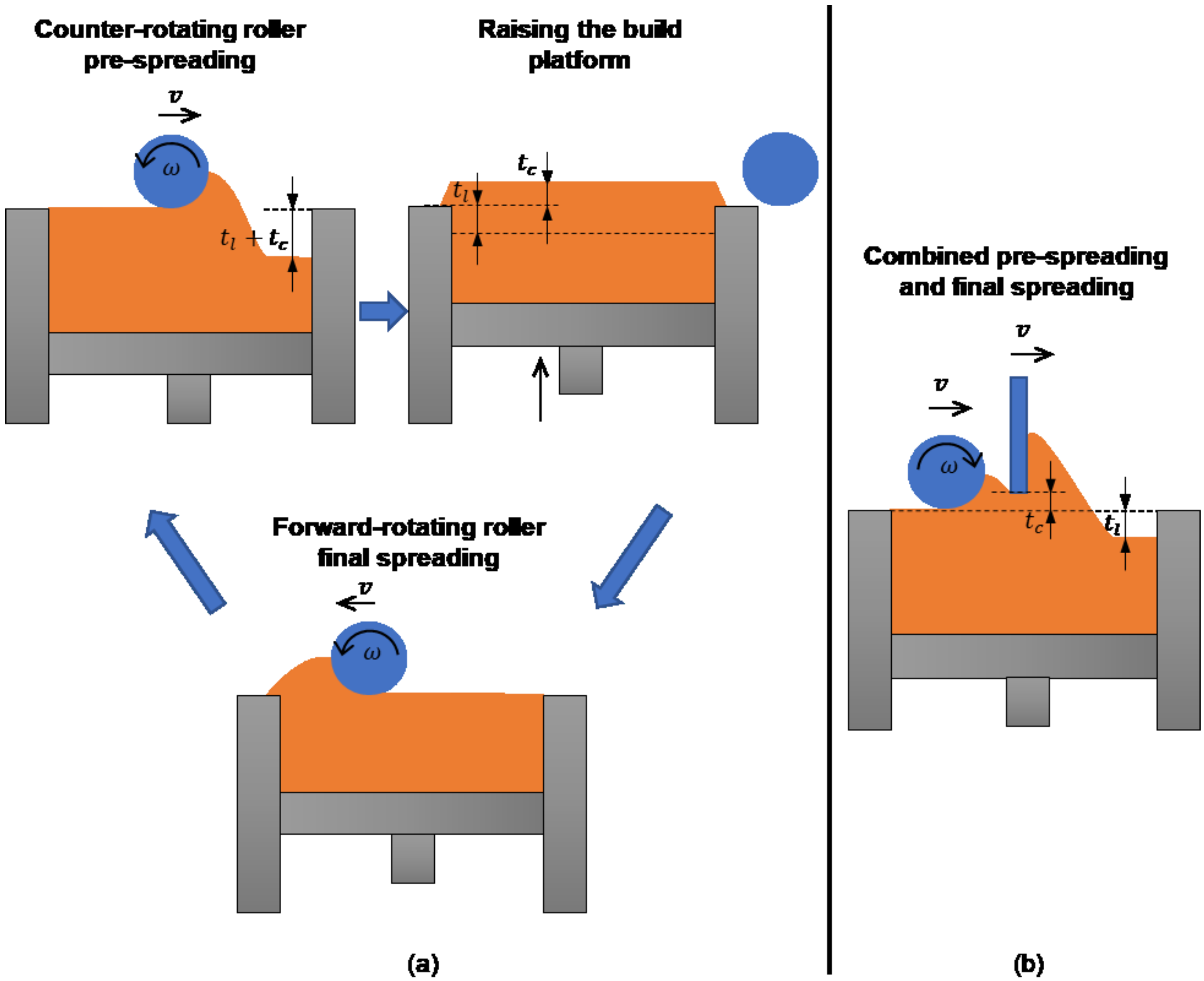

Figure 7. Schematic illustration of the two methods to conduct pre-spreading and final spreading (t_l means layer thickness and t_c means compaction thickness): (a) in separate traverses and (b) within a single traverse

The above-reviewed studies on forward-rotating roller spreading are summarized in Table 5.

Table 5. Summary of reported studies on forward-rotating roller spreading

Conclusion	Material	Reference
Forward-rotating roller led to higher powder bed density than wiper and counter-rotating roller	Alumina, plaster, stainless steel, polyamide, and mixture of polycaprolactone and demineralized bone	[24, 26, 33, 37, 42, 65]
Forward-rotating roller could have negative effects (e.g., uneven surface, craters, and shifted part) on powder bed quality	Zirconia, polyamide, and mixture of demineralized bone and polycaprolactone	[37, 42, 66]
Adding a pre-spreading step (using wiper or counter-rotating roller) before final spreading with forward-rotating roller was beneficial for improving powder bed quality	Plaster, alumina, and polyamide	[26, 33, 42, 65]

3.4 Vibrating spreaders

A vibrating spreader has also been used to form the powder bed [24, 34, 36, 67, 68]. Similar to a forward-rotating roller, a vibrating spreader can not only spread powder but also compact the powder bed to higher density as the energy pulses can excite particles to rearrange themselves to fill voids in a powder bed [69].

A vibrating roller was applied to powder spreading by Lee [24]. In his experiments, three different vibration patterns (i.e., longitudinal, traverse, and vertical vibration patterns as shown in Figure 8 (a)) were added to a counter-rotating roller and the resultant powder beds were compared. All the vibration patterns improved powder bed density, but to different extents: longitudinal, traverse, and vertical vibration patterns improved powder bed density by less than 8%, up to 14.2%, and up to 36.2%, respectively.

Seluga [34] modified a printer to explore a new vibration pattern called rotational vibration (shown in Figure 8 (a)). The experimental results indicated that the powder bed density achieved with rotational vibration was significantly higher than that without vibration or with diagonal vibration (i.e., combining the longitudinal vibration and vertical vibration).

Gregorski [67] experimentally tested a different vibrating spreader. As shown in Figure 8 (b), a vibrating wedge, which had a flat bottom surface, was employed to densify the powder bed after a layer of powder was pre-spread by a counter-rotating roller. The results indicated that both investigated vibration patterns (i.e., longitudinal and vertical vibration patterns) improved powder bed density. However, different from Lee's work [24], the experimental results in this paper indicated that longitudinal vibration produced a denser powder bed than vertical vibration when a similar vibrating frequency was used. However, no explanation was given for this conclusion.

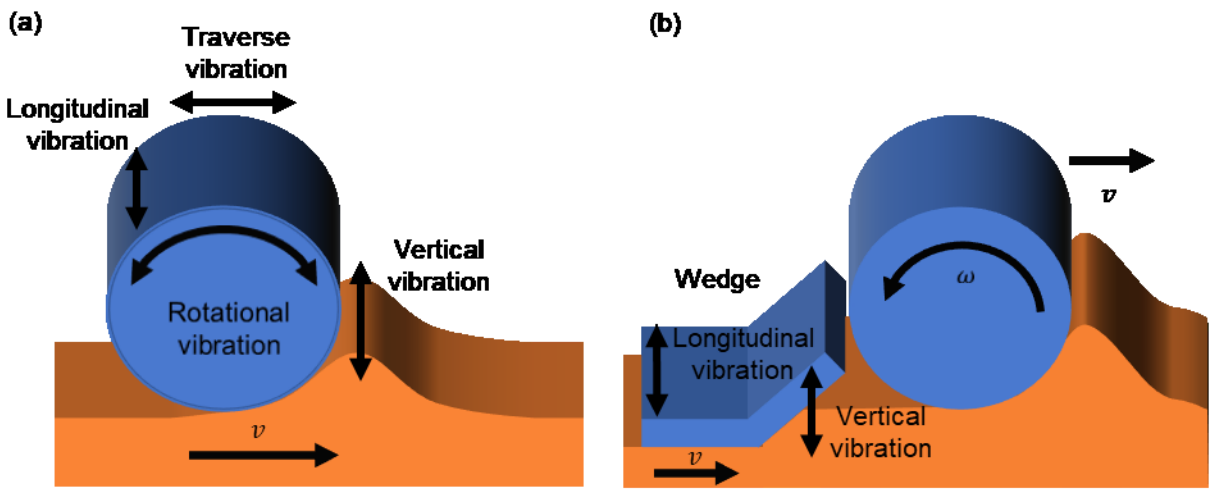

Figure 8. Vibrating spreaders: (a) a vibrating roller and (b) combination of a counter-rotating roller and a vibrating wedge

The extent of powder bed density improvement achieved by the vibration patterns reviewed above are compared and summarized in Table 6.

Table 6. Summary of reported studies on the effects of vibration patterns on powder bed density

Spreading method	Extent of powder bed density improvement	Material	Reference
Counter-rotating roller spreading	Vertical vibration > traverse vibration > longitudinal vibration > no vibration	Alumina	[24]
Counter-rotating roller spreading	Rotational vibration > diagonal vibration or no vibration	Stainless steel	[34]
Counter-rotating roller pre-spreading and wedge final spreading	Longitudinal vibration > vertical vibration > no vibration	Stainless steel	[67]

4. Effects of spreading parameters

This section discusses the effects of some critical spreading parameters. Sections 4.1 and 4.2 are about spreading parameters applicable to different spreaders. Sections 4.3, 4.4 and 4.5 are about spreading parameters associated with a counter-rotating roller, a forward-rotating roller, and a vibrating spreader, respectively.

4.1 Layer thickness

Layer thickness is one of the most important spreading parameters, and its effects have been extensively studied through both experimentation and simulation. Both multi-layer and single-layer powder bed densities (discussed in Section 2.1.2) have been used to evaluate the performance of different layer thickness values in the literature. In this section, these two powder bed density measures are intentionally distinguished because the effects of layer thickness are found dependent on the measures used to evaluate powder bed density.

All the reviewed experimental studies on the effects of layer thickness on multi-layer powder bed density are plotted in Figure 9. Because different values of particle size and layer thickness have been used in these reported studies, to make the results more comparable, all the layer thickness values are normalized by the particle size. According to the figure, when the layer thickness is close to particle size (as in the studies by Cao et al [36] and Ziaee et al. [37]), powder bed density increases with increasing layer thickness. This was because large particles were dragged by the spreader, and thus, caused defects and decreased powder bed density [36, 37]. When the layer thickness is larger than twice particle size (as in the papers by Lee [24], Budding et al. [33], and Cao et al. [36]), powder bed density decreases with increasing layer thickness. No explanation has been provided for such a trend yet.

It is worth noting that, when measuring multi-layer powder bed density, some powder in the new layer could be mixed with that in the previous layer. This powder spreading scenario could be different from that when the new layer is spread on a previously printed layer, depending on the geometry. Therefore, any knowledge about multi-layer powder bed density should be used with caution.

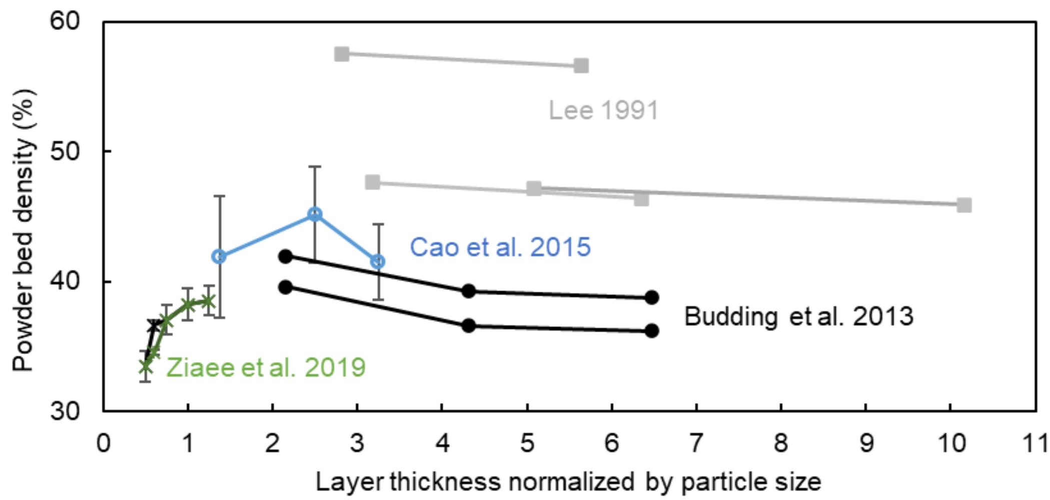

Figure 9. Experimental results regarding the effects of layer thickness on multi-layer powder bed density [24, 33, 36, 37]

Different from the divergent results on multi-layer powder bed density, nearly all the studies (with either experimental or numerical methods) that evaluated single-layer powder bed density showed that it monotonically increased with increasing layer thickness (as shown in Figure 10. [46-49, 55, 56]. This monotonic increasing trend holds over a wide range of layer thickness normalized by the particle size. This trend was explained differently in different studies. Chen et al. [46] claimed the significant static and dynamic wall effects were the dominant cause for a lower powder bed density at a smaller layer thickness. Meier et al. [49] attributed the higher density at a larger layer thickness to the combination of more space for particle rearrangement and decreased static wall effect. Fouda et al. [55] stated that a particle assembly was dilated when subject to shear force because the particle assembly must expand by creating more void spaces to allow the particles to pass by each other and overcome the particle interlocking. This dilation was more serious when layer thickness was small, which resulted in a low powder bed density.

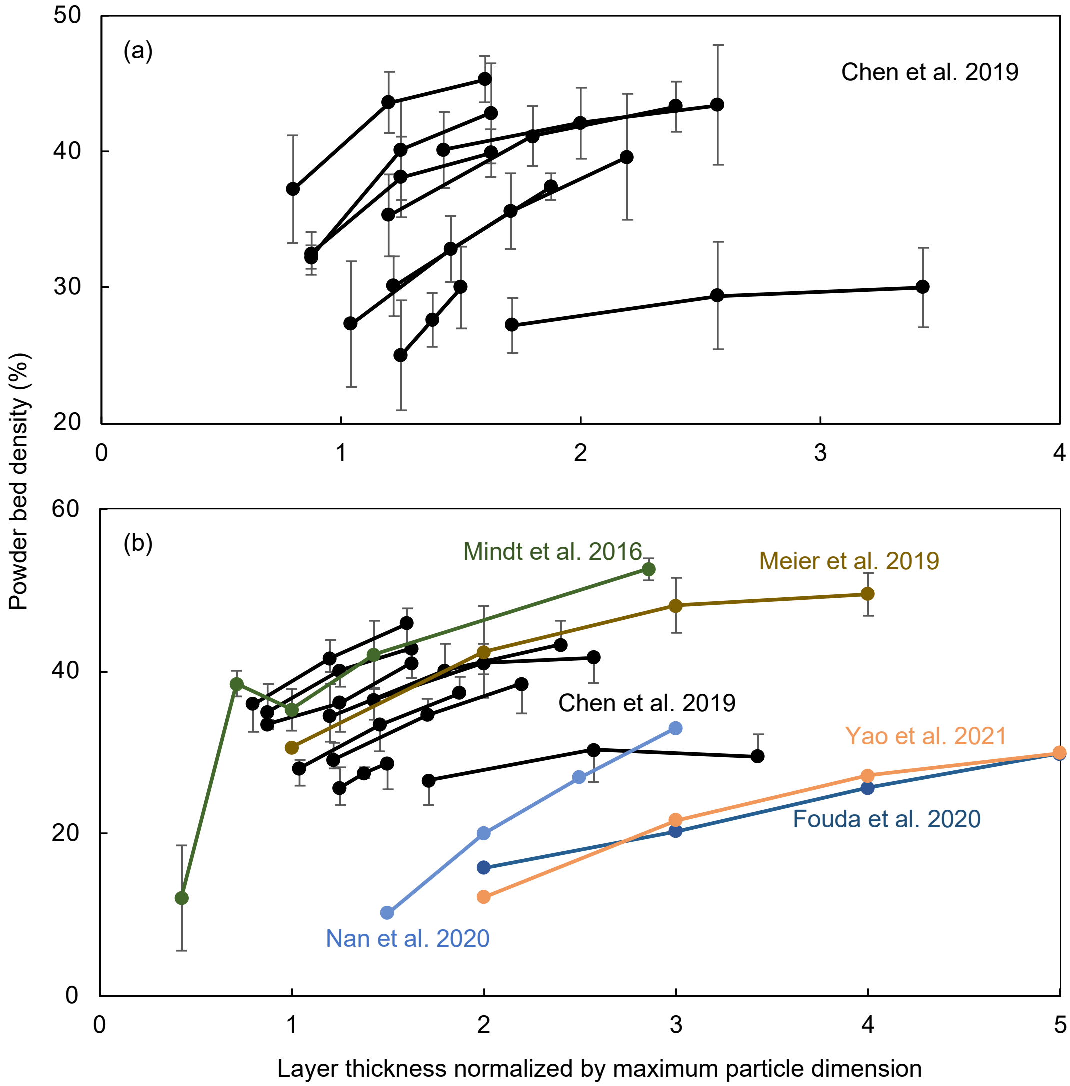

Figure 10. Reported results regarding the effects of layer thickness on single-layer powder bed density: (a) experimental studies [46] and (b) simulation studies [46-49, 55, 56]

As for the effects of layer thickness on powder bed surface condition, all the reported studies indicated that a small layer thickness deteriorated powder bed surface condition. The experimental work by Cao et al. [36] showed that, when layer thickness was decreased, the fraction of cavity area on the powder bed surface increased. The simulation work by Meier et al. [49] indicated that, when the layer thickness was only slightly above the maximum particle diameter, the powder bed was discontinuous. A continuous powder bed was achieved by using a layer thickness that was twice the maximum particle diameter or above. By further increasing layer thickness, the surface was only slightly improved. Similarly, the simulation work by Haeri et al. [50] also showed that the surface roughness was slightly higher when small layer thickness was used.

The reviewed studies on the effects of layer thickness on both powder bed quality are summarized in Table 7.

Table 7. Summary of reported studies on the effects of layer thickness on powder bed quality

Conclusion	Material	Reference
Multi-layer powder bed density decreased with increasing layer thickness	Plaster, alumina, and stainless steel	[24, 33]
Multi-layer powder bed density increased and then decreased with increasing layer thickness	Mixture of urea formaldehyde and alumina	[36]
Multi-layer powder bed density increased with increasing layer thickness	Mixture of demineralized bone and polycaprolactone	[37]
Single-layer powder bed density increased with increasing layer thickness	Stainless steel and titanium alloy	[46-49, 55, 56]
Powder bed surface condition was better at larger layer thickness	PEEK, titanium alloy, and mixture of urea formaldehyde and alumina	[36, 49, 50]

4.2 Spreader traverse speed

Spreader traverse speed is another important spreading parameter that has been extensively studied and its effects are reviewed in this section. Figure 11 summarizes reported experimental and simulation studies on the effects of spreader traverse speed on powder bed density. In most of the studies, increasing traverse speed lowered powder bed density [45, 47, 49, 50, 54, 55, 64]. One explanation for this trend is related to post-flow. According to the simulation study by Meier et al. [49], when traverse speed was high, particles that had been deposited on the powder bed continued flowing for a distance due to their large momentum. This post-flow phenomenon caused an uneven surface, and even a discontinuous layer [45, 49, 55]. Another explanation is the presence of force arches. According to the simulation study by Chen et al. [45], more force arches formed at a higher traverse speed, which decreased powder bed density.

An opposite trend is also reported in the literature. As shown in Figure 11 (a), the experimental work by Seluga [34] showed a slightly increased powder bed density when traverse speed was increased in the low speed regime (below 12 mm/s). As stated by the author, further experiments with an expanded range of roller traverse speed were needed to verify this finding.

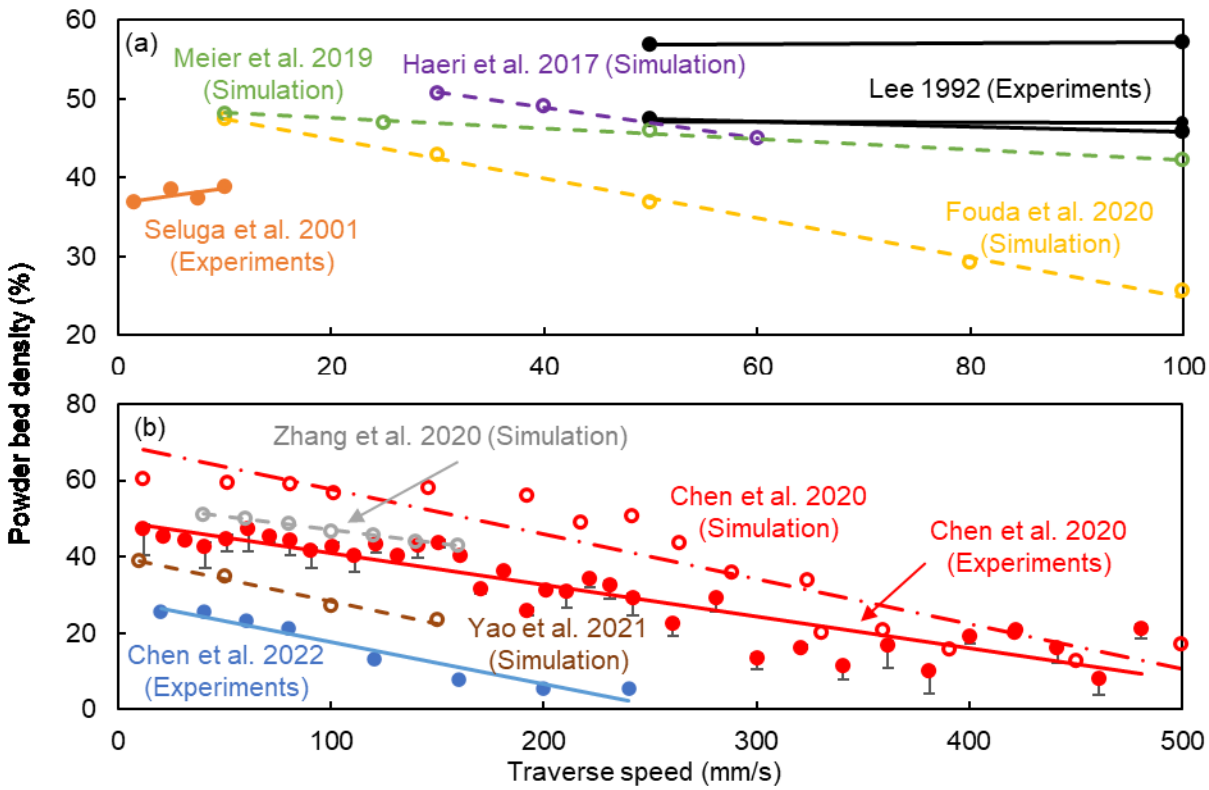

Figure 11. Powder bed density as a function of spreader traverse speed: (a) in the low speed regime [24, 34, 49, 50, 55] and (b) in the high speed regime [45, 47, 54, 64] (solid and hollow dots indicate experimentation and simulation, respectively)

The different materials used in these studies could be a possible cause of the inconsistent results. Lee's experiments [24] showed that the effects of traverse speed were different for different materials: a lower traverse speed resulted in a higher powder bed density for alumina, but lower powder bed density for steel.

Different from the divergent trends observed in powder bed density, all the studies (including both simulation [49, 50, 70] and experimental studies [45]) on powder bed surface condition concluded that a high spreader traverse speed deteriorated powder bed surface condition.

The aforementioned studies on the effects of spreader traverse speed on powder bed quality are summarized in Table 8.

Table 8. Summary of reported studies on the effects of spreader traverse speed on powder bed quality

Conclusion	Material	Reference
Powder bed density decreased with increasing spreader traverse speed	Titanium alloy, nickel alloy, stainless steel, PEEK, and alumina	[24, 45, 47, 49, 50, 54, 55, 64]
Powder bed density increased with increasing spreader traverse speed	Stainless steel and alumina	[24, 34]
Powder bed surface condition was poorer at high spreader traverse speed	Titanium alloy, stainless steel, polyamide, and PEEK	[45, 49, 50, 70]

4.3 Rotation speed of a counter-rotating roller

Counter-rotating roller is a widely used spreader for powder-bed additive manufacturing, and the rotation speed of a counter-rotating roller significantly affects the powder bed quality. The effects of rotation speed are reviewed in this section.

As summarized in Table 9, most of the reviewed studies indicated that powder bed density decreased with increasing rotation speed [24, 34, 48]. This decreasing trend was explained by Nan et al. [48] through simulation: when the roller was rotating fast, the severe circulation of particles in the powder heap in front of the roller prevented particles being deposited on the powder bed. Distinct from the decreasing trend, the simulation work by Zhang et al. [54] showed that powder bed density was not significantly affected by rotation speed. No explanation was provided for this trend.

Rotation speed also affects powder bed surface condition, but it is still unclear how the surface condition changes with rotation speed. As shown in Table 9, the experimental work by Seluga [34] indicated that surface roughness increased as rotation speed decreased, and the experimental work by Meyer et al. [38] indicated that the effects of rotation speed were different for different powders.

Instead of studying the effects of roller traverse and rotation speeds separately, Meyer et al. [38] studied the effects of total surface velocity (considering both traverse and rotation) through experiments. They found that this total surface velocity was more closely related to powder bed density than the traverse or rotation speed individually.

The aforementioned studies on the effects of rotation speed on powder bed quality are summarized in Table 9.

Table 9. Summary of reported studies on the effects of rotation speed on powder bed quality

Conclusion	Material	Reference
Powder bed density decreased with increasing rotation speed	Stainless steel and alumina	[24, 34, 48]
Powder bed density was not significantly affected by rotation speed	Alumina	[54]
Powder bed surface condition was poorer at high rotation speed	Stainless steel	[34]
The effects of rotation speed on powder bed surface condition were different for different powders	Polyamide	[38]
Total surface velocity was a better predictor for powder bed density than roller traverse or rotation speed separately	Polyamide	[38]

4.4 Compaction ratio of a forward-rotating roller

As discussed in Section 3.3, to alleviate or avoid the negative effects of a forward-rotating roller, the spreading process is usually completed in two steps: pre-spreading with a wiper or counter-rotating roller and final spreading with a forward-rotating roller. According to Moghadasi et al. [26], for such a two-step spreading process, powder bed density was governed by a factor called compaction ratio (r_c) defined as follows:

$$r_c = \frac{t_l + t_c}{t_l} \quad (2)$$

A similar compaction factor was studied by Niino et al. [42]. They found that powder bed density increased with increasing compaction factor. They also reported that defects (e.g., craters) would appear if the compaction factor went beyond a certain threshold.

The above-reviewed studies on the effects of compaction ratio on powder bed quality are summarized in Table 10.

Table 10. Summary of reported studies on the effects of compaction ratio on powder bed quality

Conclusion	**Material**	**Reference**
Higher compaction ratio led to higher powder bed density	Alumina and polyamide	[26, 42]
High compaction ratio led to defects	Polyamide	[42]

4.5 Vibration frequency and amplitude of vibrating spreaders

For vibrating spreaders, vibration frequency and amplitude are two important parameters that affect powder bed density.

For vertical vibration, according to the experimental study by Lee [24], increasing vibration amplitude improved powder bed density because more energy was put into powder compaction. Using a frequency close to the resonance frequency of the powder bed also helped to improve powder bed density.

For longitudinal vibration, according to the experimental study by Gregorski [67], powder bed density increased with both increasing amplitude and increasing vibration frequency. Compared with the amplitude, the frequency had a stronger effect.

For rotational vibration, according to the experimental study by Seluga [34], vibration frequency should be carefully selected so that total steady state surface velocity (sum of traverse speed and roller circumferential velocity) was always positive. Otherwise, when the vibration frequency was high, the total steady state surface velocity was negative, and ridges formed on the powder bed surface.

The above-reviewed studies on the effects of vibration frequency and amplitude on powder bed quality are summarized in Table 11.

Table 11. Summary of reported studies on the effects of vibration frequency and amplitude on powder bed quality

Conclusion	Material	Reference
For vertical vibration, large amplitude and frequency close to resonance frequency led to high powder bed density	Alumina	[24]
For longitudinal vibration, large amplitude and high frequency led to high powder bed density	Stainless steel	[67]
For rotational vibration, a negative total steady state surface velocity led to ridges	Stainless steel	[34]

5. Effects of feedstock powder properties

5.1 Particle size

The effects of particle size on powder bed density have been experimentally studied and the results are summarized in Figure 12. It is noted that powder bed density is usually low for fine powder [29, 43, 47, 71] because the interparticle cohesion (e.g., van der Waals force, electrostatic interaction, hydrogen bonding, and capillary bridging) between fine particles can be comparable to or even greater than gravity [19, 72, 73]. Therefore, due to the effects of the strong cohesion, fine powder has a poor flowability, and thus is hard to rearrange during spreading [74]. For coarse powder, further increasing particle size will not increase powder bed density much [27, 43, 47, 71] or can even decrease powder bed density [43, 47, 73]. The decreased powder bed density at an increased particle size was explained by a stronger static wall effect and more force arches by Yao et al. [47].

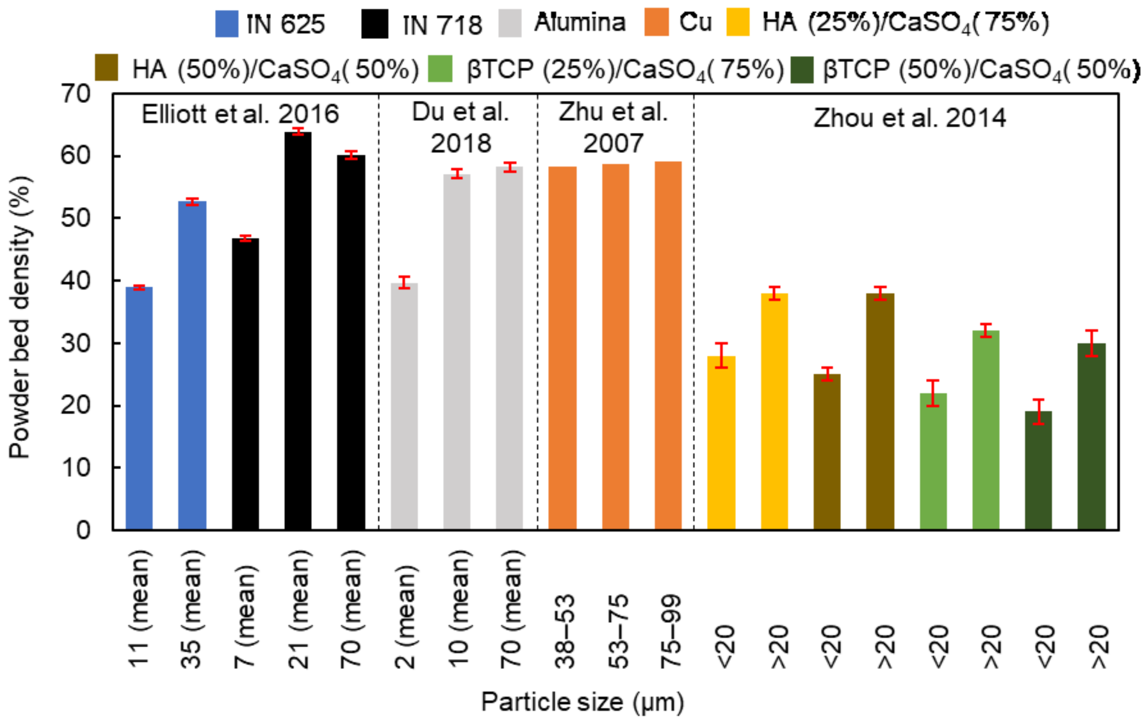

Figure 12. Reported effects of particle size (mean size or size range) on powder bed density for different materials including Inconel (IN), alumina, copper (Cu), and hydroxyapatite (HA) and beta-tricalcium phosphate (βTCP) mixtures (all composition percentages are by weight) [27, 29, 43, 71]

Besides powder bed density, particle size also has a significant influence on powder bed surface condition. Fine powder tends to agglomerate and deteriorate powder bed surface condition. To find the most suitable particle size range for a smooth powder bed, Spath et al. [61] spread spray-dried hydroxyapatite granules of different sizes using a counter-rotating roller. The powder bed surface for each spreading was captured by a camera. The powder bed surface was uneven and had cavities using granules smaller than 45 μm. The powder bed surface was rough but showed no defects when the granule size was 45–63 μm. The powder bed surface became smooth and homogeneous when the granule size was larger than 63 μm.

The above-reviewed studies on the effects of particle size on powder bed quality are summarized in Table 12.

Table 12. Summary of reported studies on the effects of particle size on powder bed quality

Conclusion	Material	Reference
Powder bed density was low for fine powder	Alumina, calcium phosphate, nickel alloy, copper, and stainless steel	[27, 29, 43, 47, 71]
Powder bed density was not significantly affected by particle size for coarse powder	Alumina, nickel alloy, copper, and stainless steel	[27, 43, 47, 71]
Powder bed density decreased with increasing particle size when particles were larger than a threshold	Stainless steel and nickel alloy	[43, 47, 73]
Powder bed surface was smoother for coarser powder	Hydroxyapatite	[61]

5.2 Particle size distribution

Research has proved that particle size distribution has a strong influence on powder packing density [75-77]. This finding also applies to powder spreading in powder-bed additive manufacturing [39, 40, 58, 67, 71, 78-81]. Feedstock powder for additive manufacturing can be either monomodal or multimodal. Compared with monomodal powder, multimodal powder can achieve a higher density because fine particles can fill the voids between coarse particles if the sizes and fractions of fine and coarse particles are carefully chosen [39, 67, 71, 78-81]. Du et al. [80] employed a powder mixing model to predict the optimal mixing ratio for powders with different particle sizes. To verify the prediction, powder spreading experiments were conducted using a customized device. The results indicated that powder bed density was improved by mixing powders of different sizes following the optimal mixing ratios predicted by the model.

As for monomodal powder, a wider particle size distribution is preferable to achieve a higher packing density. Liu et al. [40] experimentally compared powder bed density achieved with two stainless steel 316L powders that have similar mean particle sizes but different widths of particle size distribution. The powder with a wider particle size distribution led to a higher powder bed density. This higher density for the wider distribution could be explained by the more significant filling effect of fine particles. When the particle size distribution was wide, fine particles were small enough to fill the voids between coarse particles. While the distribution was narrow, the sizes of fine and coarse particles were close, and thus fine particles were too large to fill the voids between coarse particles.

Simulation has been used to study the effects of particle size distribution since it is easier to generate powders of different distributions through simulation. The simulation work by Lee et al. [58] showed that powder bed density monotonically increased when the particle size distribution changed from negatively skewed distribution to equal-sized (monodisperse), to Gaussian, and to positively skewed distribution. Here, the negatively and positively skewed distributions stand for distributions that have a higher fraction of coarse and fine particles than the Gaussian distribution, respectively.

It is worth mentioning that using multimodal powder can also negatively impact powder bed density. For example, according to the study by Du et al. [80], mixing 10 μm and 2 μm alumina powders decreased powder bed density. In addition, in presence of both fine and coarse particles, segregation might occur and could deteriorate powder bed homogeneity [49, 82]. Therefore, although using multimodal powder or powder that has a wide distribution can improve powder bed density, the effects of particle segregation on powder bed quality should be considered.

The above-reviewed studies on the effects of particle size distribution on powder bed quality are summarized in Table 13.

Table 13. Summary of reported studies on the effects of particle size distribution on powder bed quality

Conclusion	Material	Reference
By selecting proper size and mixing ratio for powders of different sizes, multimodal powder improved powder bed density	Copper, stainless steel, aluminum alloy, nickel alloy, and alumina	[39, 67, 71, 78-81]
Multimodal powder decreased powder bed density when the size and mixing ratio were not properly selected	Titanium alloy, stainless steel, and alumina	[49, 80, 82]
Monomodal powder that had a wider distribution led to higher powder bed density	Stainless steel	[40]

5.3 Particle shape

Particle shape of feedstock powder is also a factor that can affect powder bed density. Haeri et al. [50] simulated powder bed density and powder bed surface roughness using particles of different aspect ratios. In wiper spreading, the highest powder bed density was achieved at the aspect ratio of 1 (i.e., spherical particle shape), and the surface roughness monotonically increased with increasing aspect ratio. When a counter-rotating roller was used to spread powder, the highest powder bed density was observed at the aspect ratio of 1.5, and the surface roughness followed the same trend as in wiper spreading. The different spreading results obtained with the wiper and roller can be explained from two aspects. Firstly, when well aligned, ellipsoidal particles (at the aspect ratio of 1.5) can achieve a higher powder bed density than spherical particles [83]. Secondly, a counter-rotating roller is more efficient in rearranging and aligning particles than a wiper due to the larger contact area between the counter-rotating roller and particles [50]. Thus, ellipsoidal particles can achieve higher powder bed density in counter-rotating roller spreading while spherical particles are more suitable for wiper spreading.

The spreading of the mixture of spherical particles and fibers was investigated by Chen et al. [63, 84]. The simulation results showed that, compared with spherical particles (30 μm to 70 μm in diameter) alone, adding fibers with a diameter of 10 μm and a length of 15 μm (i.e., aspect ratio of about 1.5) to spherical particles improved powder bed density for both wiper spreading and counter-rotating roller spreading. However, adding longer fibers decreased powder bed density because of the decreased flowability of the powder mixture.

The above-reviewed studies on the effects of particle shape on powder bed density are summarized in Table 14.

Table 14. Summary of reported studies on the effects of particle shape on powder bed density

Conclusion	Material	Reference
Spherical particles led to higher powder bed density than non-spherical particles for wiper spreading	PEEK	[50]
Particles with an aspect ratio of 1.5 resulted in the highest powder bed density for counter-rotating roller spreading	PEEK	[50]
Adding fibers with the proper fiber length to spherical particles improved powder bed density	Mixture of carbon fibers and polyamide spherical particles	[63, 84]

6. Concluding remarks

Powder spreading is a critical step in powder-bed additive manufacturing. This paper summarizes the effects of spreaders, powder spreading parameters, and feedstock powder properties from the literature. To prompt the understanding of powder spreading, existing knowledge gaps and future research opportunities are summarized as follows.

Some spreaders can not only spread but also compact powder to improve powder bed density. However, the exact compaction force provided by different spreaders is unknown. The effects of extra compaction force on the printed part are not well studied. More studies are needed to fill these knowledge gaps.

The effects of various spreading parameters such as layer thickness, traverse speed, and rotation speed have been investigated by many researchers. However, there is still not a consistent conclusion on their effects on powder bed density and powder bed surface condition. Some simulation work has been conducted to study the dynamic powder flow and thus to explain different spreading results from using different spreading parameters. Experimental work is needed to verify these simulation results.

Fine powder is an excellent feedstock material because it has high sinterability. However, fine powder is difficult to be uniformly and smoothly spread because of the interparticle cohesion. The source of the interparticle cohesion is still not clear. Van der Waals force, electrostatic interaction, hydrogen bonding, and capillary bridging are all possible sources. More research is needed to reveal the dominant interparticle cohesion in powder-bed additive manufacturing.

Acknowledgement

This material is based upon work supported by the National Science Foundation under Grant No. 2047908.

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