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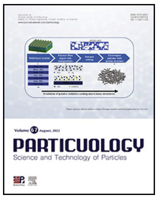

Spreadability of powders for additive manufacturing: A critical review of metrics and characterisation methods

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ABSTRACT

Powder bed fusion methods of additive manufacturing (AM) require consistent, reproducible, and uniform layers of powder for the reliable production of high-quality parts, where properties of powder are central to achieving this. Among these properties, powder flowability and spreadability play critical roles in determining the quality of these powder layers.

While extensive research has been conducted on powder flow and spreading behaviour, and on their characterisation, there is little critical comparison and review of these terms in the context of AM. Such a review is necessary to further develop and enhance our comprehension of spreading dynamics and its relation to powder properties in AM systems.

This review paper aims to build a coherent understanding of the correlation between powder characteristics and spreading in powder based additive manufacturing and its impact on manufactured parts. It highlights the current progress in comprehending spreading dynamics, the influence of powder characteristics, environmental conditions, spreading system, and the development of testing tools to assess powder spreadability. Furthermore, the paper critically discusses the challenge of finding appropriate quantitative metrics and recent advances in the use of standardised methods for evaluating powder spreadability.

1. Introduction

Additive manufacturing (AM), commonly referred to as “3D printing,” is an established and rapidly advancing technology in the field of manufacturing. Unlike traditional manufacturing methods, AM allows for the direct production of products through a layer-by-layer process, guided by digital models. The process begins with the creation of a three-dimensional digital model using computer-aided design (CAD) software. According to the American Society for Testing and Materials (ASTM), additive manufacturing is classified into 7 categories, namely, vat photopolymerisation, material jetting, binder jetting, material extrusion, powder bed fusion (PBF), sheet lamination and direct energy deposition (ASTM, 2012).

PBF is a popular method of AM, where in a stepwise manner, thin layers of powder are spread over a build plate following which a source of heat is used to melt or sinter desirable locations of the powder bed. Laser sintering, electron beam, direct metal laser sintering and selected laser melting are the most common methods used in PBF (Omnexus, 2020). Despite the significant progress made in AM, there are challenges that hinder its widespread industrial adoption. Replicability issues and variations in the quality of final components produced through additive manufacturing have been identified as barriers to its mass utilisation. This is often related to the variation in powder properties which can affect their behaviour during the spreading stage in AM. The ease with which the powder is spread (known as ‘spreadability’) to provide a uniform layer strongly influences the quality of the finished part, with a greater packing density leading to improved mechanical properties (Beitz et al., 2019). As a result, a detailed understanding of the powder flow during the spreading stage is required because it has a

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Abbreviations

AM	Additive manufacturing
AOR	Angle of repose
AR	Aspect ratio
ASTM	American Society for Testing and Materials
BFE	Basic flowability energy
CAD	Computer-aided design
DEM	Discrete element method
EBM	Electron beam melting
HR	Hausner ratio
PBF	Powder bed fusion
PS	Particle size
PSD	Particle size distribution
SE	Specific energy
SLM	Selective laser melting
SLS	Selective laser sintering

significant impact on the powder layer quality and the ultimate product quality.

There has been a growing emphasis on characterising and understanding powder material behaviour and processability. However, when it comes to AM technologies that utilise powder beds, there remains a limited understanding of the behaviour of powders during the spreading process (Capozzi, Sivo, & Bassini, 2022). For instance, powder spreading in AM occurs under low stress and high strain rate processes through a narrow gap between the build plate and the spreader, however these conditions are not reproduced in common powder flow measurement devices that are used to characterise powders used in AM processes. Although several metrics have been developed to describe the powder spreading in AM (Capozzi, Sivo, & Bassini, 2022), e.g. visual inspection, powder bed's surface roughness, packing fraction and coordination number, powder spreading is often conflated with powder flowing, and the terms “spreadability” and “flowability” have been used interchangeably. Despite attempts to correlate standardised measurements with spreadability, such efforts have often fallen short due to the discrepancy between the typical conditions occurring during powder spreading and those simulated by standardised tests.

In this review, we provide an overview of powder-based AM manufacturing and delve into the current state of research and understanding regarding powder spreading. Our aim is to assemble a coherent and comprehensive understanding of the existing knowledge. Drawing on the literature, we also aim to rationalise the concept of powder spreadability and provide a clear overview of the metrics proposed by researchers to quantify spreadability and of approaches to establish correlations with the physical and bulk properties of powders. By exploring the challenges and advancements in understanding of powder spreading and spreadability, this review contributes to the broader objective of advancing AM technology and facilitating its industrial implementation. A deeper understanding of powder behaviour and spreadability will not only aid in improving the AM process but also pave the way for enhanced quality control and standardisation in the field.

2. Overview of powder properties in additive manufacturing: influence of powder properties on the final manufactured part

Powder characteristics such as size and size distribution, morphology, particle structure and surface properties as well as bulk powder properties including packing and powder flow behaviours, are important parameters that influence the processability of the powders in AM production, and ultimately the quality of the end product. To date, there are several methods available to characterise AM powders, which are required to meet the specific industrial demands. In this section, we focus on the influence of the most important single particle and bulk properties on the quality of final manufactured parts in AM industry.

2.1. Effect of particle size and distribution

Particle size distribution as a powder property that can alter the quality of the final AM product (Vock, Klöden, Kirchner, Weißgärber, & Kieback, 2019). Mechanical resistance, quality of surface and density of final product are directly influenced by the particle size and size distribution in powder-based AM manufacturing (Sutton, Kriewall, Leu, & Newkirk, 2016). Liu et al. (Liu, Wildman, Tuck, Ashcroft, & Hague, 2011, pp. 227–238) stated that narrow particle size distributions often lead to high tensile strengths and hardness, while wider particle size distributions increase the final part density. However, a wider particle size distribution could results into high surface roughness in the final part (Nguyen et al., 2017) most probably due to uneven spread layers.

Simchi (Simchi, 2004), states that varying the particle size distribution has a significant effect on the porosity of final AM products. While larger particle can lead to higher elongations at break, they have the propensity to not fully melt due to less laser interaction which results into higher surface roughness and a reduced solid part density (Spierings, Herres, & Levy, 2011). In PBF, is high packing density and uniformity are a prerequisite of high-quality layers. Uneven spread layers results into variations of laser and powder interactions which may pose major impact on the quality of final part (Brika, Letenneur, Dion, & Brailovski, 2020).

While Shi et al. (Shi, Li, Sun, Huang, & Zeng, 2004) reports that for polymer powders smaller particles size favours the precision and density of manufactured parts, Simchi (Simchi, 2004) state that agglomeration of fine metal powders can significantly increase the reflectivity of powder bed, leading to a reduction in the amount of energy absorption for laser sintering. Additionally, Sutton et al. (Sutton et al., 2016) states that agglomeration of finer particles negatively impacts the flowability which, leads to irregularities and consequently non-uniform interaction of laser or electron beam. At the same time utilising finer particles could improve the quality of the surface of built component (Yang, Yu, Choi, Coates, & Chan, 2008). Sutton et al. (Sutton et al., 2016), Bierwagen and Sanders (Bierwagen & Sanders, 1974), Hoffman and Finkers (Hoffmann & Finkers, 1995), Zheng et al. (Zheng, Carlson, & Reed, 1995), Karapatis and Egger (Karapatis, Egger, Gygax, & Glardon, 1999), suggest that finer particles can be advantageous as they exhibit particle packing with reduced surface roughness (Spierings and Levy, 2009) and provide the ability to manufacture small pieces.

A graded size distribution including sufficient amounts of coarse and fines could result in better performance, however, for free-flowing powders there is a risk of segregation during the spreading stage. According to Bridgwater (Bridgwater, 1994), Sommier et al. (Sommier et al., 2001), Duffy and Puri (Duffy & Puri, 2002), when size ratio for free-flowing powders increase, the segregation also increases. However, to minimise segregation, particle properties can be improved through narrowing size distribution spread, avoiding irregular shaped powders and reducing absolute size (Tang & Puri, 2004). It is widely accepted that narrow particle size distribution is preferably applied in order to hinder inter-particle friction and enhance flowability. The enhancement of flowability improves the homogeneity of layer and consequently reduces porosity and in turn increases the strength of the end product (Berretta, Ghita, Evans, Anderson, & Newman, 2013).

Therefore, tailoring the particle size distribution is imperative to achieve an optimised powder bed density as the voids between the larger particles can be filled with the finer particles (Bierwagen & Sanders, 1974).

For mixtures biased towards larger particles, there will be insufficient fine particles to fill the voids, and consequently results into “loosening effect”, where the finer particles are too small to fill the interstices of the larger particles (Abu-Lebdeh, Damptey, Lamberti, & Hamoush, 2019). Additionally, larger particles tend to result into the “balling effect” which is the solidification of molten material into spheres due to the interaction of molten pool and metal powder (Chen et al., 2021; Zhou, Liu, Zhang, Shen, & Liu, 2015). The balling effect results into increased surface roughness of the final part and reduce its density and mechanical properties. Fig. 1 below illustrates SEM images of typical surface topographies of multi-layer samples at different powder layer thicknesses (Gu & Shen, 2009). In a batch dominated by larger particles as illustrated in Fig. 2(a), “wedging effect”, as defined by Abu-Lebeh et al. (Abu-Lebdeh et al., 2019), occurs when the finer particles reduce the coordination number of larger particles by positioning themselves between the larger particles rather than filling the voids. Additionally, in a batch dominated by finer particles as shown in Fig. 2(b), the “wedging effect” occurs when the larger particles obstruct the arrangement of the fine particle layer that results into the formation of miniature voids that are incapable of being filled by the finer particles (Abu-Lebdeh et al., 2019). The “wedging effect” results into heterogeneous and uneven spread layers due to the formation of voids, which leads to the reduction in the packing density of layers and consequently the solid density of the final manufactured part. It is important to consider that particle size and size distribution, morphology and flowability are influential factors in the packing behaviour of powders (Abu-Lebdeh et al., 2019).

To summarise, a narrow distribution leads to higher tensile strength and hardness in the final product, while a wider distribution can improve packing efficiency but results in higher surface roughness. Additionally, the use of larger particles could improve powder flowability but may reduce the density and increase the surface roughness of the manufactured part. On the other hand, finer particles improve surface quality but decrease flowability, which could lead to lower packing density. It is suggested that a graded size distribution, including both coarse and fine particles, could result in better performance, but segregation during the spreading stage needs to be considered.

2.2. Effect of particle morphology

Morphology is mainly related to the size, shape and surface roughness of particles (Sutton et al., 2016). It can describe the overall shape of an individual particle such as spherical, dendritic and angular geometries, which has a direct effect on the flowability, surface area, bulk density and packing efficiency in AM processes (Mikli, Kaerdi, Kulu, & Besterci, 2001; Sutton, Kriewall, Leu, & Newkirk, 2017). The manufacturing process of powders has a significant impact on the morphological characteristics, where a spherical and smooth shape is generally desirable as they pack more efficiently (Dawes, 2017; Zhu et al., 2023). Attar et al. (Attar et al., 2015) suggested that spherical shaped particles increase the homogeneity of layer deposition as well as molten liquid during SLM (selective laser melting) that results in lower porosities in the end product.

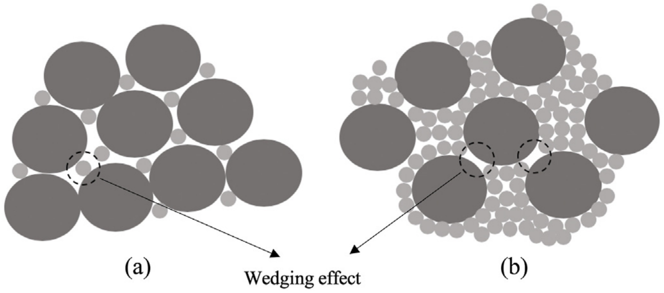

Fig. 2. Wedging effect as a result of (a) larger particle and (b) finer particle being dominant in a batch.

On the other hand, mechanical interlocking of irregular particles tends to increase inter-particular friction which in turn reduces flowability (Dawes, 2017). Additionally, a study performed by Olakanmi (Olakanmi, 2013), suggests that irregular particles can often lead to the production of defected end-parts due to the increased inter-particle friction, which adversely affects particle packing and bed densities. It is further added that the use of spherical and irregular mixtures results into higher relative density, greater compressive strengths and compression strain of end products (Attar et al., 2015).

According to a study by Schiochet Nasato and Pöschel (Schiochet Nasato & Pöschel, 2020), spherical particles tend to have better performance due to their increased flowability, however, utilising elongated particles that have lower aspect ratios (defined as smallest to largest dimensions) exhibit more compacted powder layers.

There have been great attempts in producing low-cost spherical powders that maintain the overall quality of the final product within the additive manufacturing industry. Sun et al. (Sun, Fang, Xia, Zhang, & Zhou, 2016) suggests a novel method for producing low cost spherical Ti–6Al–4V powders, where “granule spheroidisation, sintering and de-oxygenation (GSD) are integrated” as a production process. The advantage of this method is its versality in producing other metal alloy powders such as stainless steel and nickel, where their particle size, size distribution and low oxygen content can be controlled (Sun et al., 2016). They continue stating that the true density of powders produced by GSD is 99.5 ± 0.1%, with a porosity of only ~0.5 vol% in the final product. Hou et al. (Hou

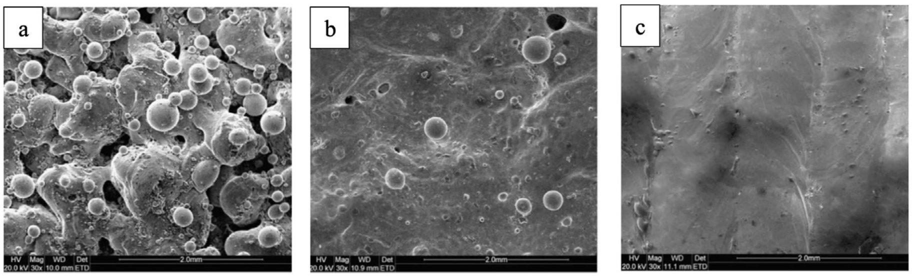

Fig. 1. SEM images of surfaces multi-layer laser sintered samples at different powder layer thicknesses (a) $d = 0.25$ mm, (b) $d = 0.15$ mm and (c) $d = 0.10$ mm (Gu & Shen, 2009).

et al., 2019) developed a powder modification method that turned irregular unprintable low cost HDH-Ti powders into ultra-low cost printable Ti powders for SLM through ball milling and mechanical alloying. This method can be a novel and significant achievement as it drastically reduces the cost of US$400 per kg of gas atomized Ti powders to US$30 per kg of hydrogenation–dehydrogenation (HDH) Ti powders. The modified powders exhibit excellent mechanical properties displaying high fracture strength (~895 MPa) and high ductility (~19.0% elongation) (Hou et al., 2019).

Furthermore, recyclability and reusability of powders can help achieve both an economic and environmentally-friendly feedstock. For instance, Ardila et al. (Ardila et al., 2014) states that after recycling IN718, nickel alloy up to 14 times, the powder's metallurgic and mechanical conditions do not critically change the mechanical properties of the final product. This result is due to the powder maintaining its original sphericity and particle size distribution after recyclability (Ardila et al., 2014).

Surface imperfections are powder-related defects which degrades the quality of final product. Satellite welded particles on the surface of particles is a defect that negatively impacts the bulk behaviour of powders such as flowability and uniform powder packing (Anderson, White, & Dehoff, 2018). Accordingly, these powder defects stimulate the formation of voids and surface impurities on the final product (Delroisse, Jacques, Maire, Rigo, & Simar, 2017; Klar & Fesko, 1984). Attar et al. (Attar et al., 2015) addresses that particles with rough surfaces also display poor flowability compared to smooth particles, due to an increased interlocking. Moreover, Schultz et al. (Schultz, Martin, Kander, & Suchicital, 2000) states that nylon-12/PEEK 75-25 vol% (CMA 30 min) exhibits higher bed porosity due to the presence of finer particles with rough surfaces.

2.3. Effect of particle porosity

Intra-particle porosity, or particle internal porosity, is referred to the voids within a single particle and can be the result of powder manufacturing conditions. As stated by Cordova et al. (Cordova, Campos, & Tinga, 2017) the use of powder with higher internal porosity leads to production of final parts with high porosity. The increase in internal particle porosity has a negative impact on the density and porosity of the final product (Sutton et al., 2017). It should be noted, some parts require low porosity, higher density and mechanical strength because their applications, while others are destined to be more porous and less dense (Slotwinski & Garboczi, 2014). Chen et al. (Chen et al., 2018) suggest that internal porosity of particles increases with the increase of particle size, which means larger powders are prone to larger internal porosities compared to fine powders.

It is important to note that process-induced porosity is also an important factor related to the AM production. For example, inconsistent deposition of layers on top of each other ultimately reduces the density of the final product (Vock et al., 2019).

As stated by Sola and Nouri (Sola & Nouri, 2019) there are three types of pores in PBF namely; microstructural pores, functional pores and structural pores. Microstructural pores are residual voids within the microstructure of the built part, which adversely impacts mechanical properties and must be mitigated to ensure consistency of the final AM part (Sola & Nouri, 2019). Structural pores are deliberately introduced for a specific aim such as biomedical scaffolds, which improve tissue in-growth and delivery of nutrients. Moreover, functional pores are open and connected voids formed by the debinding process, which is a thermal treatment to remove sacrificial binder material from powders that were initially incapable of sintering (Sola & Nouri, 2019). The functional pores significantly affect the density of the final part. Iebba et al. (Iebba et al., 2017) compared powder porosity in SLM and EBM. It is revealed that two types of pores emerge: small, irregular gaps formed during powder manufacturing and bigger spherical pores formed as a result of gas entrapment. It is further added by Iebba et al. (Iebba et al., 2017) that spherical pores during additive manufacturing can occur by powder denudation and fluctuation in the surface roughness of the powder bed. The oxidation of the powder feedstock owing to powder handling, storage conditions, and recyclability promotes the creation of pores and spatter (Sola & Nouri, 2019). It should be noted that powder porosity features might also influence process-induced porosity (Benson & Snyders, 2015).

2.4. Effect of particle packing behaviour

The apparent density, which is also referred to as bulk density, is defined as the ratio of the weight of powder to its volume including the voids (Rosato & Rosato, 2003). Tapped density, on the other hand, is the “ratio of a known weight of a powder to the least volume the powder could occupy upon tapping” (Chi-Ying Wong, 2000). It was observed by Ziegelmeier et al. (Ziegelmeier et al., 2015) that utilising powder size fractions with higher bulk densities and flowability produced manufactured parts with enhanced tensile properties (elongation at break (% EaB) and ultimate tensile strength (UTS)). Furthermore, Schultz et al. (Schultz et al., 2000) states that low bulk density of the powder bed, has a direct impact on the mechanical strength of final part. According to Nguyen et al. (Nguyen et al., 2017), there is a reduction in bulk density upon the use of recycled powders, which lowers the solid density of the final part. Barretta et al. (Berretta et al., 2013), suggests that the use of particles with lower true densities (solid density) will result into less dense structures and consequently, weak parts with higher porosity. Moreover, smooth and spherical particles have higher bulk density and better flowability, which reduces the number of pores in the deposited layer (Markusson, 2017).

Using powders with a lower tapped density results in high porosity and shrinkage during the sintering (Frykholm, Takeda, Andersson, & Carlstrom, 2016). Since, tapped density refers to the densely packed condition of powders, ensuring adequate tapped density allows particles to pack efficiently where they are rearranged thoroughly to fill as many voids within the powder layer, thus, minimising the inter-particle porosity which results into end parts of high density (Frykholm et al., 2016). For powders with low bulk density, and high porosity, the likelihood of voids inside the deposited layers increases, resulting in the formation of balling effects and rougher surfaces (Rausch, Küng, Pobel, Markl, & Körner, 2017). The surface quality and energy required to produce dense artefacts are directly proportional to the bulk density of powders (Rausch et al., 2017). This means that utilising a powder with a low bulk density can also cause the increased surface roughness, which is a flaw in the finished item. This can be offset by consuming more energy. As a result, it is advantageous to use powders with high bulk density to produce dense parts in a more efficient and cost-effective manner (Rausch et al., 2017). Additionally, Schmidt et al. (Schmidt et al., 2020) utilised X-ray microtomography to determine the packing densities of micron-sized spherical particles, which were then compared to DEM simulations. The motivation of their work was to assess the prediction of packing characteristics of bulk materials in the micrometer size range, through measuring the packing fraction obtained by DEM simulations and validated against experimental bulk density measurements. Their work not only confirmed the simple relationship for dependence of packing fraction on size, where the packing fraction decreased with particle size due to particle interactions; but also enabled a deeper understanding of the powder packing behaviour and the optimisation of powder feedstock to create quality final parts (Schmidt et al., 2020).

2.5. *Effect of powder flow behaviour*

The ability of a powder to flow, commonly known as powder flowability (Prescott & Barnum, 2000), is considered to be a complex phenomenon. It is important to note that flowability is not an intrinsic powder characteristic as it is not only affected by the physical characteristic of the powder but also the handling procedure, storage and process conditions (Prescott & Barnum, 2000). These factors require thorough attention as each one of them can significantly change the flow behaviour of the same powder (Prescott & Barnum, 2000). This is due to the powder behaving differently under different conditions such as when they are loosely packed, fully aerated or consolidated.

As stated by Sun et al. (Sun et al., 2015) good flowability measured by the Hall funnel, static AOR together with apparent and tapped densities, is crucial to produce a homogenous layer in AM. This suggestion is further confirmed by Ma et al. (Ma, Evans, Philips, & Cunningham, 2020) who stated poor flowability results the formation of excessive voids and consequently, discontinuities within the final part. Furthermore, flowability has a substantial impact on process performance, such as the porosity of the spread layer, which results in reduced mechanical strength and quality of the finished product (Ziegelmeier et al., 2015). In conclusion, it has been agreed in literature that increased flowability results into better packing efficiency, surface quality, and higher ultimate tensile strength for the final part (Ziegelmeier et al., 2015). However, the link between powder flow characteristics and the deposition of desirable powder layer prior to sintering needs to be understood. This requires simultaneous consideration of both the powder feeding system (e.g. gravity fed from hopper or force fed using a piston) and the spreading conditions. Nevertheless, combination of different factors such as user dependency, condition of apparatus, inherent nature of the powders and environmental conditions poses limitations on the flowability measurement process, which can sometimes fail to capture the powder flow behaviour representative of the AM application (Mehrabi et al., 2023; Haydari et al., 2024; Zinatlou Ajabshir, Sofia, Hare, Barletta, & Poletto, 2024 b). Therefore, an alternative approach is to apply the combination of the different flowability techniques to reduce inaccuracies of the measurements. With this, there is a requirement to develop multiple flow characterisation methods in order to that are able to identify the design parameters required to achieve desirable final product quality (Clayton, Millington-Smith, & Armstrong, 2015).

3. Overview of the spread powder bed quality: influence of powder properties and spreading conditions

In additive manufacturing, ensuring desirable spread powder bed quality is critical to optimal printing outcomes. This procedure entails determining how powder characteristics and spreading conditions affect the overall quality of the powder bed. We may acquire insights into how these variables affect the powder bed qualities by carefully examining elements such as particle size distribution, morphology, and flowability, as well as changing the spreading parameters. Understanding the relationship between powder characteristics, spreading circumstances, and bed quality enables AM process improvement, resulting in improved surface polish, porosity control, and mechanical performance of printed components.

3.1. *Effect of particle properties on the quality of spread layer*

3.1.1. *Particle shape*

Particle morphology can have a stronger influence on a particulate material's flow properties than its size distribution (Berretta et al., 2013). The particle shape, as a results of different atomization techniques, influences the powder bed packing behaviour. Powder bed packing fraction decreases for water atomized powders because of their irregularly shaped particles. Spherical or spheroidal particles are more appealing for both powder bed fusion and selective laser sintering processes. Gas atomization and rotating electrode processes produce more spherical particles compared to water atomization processes (Drake, 2018). Sun et al. (Sun et al., 2015) found that powder with spherical particles makes a more uniform spread layer compared to powder with elongated particle shape or recycled powders with small imperfection on the particles' surface. Jacob et al. (Jacob, Jacob, Brown, & Donmez, 2018) investigated the effect of powder spreading on shape segregation of two nitrogen gas atomized powders, namely stainless steel (S17-4) with D_{92} of 53 μm and nickel alloy (IN625) with D_{50} of 28.4 μm. They reported that spreading the two tested powders did not cause a significant particle shape segregation over the build plate.

Aspect ratio (AR) of a particle can be described as the ratio of the minimum to maximum particle Feret's diameters where a perfect sphere has a ratio of 1:1. It is also common to define a particle AR as the ratio of maximum to minimum particle dimensions. Changes in AR, and consequently the particle shape, t can therefore play a significant role in powder spreading. Lee et al. (Lee, Nandwana, & Zhang, 2018) reported that the particle aspect ratio has a very strong impact on the powder bed density. Haeri et al. (Haeri, Wang, Ghita, & Sun, 2017) used DEM simulation to explore the impact of particle aspect ratio (between 1 and 2.5, here AR was defined as the ratio of maximum to minimum particle dimensions) on powder bed surface roughness, powder bed volume fractions and particle alignments to flow. They reported that increasing aspect ratio from 1 to 2.5 causes higher surface roughness for the both the spreader designs tested. At higher aspect ratios, the rotational speed of the roller has a greater impact on powder bed surface roughness, but at lower aspect ratios, the rotational speed of the roller has a considerably smaller impact on surface roughness. They reported a divergent trend in terms of powder bed solid volume fraction when a roller or blade was used for spreading. When using the roller, the solid volume fraction grew by the aspect ratio and reached its maximum value at an aspect ratio of 1.5. Solid volume fraction began to drop at aspect ratios greater than 1.5 and reached its lowest value at aspect ratios of 2.5. In contrast, when using the blade spreader, the solid volume fraction dropped by increasing the particle aspect ratio. The other metric which was studied by Haeri et al. (Haeri et al., 2017) is "particle rotation towards the direction of flow". They reported that particles with bigger aspect ratios have a higher tendency of particle rotation towards the direction of flow. This causes higher powder bed roughness/degradation since these large particle rotations could disturb the nearby particles. Their experimental results showed that particles alignment to flow is a function of aspect ratio.

Haeri et al. (Haeri et al., 2017) used DEM simulation to investigate the segregation behaviour of a mixture of different particle aspect ratio (1.5, 2.0, 2.5) as a function of roller speed (0.03, 0.04 and 0.06 m/s). They discovered that the likelihood of detecting rod-shaped particles in different slabs of the powder bed is not the same. For example, simulation findings showed that the likelihood of discovering particles with an aspect ratio of 2.5 is lower in the bottom slab than in the top slab. The probability of finding particles with an aspect ratio of 1.5 is greater in the lower levels of the powder bed than in the upper layers.

Hulme et al. (Hulme et al., 2023) investigated the effects of aspect ratios of twenty four commercially available powders including steels, nickel-base superalloy, titanium alloy and aluminium alloy on the quality of spread layers. They concluded that more spherical particles resulted into higher apparent, tapped and layer densities (Hulme et al., 2023).

3.1.2. Particle size and size distribution

Particle size, and size distribution, play a crucial role in determining the quality of both the spread layer and, ultimately, the final AM product. Quality of surfaces and the degree of porosity within the multi-layers are significantly influenced by the particle size and size distribution. As stated by Liu et al. (Liu et al., 2011, pp. 227–238) wider particle size distributions increase the packing efficiency, probably due to the better flowability. However, it was also reported that a wider particle size distribution results into uneven spread layers and consequently, high surface roughness in the final part (Nguyen et al., 2017). Ma et al. (Ma et al., 2020) investigated the effect of adding different volume fractions of fine particles (in the range from 20 μm to 40 μm) to a metal powder with a particle size distribution (ranging from 45 μm to 150 μm) on its flow properties during spreading. The simulation results showed that the baseline material (45–150 μm), with no fine powder addition, had a better flowability and no voids can be visually observed after powder spreading. The same observation was reported when fine content increased to 2%. However, addition of fine content by 4%, caused the formation of aggregates during spreading. This causes the formation of non-homogeneous powder bed. Meier et al. (Meier, Weissbach, Weinberg, Wall, & Hart, 2019) used DEM simulation to evaluate the powder bed quality, produced by a blade spreader. They used Ti–6Al–4V powders with different size distributions to vary bulk cohesion and bulk surface energy. Increasing the surface energy, causes the reduction in powder bed mean packing fraction as well as mean layer height due to particle agglomerates. Using experimental and modelling approaches Parteli et al. (Parteli et al., 2014) proposed a mathematical expression to estimate the packing fraction of fine polydisperse powders as a function of the average particle size. They explained that simulations incorporating the JKR-type adhesive model demonstrated a clear decay of the packing fraction with a decrease in particle size and was in agreement with the experiments for particle sizes less than 20 μm, (Parteli et al., 2014). Further improvements on the model were made by including the inter-particle forces due to viscoelastic, JKR-adhesive and non-bonded van der Waals interaction, which allowed the generation of the experimentally found packing fraction for the full particle size interval between 4 μm and 52 μm (Parteli et al., 2014). Additionally, Roy et al. (Roy, Shaheen, & Pöschel, 2023) investigated the effect of cohesion on the quality of Ti–6Al4V spread layers, where they stated that higher interparticle cohesion resulted to reduced spreadability, more heterogenous powder layer structures and enhanced particle size segregation. From their observations of the particle size distribution in the powder layers, it was suggested that the percentage of the retained fraction of larger particles monotonically decreased with an increase in Bond number (ratio of cohesive/adhesive forces over particle weight) (Roy et al., 2023). Therefore, cohesion increases the segregation effect and leads to strong segregation as the majority of the larger particles are removed from the spread layer (Roy et al., 2023).

Neveu et al. (Neveu, Francqui, & Lumay, 2022) related the spreadability of powders to layer homogeneity and stated that by a decrease in the particle size, the cohesiveness increases and spreadability decreases resulting into uneven powder layers. However, Hulme et al. (Hulme et al., 2023) stated that an increase in the particle size (characterised by the median particle diameter d_{50}) resulted into a decrease in layer density due to the formation of larger interstices between particles. In the following, we review the influence of particle size distribution on different spread layer attributes.

3.1.2.1. Effect of particle size distribution on the powder bed density.

Size distribution can affect the way individual particles are packed during spreading. Unlike large particles, smaller particles would be more cohesive, due to a higher Bond's number, and could have poor packing leading to lower powder bed density. On the other hand, a combination of large and small particles could allow occupation of the voids between larger particles by the smaller ones, leading to higher powder bed density. Theoretically, there could be an optimum particles size distribution that leads to the highest powder bed density. Karapatis et al. (Karapatis et al., 1999) investigated the effect of ratio of small to coarse particles on the powder bed density. They used spherical, smooth nickel-base alloy powders in their study and reported that adding 30% of fine (25–40 μm) to the coarse powder (100–150 μm), could increase the powder bed density by 15%.

Muñiz-Lerma et al. (Muñiz-Lerma, Nommeots-Nomm, Waters, & Brochu, 2018) investigated the effect of particle size and size distribution of gas atomized aluminum powders. D_{50} of the three samles, A, B and C, were 63, 70, 31 μm, respectively. Samples A and B had narrow particle size distribution while sample C had wider particle size distribution with more amounts of fine particles. Humidity from surounding enviroments could be more easily adsorbed/absorbed by powders having a high fine fraction. This presumably increased powder cohesivness, lowering the quality of the powder bed. In contrast, when the powder had a narrow particle size distribution with large quantity of large particles, i.e. 48 μm, powder bed density increased since the bulk cohesion was reduced. The spread density obtained from two powders with narrow particle size distributions (powders A and B) were higher than the powder with wide particle size distribution and higher portion of fine particles (powder C). This was attributed to the fact that powder C had higher surface energy, due to having higher number of fine particles, compared to samples A and B. Powder C also had higher work of cohesion (the energy required to break an adhesive/cohesive contact) values than the other two powders, which contributed to sample C's lower powder bed density. Furthermore, fine particles have higher affinity to adsorb water on their surface which cause the formation of liquid and solid bridges. The detailed description of the effect of liquid and solid bridges on powder flow properties are illustrated in detail in many research, (Cleaver, Karatzas, Louis, & Hayati, 2004; Hirschberg, Sun, Risbo, & Rantanen, 2019; Karde, Dixit, & Ghoroi, 2017; Leaper et al., 2003; Mauer & Taylor, 2010; Salehi et al., 2019; Zafar, Vivacqua, Calvert, Ghadiri, & Cleaver, 2017).

Spreading powders with wide particle size distribution resulted in a high powder bed's density because fine particles can relocate between larger particles (Liu et al., 2011, pp. 227–238). However, Liu et al. (Liu et al., 2011, pp. 227–238) reported that the high bed density leads to high friction value between particles and hence more possibility for particle interlocking. This will result in lower spreadability of powder and reduce the quality of powder bed. Benson and Snyders (Benson & Snyders, 2015) reported in their review paper that wide particle size distribution and finer particles cause better layer density. Furthermore, the optimum powder bed density was attained when the span of particle size distribution is large.

Mussatto et al. (Mussatto et al., 2021) reported that spreading metal powders with a wide particle size distribution, contain high fraction of fine particles smaller than 25 μm, with a blade spreader, forms a uniform and dense powder beds with low void fraction. Lee et al. (Lee et al., 2018) used DEM simulation to study the effect of particle size and particle size distribution on the powder bed packing density. Powder bed packing density was not affected by the particles' mean radius, on the other hand, the particle size distribution had a larger impact on the powder bed density. Jacob et al. (Jacob et al., 2018) investigated the effect of particle size and size distribution of stainless steel powder (S17-4) with D_{92} of 53 μm and nickel alloy powder (IN625) with D_{50} of 28.4 μm using on the powder bed density. They concluded that a wider particle size distribution of S17-4 can produce a powder bed with a higher density. This is mainly due to the fact that smaller particles can fill the gaps between larger particles. Ma et al. (Ma et al., 2020) investigated the effect of adding varying volume fractions of fine metal powder (in the range from 20 μm to 40 μm) to a metal powder with particle sizes ranging between 45 μm and 150 μm on the solid volume fraction of powder bed. Addition of small quantity of fine particles reduced the “total volume of voids”. However, the solid volume fraction, reduced by 5.6% compared to the baseline material when the fine content increased to more than 1.5%. Gürtler et al. (Gürtler et al., 2014) and Yao et al. (Yao et al., 2021a) investigated the effect of powder's fine content on powder bed density. Powder blends with large quantity of fine particles led to a higher powder bed relative density. However, Chen et al. (Chen et al., 2020) stated that higher portion of fine particle in the bulk powder led to powder agglomeration and a reduction in the powder bed density.

Xiang et al. (Xiang, Yin, Deng, Mei, & Yin, 2016) used DEM for the spreading of randomly distributing powder with monosize, bimodal and Gaussian distributions spheres. They reported that the packing density of monosize distribution is larger than Gaussian distribution which in turn is larger than the packing density of bimodal size distribution powders. Van den Eynde (Van den Eynde, 2018) reported a smooth layer was attained with a powder containing monodisperse spheres particles compared to the powder containing cryogenically milled elastomeric particles.

3.1.2.2. Effect of particle size distribution on the segregation. Mussatto et al. (Mussatto et al., 2021) reported that metal powders with a wide particle size distribution and high fraction of fine particles smaller than 25 μm were more prone to size segregation over the powder bed. Jacob et al. (Jacob et al., 2018) also investigated the effect of particle size and size distribution on the powder bed size segregation. Two nitrogen gas atomized powders were used in their study, namely stainless steel (S17-4) with D_{92} of 53 μm and nickel alloy (IN625) with D_{50} of 28.4 μm. For the both powders, the PSD did not change considerably across the build plate, but particle size slightly increased towards the end of the powder bed (in the direction of the spreader blade). The ratio between the effective layer thickness and D_{90} (E/D_{90}) of the same two powders were investigated by Jacob et al. (Jacob et al., 2018). E/D_{90} smaller than 1 was an indication that all particles bigger or in the same size of D_{90} were not deposited into the powder layer and end up in the collector bin. The E/D_{90} for the nickel alloy was close to 1, indicating that the powder layer contained particles close to powder's D_{90}. In comparison, the stainless steel powder with a higher concentration of coarse particles had a much lower $E/D90$ (0.66–0.70), indicating that not all of the large particles were deposited in the powder bed and some ended up in the collecting bin.

In another study, Muñiz-Lerma et al. (Muñiz-Lerma et al., 2018) investigated the effect of particle size and size distribution of gas atomized aluminum powders on powder bed segregation. An aluminum powder with wide particle size distribution and D_{50} of 31 μm was spread over the previously build plate and then its bed particle size distribution was measured at different locations. The analysis of particle size distribution at different positions of the powder bed showed that at the beginning of the powder spreading, the powder layer had relatively larger particles than towards the end of powder bed. In contrast, powder bed towards the end, contained smaller particles with a D_{50} of 9.8 μm. However, Lee et al. (Lee, Gurnon, Bodner, & Simunovic, 2020) reported that the portion of large particles increased in the direction of blade spreader during spreading of Co–Cr powder with D_{50} of 52.08 μm. The same observation were reported by Chen et al. (Chen et al., 2020), where they used DEM simulation and experimental validation to investigate the impact of using bimodal particle size distribution of 316 L stainless steel powder on the powder bed segregation. The percolation effect was found during powder spreading, with a lower number of fine particles deposited in the spreader's direction of travel.

Zhang et al. (Zhang, Tan, Xiao, & Jiang, 2022) investigated the effect of particle segregation of nylon powders using a roller and blade spreader in SLS processes. They stated that due to the complex movement of a roller, complicated dispersion and circular movements occurs within the powder pile resulting into enhanced particle segregation. They further added that an increase in the layer thickness led to higher segregation for roller spreader compared to the blade (Zhang et al., 2022).

3.1.2.3. Effect of particle size distribution on the powder bed surface roughness. According to Escano et al. (Escano et al., 2018) spreading powders with larger average particle diameter results in an average roughness value (*Ra*) of 38 μm, whereas spreading the powder with lower average particle diameter of 23 μm results in a *Ra* value of 20 μm. They also determined the ratio between *Ra* and average particle diameter. This ratio was 0.57 and 0.87 for powder with large and small particle diameters, respectively. The lower ratio for powder with larger particle diameter might be due to better flow properties than the powder with smaller average particle diameter.

Ma et al. (Ma et al., 2020) reported that adding 1.5% fine particle reduced surface roughness by around 18%. However, adding fine particles greater than 1.5% caused an increase in void content in the powder bed. This was due to the increased cohesive forces between particles in powders with higher fine fraction content.

Parteli and Pöschel (Parteli & Pöschel, 2016) used DEM simulation to investigate the effect of PA12 powder particle size distribution on powder's bed surface roughness. Lower surface roughness was attained after spreading powders with narrow particle size distributions. This is due to fine particles agglomerating during spreading, resulting in a decreased powder bed packing fraction. They further modified the powder by removing particles with diameter smaller than 60 μm and obtained a slightly lower surface roughness. This behaviour was attributed to the agglomeration tendency of fine particles (Parteli & Pöschel, 2016; Parteli & Pöschel, 2017). According to Meier et al. (Meier et al., 2019), the rise in powder bed surface roughness with increasing powder bulk cohesion is due to two processes. First, coarse particle aggregation during powder bed spreading, and then particles ripped out of the powder layer due to particle-to-blade adhesion.

While many researchers reported the effect of particle size on the spread layer surface roughness, Beitz et al. (Beitz et al., 2019) reports a different trend. They investigated the effect of 3 different spreader shapes (flat, sharp and round shape) on powder bed surface roughness of PA12 powder with three different particle size distributions (D_{50} of 51, 46 and 56 μm). Two different methods were used to evaluate powder bed surface roughness, namely, advanced X-ray micro computed tomography (XMT) and a confocal laser scanning microscope (LSM). No impact of particle size distribution of the tested powders on the powder bed surface roughness were observed.

3.1.3. Other mechanical properties

Shaheen et al. (Shaheen, Thornton, Luding, & Weinhart, 2019) investigated the effect of altering mechanical properties of powder, specially inter-particle friction (cohesion), sliding and rolling frictions, on the powder bed quality and particle segregation using DEM simulation. They employed a blade spreader and one type of powder, Ti–6Al–4V, with D_{10}, D_{50} and D_{90} values of 25, 38 and 57 μm, respectively. The coefficient of sliding friction had a minor impact on layer uniformity, whereas the coefficient of rolling friction had a bigger impact on powder bed uniformity. At higher coefficients of rolling friction, the powder bed is less uniform with higher porosity. Surprisingly, when rolling and sliding friction were increased, powder bed quality improved. The authors did not provide a detailed explanation for this behaviour. The sliding friction coefficient was reported to have a larger impact on particle segregation compared to both rolling and inter-particle friction coefficients. He et al. (He, Hassanpour, & Bayly, 2020b) investigated the effect of particle cohesion ($\mathrm{Bo} = 0$ to $\mathrm{Bo} = 400$) on the powder bed surface roughness by using DEM simulation. The dimensionless Bond number (Bo) is defined as the ratio of the maximum pull-off force between particles to particle weight (He et al., 2020a). Surface roughness decreased with the bond number from 0 to 50, after which it increased with Bond number. In addition, He et al. (He et al., 2020b) reported that for cohesion-less powders ($\mathrm{Bo} = 0$), large voids were detected in the powder bed. Increasing the Bond number from 0 to 200 improve the powder bed quality. However, at larger Bo, i.e. 400, a reduction in powder bed density was observed. Spreading cohesive powders results in lower powder bed packing fractions which may be attributed to agglomeration during spreading (Meier et al., 2019). Furthermore, Roy et al. (Roy et al., 2023) studied the effect of cohesion on the structure and uniformity of powder layers, where they characterised the layer uniformity by extracting the solid volume fraction after spreading using discrete data. They concluded that an increase in the inter-particle cohesion created heterogenous spread layers and consequently reduced spreadability (Roy et al., 2023).

3.2. Flow measurements for powder spreadability

One of the major challenges posed in powder bed based additive manufacturing is the measurements of powder flow as majority of techniques such as shear cell, Hausner ratio, angle of repose and powder rheometer measure indices rather than intrinsic powder properties. An index can be explained as a system property, where obtained value is dependent on not only the powder itself but also the equipment utilised and the resulting flow field (Van den Eynde, 2018). Hence, the indices provided by different techniques can enable the comparison of different powders of different flow and stress conditions, which in turn may shed more light on their spreading behaviour. Fig. 3 below provides a schematic of common bulk flow measurements under different flow and stress conditions. This section focuses on the effects of bulk flow properties such as angle of repose, powder rheometer, Hausner ratio, shear cell and Hall flowmeter on the spreading behaviour.

3.2.1. Angle of repose (AOR)

The angle of repose (AOR) is a commonly used technique that provides an index for powder flow, where the angle of inclination of a powder heap is measured. Higher angles indicate stronger inter-particle forces, which indicates poor powder flow. The static and dynamic angle of repose are two distinct versions of the angle of repose where that former measure the angle of the powder heap at rest while the latter measures the powder heap in continuous agitation (Van den Eynde, 2018). Fig. 4 below represents the schematics for the static and dynamic angle of repose.

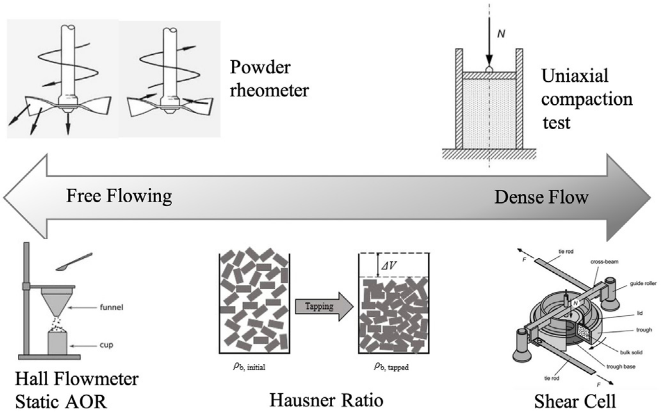

Fig. 3. Common powder bulk flow measurements under different flow and stress conditions adapted from (Hassanpour, Hare, & Pasha, 2019; Schulze, 2021; Van den Eynde, 2018).

Snow et al. (Snow, Martukanitz, & Joshi, 2019) reported that the angle of repose is the most significant variable and it is inversely proportional to the "percentage of the built plate covered by powder". They found that increasing the repose angle from 40° to 50° reduced the percentage of the built plate covered by powder by 28.5%. They also studied the deposition rate of the tested powders, calculated from Equation (1), with different angle of repose (3 levels).

$$\dot{m} = \rho_a L \frac{\mathrm{d}A}{\mathrm{d}T} \tag{1}$$

Where ρ_a is apparent density, L is the width of the build plate, and $\mathrm{d}A/\mathrm{d}T$ is the rate of change of the cross-sectional area of the powder during the spreading process. Powders with lower angle of repose had higher deposition rate. This metric was attained through the video analysis of the spread layer taken by the DynoLite microscope which was mounted parallel to the powder bed. Furthermore, the effects of repose angle on the rate of change of avalanche angle was studied. The authors stated that the avalanching angle of the three powders in front of the blade, increased linearly when the powder with the lower angle of repose was spread, whereas powders with the greater angle of repose showed no variation/change in the avalanching angle. The authors also looked at the effect of angle of repose on average avalanching angle, however they did not uncover a strong relationship between the factor and the measure.

Gärtner et al. (Gärtner et al., 2021) found that adding a glidant agent (SiO_2) with a size of 13 nm size to alloy metal powder (CoCrFeNi) reduced the powder's dynamic angle of repose by 30–50%. Escano et al. (Escano et al., 2018) used in-situ x-ray imaging to construct a powder spreading system to analyse the dynamic repose angle of two powders during spreading. They spread two distinct 316 L stainless steel powders with an average diameter of 67 μm (wider particle size distribution) and 23 μm (narrow particle size distribution) using an aluminium blade. Powder with smaller average particle size of 23 μm exhibited a higher dynamic repose angle and greater variation during spreading. This indicated that the powder had a low flowability. Lee et al. (Lee et al., 2020) investigated "evolution of the dynamic angle of repose" (i.e. angle of repose in front of the blade during spreading) of Co–Cr powders with D_{50} of 52.08 μm at the fixed blade velocity of 2.54 cm/s. Dynamic AOR grew somewhat during the early spreading time and thereafter remained pretty stable. When the blade spreader speed was raised by factor of 5, the dynamic AOR increased from 27.3° to 38.3°.

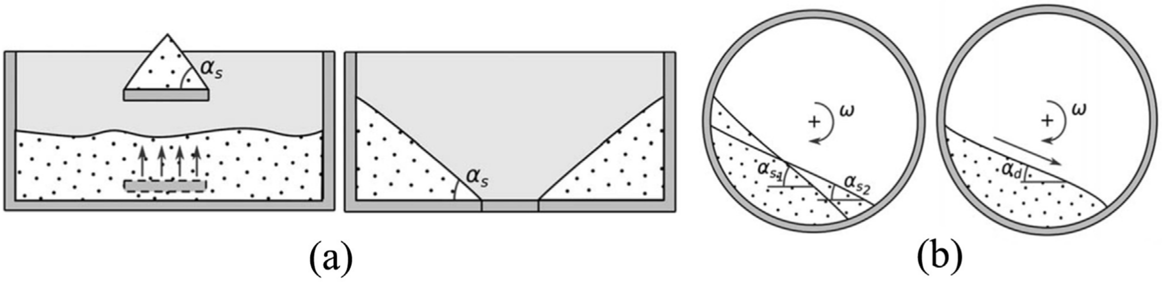

Fig. 4. (a) Angle of spatula and drained angle-static angle of repose and (b) avalanche angles and dynamic angle of repose (Hassanpour et al., 2019).

3.2.2. *FT4 powder rheometer*

Powder rheometers such as the Freeman powder rheometers (FT4 Powder Rheometer) can be utilised for the evaluation of powder flow properties in additive manufacturing (Van den Eynde, 2018). The FT4 allows the assessment of two powder flow patterns, where values of the Basic Flowability Energy (BFE) and Specific Energy (SE) are provided. Freeman defined the BFE as the energy required to displace a conditioned powder sample during downward testing under confined flow conditions, while the SE as the energy per unit of mass required to displace conditioned powder during upward testing, under unconfined flow conditions, as illustrated in Fig. 5 below (Freeman, 2007). Van den Eynde (Van den Eynde, 2018) measured the flow energy of different polymer powders using an in-house rheometer based on the same protocol as FT4, and showed that the flow energy of powders at different temperatures can be directly correlated with the powder spreading behaviour. Mehrabi et al. (Mehrabi et al., 2023) utilised the FT4 powder rheometer to determine the flowability of regular shape gas atomized (GA) and irregular shape hydride-dehydride (HDH) Ti6Al4V powder in a dynamic regime. They showed that HDH powder exhibited a higher SE value and reduced flowability than GA powder which indicates due to the irregular particle morphology and particle interlocking, which was correlated with its poorer spreadability. However, they concluded that the flow measurements under dynamic conditions using the FT4 rheometer showed that both samples had a higher flow resistance under lower blade rotation speeds, which disagreed with powder behaviour during spreading when the blade speed was increased (Mehrabi et al., 2023). More recently, Haydari et al. (2024) reported a lack of correlation between the flow energy and the spreading of two stainless steel batches that exhibited significantly different behaviours.

3.2.3. *Hausner ratio (HR)*

The Hausner ratio (HR) is defined as the ratio of the tapped density of a powder to the conditioned bulk density of the same material as expressed in Equation (2), that is commonly used to provide an index for powder flow. Zocca et al. (Zocca, Gomes, Mühler, & Günster, 2014) studies powder-bed stabilisation for powder based additive manufacturing where they used the Hausner ratio as a method for assessing powder flow. Abdullah and Geldart reported that HR can be utilised to describe the packing behaviour of powders where powders with HR $\leq$ 1.25 are considered free flowing while powder with HR $>$ 1.4 are considered cohesive and non-flowing (Abdullah & Geldart, 1999). Mehrabi et al. (Mehrabi et al., 2023) utilised the Hausner ratio as a technique to investigate the effect of powder flowability on spreading in additive manufacturing, where a lower Hausner ratio was an indicator of higher flowability which led to a higher spreadability index. However, Spierings et al. (Spierings, Voegtlin, Bauer, & Wegener, 2015) on their study of powder flowability characterisation for powder bed based additive manufacturing stated the HR does not correlate well with optical evaluation of powder flow. They also stated that measurements of bulk and tapped densities was comparably far from the situation in powder bed-based AM, where only a small quantity of powders were put on the build plate. Furthermore, Haydari et al. (2024) reported that HR did not correlate with the spreading of two stainless steel batches that had significant differences in their behaviours. Fig. 6 below illustrates the principle behind the Hausner ratio.

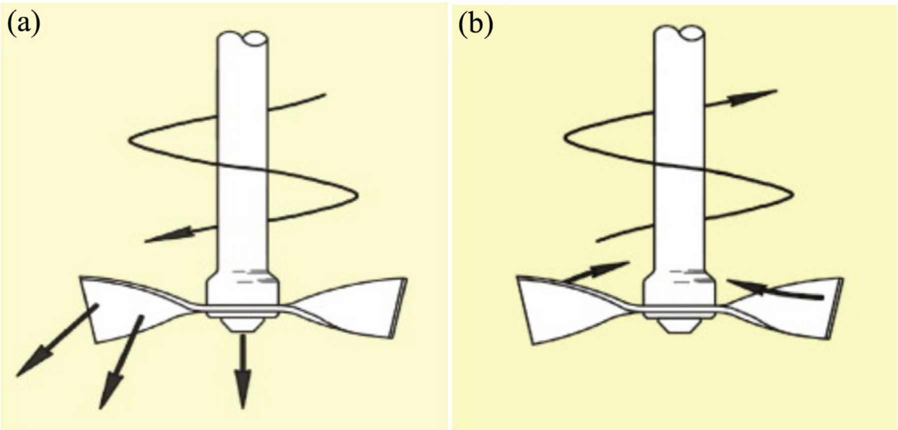

Fig. 5. (a) Downward, confined testing mode and (b) upward, unconfined testing mode (Freeman, 2007).

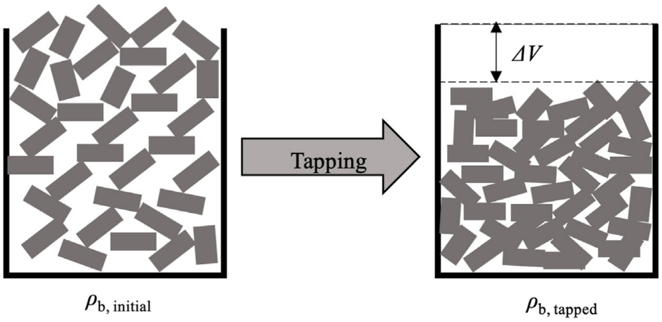

Fig. 6. Schematic drawing of the principle of Hausner ratio.

$$HR = \frac{\rho_{b,tapped}}{\rho_{b,initial}} \tag{2}$$

3.2.4. Shear cell

Shear cell measurements are widely utilised to assess the flow behaviour of powders during applications that involve powder discharge. They were originally used in the design of silos and hoppers but have become increasingly useful for the characterisation of granular materials (Bruni, Lettieri, Newton, & Barletta, 2007). This method measures the friction between particles as well as between particles and the wall, and provides valuable insight on the compressive strength, powder compressibility, consolidation time and bulk density (Schulze, 2021). Fig. 7 below depicts the Schultze shear cell, where important parameters based on the Mohr's circle analysis is obtained such as the major principle stress (σ_1), unconfined yield strength (σ_c), cohesion strength (τ_c), angle of internal friction (ϕ) and effective angle of internal friction (ϕ_e) (Leturia, Benali, Lagarde, Ronga, & Saleh, 2014). Additionally, Jenike proposed the flowability index (ffc) so as to characterise flowability, which is the ratio of the major principle stress (σ_1) to the unconfined yield strength (σ_c) as expressed by Equation (3) below (Jenike, 1961). Jenike's classification on flow behaviour was further developed by Thomas and Schubert (Thomas, Hickis, Jackson, & Newlin, 1979) and is presented in Table 1 below.

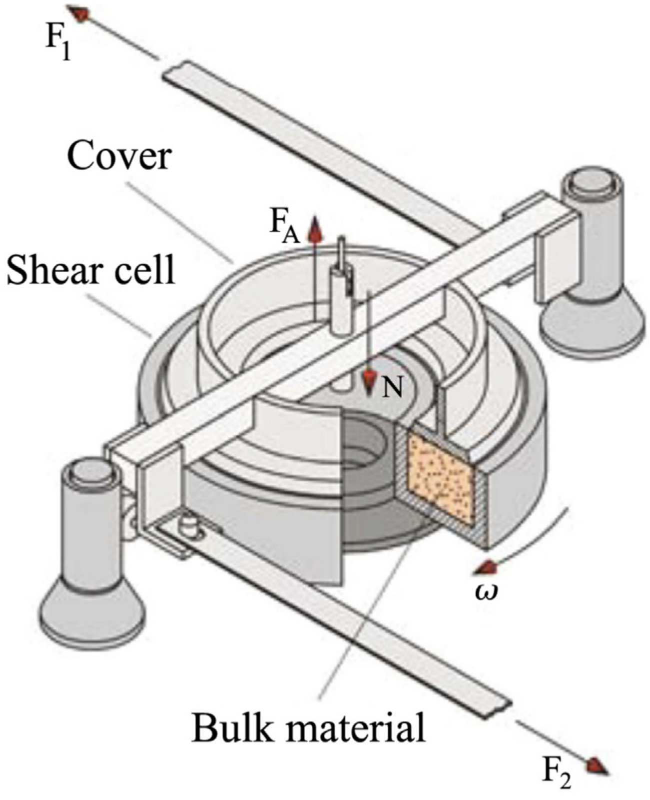

Fig. 7. Schultze shear tester (Schulze, 2021).

$$ffc = \frac{\sigma_1}{\sigma_c} \tag{3}$$

Tan et al. (Tan, Zhang, Li, Xu, & Wu, 2021) measured the flowability of twelve commonly used powders in additive manufacturing and stated the complexities of powder flow behaviour during the spreading process. They utilised the shear cell, where a shearing head was moved downwards and applied on to the powder so as to induce both vertical and rotational stresses (Tan et al., 2021). They concluded that the flow factor results obtained from the shear cell carried the lowest weight in correlating flowability to the spreading process (Tan et al., 2021). Mehrabi et al. (Mehrabi et al., 2023) stated that despite the wide usage of the shear cell in literature, it is not a technique suitable for measuring powder flow at higher shear rates which resembles the spreading process in AM (Mehrabi et al., 2023). Spierings et al. (Spierings et al., 2015) also stated that the use of the ring shear tester is not suitable in powder-bed-based AM as the powders are assessed under compressive loads, which is far from the conditions in AM (Spierings et al., 2015).

3.2.5. Hall flowmeter

The Hall flowmeter is a common technique used to assess the flowability of free-flowing metal powder. The time required for a certain amount of bulk powder to pass through a calibrated orifice is used to assess the flowability. Spear et al. (Spears & Gold, 2016) stated that the Hall flowmeter only provides a simple comparison for ranking metal powders and the index may not be directly correlated to SLM processes. Schulze (Schulze, 2021) also highlighted some of the drawback associated with this method such as user dependency during the filling stage as well as the effect of aeration of powder on flowrate, which suggests that this method is only suitable simple comparative tests. Sun et al. (Sun et al., 2015) also stated that the use of Hall flowmeter for assessing the flowability of Titanium powders did not provide compelling evaluation for the suitability of powders in AM. However, in the study of Haydari et al. (2024) the flow rate test was the only technique reported to have correlation with the spreading of two stainless steel batches that exhibited different behaviours.

In summary, there are major bottlenecks in correlating bulk powder flowability to spreading dynamics under real process conditions. However, information obtained from the above techniques may act as a stepping stone into further understanding and developing spreadability metrics.

Table 1
Classification of flowability index.

Flowability index, ff_c	Flow behaviour
$ff_c < 1$	Not flowing
$1 < ff_c < 2$	Very cohesive
$2 < ff_c < 4$	Cohesive
$4 < ff_c < 10$	Easy-flowing
$10 < ff_c$	Free-flowing

3.3. Effect of powder recycling

It is important to note that the use of recycled powders may have a different outcome on the spread quality in comparison to using virgin powders. Recycled powders may contain deformed particles or particle with smaller satellites produced during sintering process. Mussatto et al. (Mussatto et al., 2021) studied the effect of particle morphology (satellites on particle surface) on their flow properties. A highly spherical powder with satellites had marginally worse flow characteristics than less spherical particles without satellites. This was attributed to the possible mechanical interlocking between particles with satellites. Nguyen et al. (Nguyen et al., 2017) investigated the effect of Inconel 718 (IN718) powder recycling on their flow properties. The recycled powders had a slightly lower flow rate measured with Hall flowmeter. The drop in flow properties was caused by particle deformation and agglomeration during recycling. Furthermore, powders may come into contact with humid air during or after recycling, which may cause a change in particle cohesion. Because of particle deformation during recycling, the apparent and tapped densities of virgin powders were reported to be higher than those of recycled powders. However, different trend has been reported for the true density. The recycled powder's true density was slightly larger than the virgin powder. This is mainly due to re-melting of the particles with porous structure and the removal of entrapped gas inside them. Furthermore, the compressibility of the virgin powders was reported to be much lower than the recycled powders. Chandrasekar et al. (Chandrasekar et al., 2020) also reported that recycled powder had a higher tendency to agglomeration during powder spreading compared to the virgin powder. Roy et al. (Roy et al., 2023) stated that recycling powders led to changes in the chemical and morphological properties which adversely affected the quality of the spread layer. The non-sphericity present in particles was a result of fractures and adhesion due to the recycling process (Roy et al., 2023).

Clayton et al. (Clayton et al., 2015) evaluated the influence of powder recycling on their flow properties at low consolidation stress which could be relevant to the state of the powder condition during spreading. The recycled powder had higher FT4 flow energy which indicating lower flowability. Sieving the recycled powder, to improve its flowability, was reported to have a small impact. Mixing virgin and recycled powders, with a ratio of 75%–25%, produced a powder blend with flow properties similar to virgin powder.

Moreover, Wu et al. (Wu et al., 2023a) numerically investigated the effects of utilising recycled Ti6Al4V powder mixtures on the spreading process in powder bed based AM. They stated that a powder mixture with less than or equal to 60% recycled material could guarantee stable laser powder bed fusion with desirable powder bed qualities, while any mixture consisting of more than 60% recycled material would degrade the powder bed and generate defected layers (Wu et al., 2023a). It was reported that after every use of Ti6Al4V powders, they further agglomerated and deformed, which broadened the particle size distribution and worsened the particle morphology distribution. They further concluded that mixture with more than 60% recycled material exacerbated the particle interaction in front of the spreader resulting into uneven and heterogenous layers (Wu et al., 2023a).

3.4. Effect of spreading conditions on the quality of spread powder layer

The spreading conditions used during the printing process have a considerable impact on the quality of the spread powder layer in additive manufacturing (AM). The homogeneity and compactness of the powder layer are influenced by a number of parameters, including spreading speed, spreading force, and powder layer thickness. Optimal spreading conditions result in a well-distributed and densely packed powder layer, which leads to better surface quality and less porosity in the final printed object. Inadequate spreading conditions, on the other hand, can result in uneven powder dispersion, layer thickness fluctuations, and poor interlayer bonding, all of which have a detrimental impact on the overall quality and mechanical qualities of the printed component. As a result, rigorous adjustment of spreading conditions is required to get high-quality and reliable powder bed. In the following, we review the influence of different spreading parameters.

3.4.1. Gap size between the spreader and build plate

The quality of spread layer is directly influenced by the chosen gap size such that a smaller gap size results into poor spreading while a larger gap size enhances a more uniform spread layer (Meier et al., 2019; Snow et al., 2019; Spierings et al., 2011). By considerably reducing the gap size, several important drawbacks such as mechanical arching and transient jamming may occur, thus impacting production speed and quality of final part (Nan et al., 2018; Xu & Nan, 2023). Jamming and patchy coverage due to the small gap sizes may lead to defects upon bonding during sintering of each layer (Khairallah, Anderson, Rubenchik, & King, 2016; Townsend, Senin, Blunt, Leach, & Taylor, 2016). Since most AM machines typically operate with the ranges of 50 and 200 μm gap size (e.g. electron beam melting (EBM)), it is therefore imperative to gain an in-depth understanding of powder behaviour in smaller gap sizes (Ahmed, Pasha, Nan, & Ghadiri, 2020; Gong et al., 2012; Herzog, Seyda, Wycisk, & Emmelmann, 2016). In order to mitigate transient jamming through smaller gaps, Nan et al. (Nan et al., 2018) suggested that a suitable gap size can be chosen based on the powder's D_{90}. Xiang et al. (Xiang et al., 2016) also states that increasing the layer thickness results in an increase in coordination number and packing density. While there is a need for having thin powder layers in the AM industry, an option to reduce their drawbacks is to improve the flowability of the powders in order to produce smoother layers (Fayazfar et al., 2018).

Furthermore, Chen et al. (Chen, Cheng, Li, Wei, & Yan, 2022) on their study of the effects of process parameters on the quality of multi-layers stated that for a given nominal powder layer thickness, lower packing density and fusion ratio is detected on the first few layers. Interestingly, the actual powder layer thickness increases layer-by-layer due to the shrinkage of the powder bed fusion. This increase gradually improves the packing density and fusion ratio of the layer which is known as the compensation effect (Chen et al., 2022). There are limited studies that focused on multi-layer spreading of powders in AM. For example, Wu et al. (Wu, Zafar, & Zhao, 2021) numerically investigated the consolidation mechanism in powder bed fusion during multi-layer process where it was stated that the generation of quality multi-layers was dependent on adequate inter and intra-layer bonding (Wu et al., 2021). They further concluded that a high layer thickness poses limitations on building effective bonding between layers, requiring more energy to melt the material (Wu et al., 2021).

3.4.1.1. Powder bed packing fraction/volume fraction. Han et al. (Han, Gu, & Setchi, 2019) developed a theoretical and experimental approach to investigate the effect of spreader gap size on the void formation in the powder bed. They reported that spreading at a gap size larger (16% or 45%) than the bulk powder average particle diameter resulted in a uniform first layer powder bed. Spreading with a gap size 45 percent bigger than the average particle size resulted in “short-feed faults” in the powder bed during multi-layer deposition. The short-feed defect occurs when there is a shortage of powder at the end of the layer-recoating when insufficient amount of powder is utilised (Han et al., 2019). Yao et al. (Yao et al., 2021a) used DEM to investigate the effect of spreader gap size on the powder bed's packing fraction. The gap height increased the packing density of the powder bed until a certain value, after which the gap height had no effect on the powder bed density. Meier et al. (Meier et al., 2019) noted that for the tested cohesive powder (attained by increasing the surface energy of the powder four times), the gap height should be 3 to 4 times greater than the powder's D_{90} to achieve a “continuous powder layer.” For the less cohesive powder, the gap height shall be 2 times larger than D_{90} of the powder to attain “continuous powder layer”.

Fouda and Bayly (Fouda & Bayly, 2020) investigated the effect of the gap thickness (from 2 to 6 particle diameters, corresponding to 100–300 μm) on packing fraction reduction caused by shear induced dilation of titanium alloy (Ti6AlV4) powder. They reported that by decreasing the gap thickness, the total bed packing fraction of the powder bed reduced approximately linearly from 33% to 15%. They proposed three mechanisms to account for this behaviour: (i) an initial shear-induced dilation imposed by the blade, (ii) the dilation and rearrangement of the powder moving through the gap and (iii) mass conservation as the particles decelerate and settle in the deposited powder layer.

Xiang et al. (Xiang et al., 2016) further investigated the packing fraction of powders beds as a function of spreader gap sizes. By increasing the gap size, the disparity in packing densities of the three different powders examined was minimised. When the gap size was increased, the packing density rose for all three tested powders and tended to stay steady (at larger gap sizes compared to the smaller ones). Furthermore, they have studied the effect of powder bed compression after powder bed layering. Except for the shortest gap size, the packing density of all investigated powders (monosize distribution, Gaussian distribution, and bimodal size distribution) following compression was more or less identical for all gap sizes. Haeri et al. (Haeri et al., 2017) reported a larger solid volume fraction and lower surface roughness at higher gap sizes. Zhang et al. (Zhang et al., 2020) used DEM to study the effect of roller's gap size on the powder's bed density of Al_2O_3 powder (D_{50} of 48 μm). Spreading at the gap size in the same range as the tested powder's D_{50} led to a very low powder bed density. The authors suggested a gap size 3 times larger than the powder's D_{50} was required to attain a uniform powder bed. Nevertheless, Nandhakumar and Venkatesan stated in their review article that a reduction in the layer thickness while utilising fine powder sizes, resulted into increased layer packing fraction and minimised porosity (Nandhakumar & Venkatesan, 2023).

3.4.1.2. Powder flow through the blade gap and empty patch formation in the deposited powder bed. Ahmed et al. (Ahmed et al., 2020) studied the effect of gap size on the size and frequency of empty patch formation during spreading of gas-atomized metal powders (D_{10}, D_{50} and D_{90} of 20 μm, 32 μm and 45 μm, respectively). The spreader blade was manually moved with a specified gap size to disperse the powder over an abrasive paper powder bed to achieve a fully-rough frictional foundation. The size and frequency of the empty patches was analysed by processing the SEM picture of the powder bed using ImageJ and MATLAB software. Large empty patches were formed at smaller gap sizes. This was due to particle jamming between the powder bed and the blade during powder spreading. The formation frequency of the empty patches decreased when the gap size increased. Nan et al. (Nan et al., 2018) analysed the transient jamming of gas-atomized metal powders (D_{10}, D_{50} and D_{90} are 20 μm, 32 μm and 45 μm, respectively) during spreading with a blade shape spreader. They focused on the influence of gap size (represented as D_{90} of the tested powder) on the probability and mean size of empty patches as an indication of jamming duration. They reported that the number of empty patches decreased sharply when normalised gap size (gap size/D_{90}) increased. No empty patches at the normalised gap size of 3 were detected. They found that when the gap size decreased, so did the mean length of empty patches in the spread layer (jamming duration) and the chance of empty patch creation. The survival time of jamming as a function of gap size were also studied. Two different jamming types were identified, the jamming with shorter duration which occurred at higher number/frequency as well as jamming with longer duration which occurred at lower number/frequency. At larger gap size, jamming duration and frequency decreased. Because of jamming at small gap sizes, the powder heap behind the blade had a higher proportion of large particles, a phenomenon akin to size segregation (Nan et al., 2018).

3.4.2. Spreader velocity

Generally, there is an agreement within literature that the spreader velocity has a notable effect on the quality of spread layer. According to Parteli and Pösschel (Parteli & Pöschel, 2016) higher spreader velocities result in a looser packing, accompanied by larger voids between particles; mainly because of the limited time for other particles to fill up the voids (Parteli & Pöschel, 2016; Yan et al., 2017). There is a consensus of authors confirming that a higher spreader velocity would not only result into a lower packing fraction but also increased surface roughness in the deposited layer (Fouda & Bayly, 2020; Haeri et al., 2017; Parteli & Pöschel, 2016; Yim, Bian, Aoyagi, Yamanaka, & Chiba, 2023). A further explanation on the reduced packing fraction of the deposited layer is due to the inertia of powder during spreading, which increases with higher spreader velocities (Fouda & Bayly, 2020). It is also confirmed by Meier et al. (Meier et al., 2019) that an increase in spreader velocity results into a lower mean layer thickness due to the powder dynamics after the blade, which ultimately reduces the packing fraction. The deposition rate increases linearly with an increase in spreader velocity, however this reaches an asymptotic value, where any value above this limit has no change on the deposition rate (Nan & Ghadiri, 2019; Snow et al., 2019). An increase of spreader velocity leads to an increase in force and pressure of the moving particles in the powder heap (Chen et al., 2020). As a result of increased velocity of the particles, the collision also increases which leads to an increased unconfined movement of particles. This process ultimately reduces the coordination number (Chen et al., 2020). All in all, implementing higher velocities aids to minimise production time and throughput. However, this may jeopardize the quality of the spread layer such as porosity and surface roughness. Hence, it is crucial to thoroughly understand the mechanism of velocity during spreading to formulate the best compromise between production time and surface quality (Desai & Higgs, 2019; Fouda & Bayly, 2020; Wang, Li, Zhou, Zhang, & Yu, 2023).

The following section thoroughly discusses the effects of spreader velocity on the spread layer's surface roughness, porosity and packing fraction and powder bed uniformity.

3.4.2.1. Powder bed surface roughness. Blade speed has large impact on powder bed surface roughness, particularly better uniformity is attained when the blade spreader speed is lower than 80 mm/s (Mussatto et al., 2021). Lee et al. (Lee et al., 2020) investigated the impact of spreader speed on the segregation behaviour of Co–Cr powder with D_{50} of 52.08 μm. They reported that the particle size distribution of the powder bed had more fine particles when the blade spreader velocity increased. Lupo et al. (Lupo, Ajabshir, Sofia, Barletta, & Poletto, 2023) provided experimental metrics for assessing the quality of the powder layer in terms of layer surface analysis (surface roughness) by developing a set-up that resembled the SLS spreading step. They stated that in most cases, the quality of the spread layer decreased with an increase in the blade spreader velocity, where an increase in the layer surface roughness was observed (Lupo et al., 2023). Haeri et al. (Haeri et al., 2017) used DEM to investigate the effects translational velocity of a blade shape and a roller spreader on powder bed quality in terms of surface roughness and bed volume fraction of two types of custom-milled PEK/PEEK powders with non-spherical particles. They reported that larger translational velocity leads to a higher surface roughness and lower volume fraction in the powder bed. In addition, they reported that for spherical particles (aspect ratio of 1), surface roughness is a weak function of roller speed. This effect was not seen for the void fraction in the powder bed. Haeri (Haeri, 2017) also compared surface roughness of powder beds attained by using roller and elliptical shape blade spreaders at different spreader velocity. The surface roughness of powder bed produced by an elliptically shaped spreader was lower than the roller at all tested transitional velocity.

Desai and Higgs (Desai & Higgs, 2019) developed a model based on DEM simulation to investigate the effect of roller spreader velocity on powder layer roughness of Ti–6Al–4V powder. For the simulation, smooth, spherical and cohesionless particles were considered. The lowest surface roughness was attained when there was not any rotational speed in the spreader. Furthermore, the increase in surface roughness was more drastic in powder beds produced with the clockwise rotated spreader (opposite direction of translational movement) compared to an anti-clockwise spreader (same direction of translational movement). Chen et al. (Chen et al., 2020) used DEM simulation and experimental validation to investigate the effect of spreader's speed on powder bed surface roughness, of a 316 L stainless powder with spherical particles and particle size range from 7.5 μm to 55 μm. The rotational speed of the roller was fixed at 2π rad/s while the spreading speed was varied. Powder bed surface roughness was increased monotonically with the increase of the roller spreading speed.

Parteli and Pöschel (Parteli & Pöschel, 2016) used DEM simulation to investigate the effect of counter clockwise rotating roller's speed on PA12 powder bed surface roughness. They tested the roller speeds in the range of 20–180 mm/s where larger roller's speed resulted in the higher surface roughness. Parteli and Pöschel (Parteli & Pöschel, 2017) numerically investigated the effects of coating speed on the powder bed's surface roughness by utilising realistic particle shapes and incorporated inter-particle attractive interactions (van der Waals). They found that an increase in the coating speed resulted into an increase in the powder bed surface roughness, which was a consequence of agglomeration due to cohesive interparticle forces (Parteli & Pöschel, 2017).

Furthermore, Lee et al. (Lee et al., 2020) studied the effects of particle spreading dynamics on powder bed quality in terms of surface roughness, by proposing a computationally efficient multi-layer powder spreading simulation model. The effect of particle-spreader interaction on powder bed quality was investigated, where they stated that an increase in the spreader velocity would enhance the particle segregation leading to inhomogeneous powder packing and rougher surfaces (Lee et al., 2020).

3.4.2.2. Powder bed's mass, density and volume fractions. When the spreader velocity is low, the particles have more time to settle and compact. This can lead to an increase in the bed's mass, as more particles are compressed within a given area. The density of the bed also tends to increase, as the particles become more closely packed together. In terms of volume fractions, a low spreader velocity typically results in a higher solid volume fraction within the bed. This is because the particles have less chance to move and rearrange, leading to a more uniform distribution of solid particles (Habiba & Hebert, 2023). This was further supported by Hulme et al. (Hulme et al., 2023), where they conducted a study on a single layer spreading to derive the layer density of twenty four powders from eight suppliers. They investigated velocities ranging from 1 mm/s to 500 mm/s and stated that an increase in the spreader velocity resulted into a reduction of the powder bed density due to insufficient time for powders to rearrange while passing below the spreader (Hulme et al., 2023).

A high spreader velocity can have the opposite effect. The kinetic energy imparted by the faster movement of the spreader can cause the particles to disperse and become more loosely arranged. This can decrease the overall mass and density of the bed, as well as reduce the solid volume fraction. It's important to note that the specific effects of spreader velocity on powder bed properties may vary depending on factors such as particle size, shape, and surface properties. Additionally, other parameters, such as the angle and design of the spreader, can also influence the outcomes.

Zang et al. (Zhang et al., 2020) used DEM to study the effect of both roller's translational and rotational velocity on the powder-bed's density of Al_2O_3 powder (D_{50} of 48 μm). They found that a higher bed density was attained at lower roller's translational velocity and a bigger roller diameter resulted in a larger compression zone in the powder bed, leading to a higher bed density (Zhang et al., 2020). Desai and Higgs (Desai & Higgs, 2019) investigated the effect of roller spreader velocity (both rotational and translational speeds) on “mass of powder retained in the sampling region” (M_S) and the “volume of powder spread throughput” (Q_s), as expressed by Equations (4) and (5), respectively.

$$M_s = \frac{\pi\rho}{6}\sum_{K=1}^{N} \varnothing_k^3 \tag{4}$$

Where N is the number of powder particles in the sampling area, $\varnothing_k$ is the diameter of the kth particle and ρ is the material density of powder particles.

$$Q_s = U \bullet thk_{avg} \tag{5}$$

Where U is the translation speed of the spreader, thk_{avg} is the average thickness of the powder bed.

They investigated a range of roller translational speed of 40–100 mm/s and rotation speed of 20 to −20 rad/s. Both metrics (M_S and Q_s) increased when spreader rotational velocity decreased from counterclockwise values (positive values) to zero. This was attributed to the fact that lower energy is transferred from the spreader to the powder bed when rotational speed is decreased. In contrast, as the roller's rotation changed from counterclockwise to clockwise both metrics increased sharply. This observation was attributed to the fact that powder spreading with roller that rotates clockwise causes many powder layers to be deposited, whereas powder spreading with a counter clockwise spreader causes a single layer to be deposited on the powder layer. When the clockwise rotational speed increased, both metrics initially increased and then decreased. The dependence of M_S on the spreader's translation speed was maximum only for the lowest clockwise value of −5 rad/s.

This study shed light on the significant influence of roller spreader velocity on powder bed characteristics. The findings indicated that lower rotational velocities resulted in increased mass of powder retained and volume of powder spread throughput, attributed to reduced energy transfer. Conversely, transitioning from counter clockwise to clockwise rotation led to a sharp increase in both metrics due to the deposition of multiple powder layers. The research emphasized the interplay between rotational and translational speeds, with the lowest clockwise speed exhibiting the strongest dependence on translation. These insights contribute to our understanding of optimizing powder bed properties.

Drummer et al. (Drummer, Drexler, & Kühnlein, 2012) investigated the effect of roller spreader speed on the powder bed density of Polyamide 12. A slight increase in powder bed density was reported when the spreader's translational speed increased from 80 mm/s to 120 mm/s. This is in contrast with the work of Haeri (Haeri, 2017). Snow et al. (Snow et al., 2019) studied the effect of spreader blade velocity at two levels (50 and 150 mm/s) on “the percentage of the build plate covered by spread powder”. The spreader velocity had no effect on the proportion of the build plate that was covered by spread powder. Haeri (Haeri, 2017) reported that at low spreader velocity, an elliptical shape spreader produced a bed with slightly lower volume fractions than a roller spreader. However, when compared to the roller, the improved blade form was reported to be less sensitive to higher spreader translational velocity. As a result, at greater translational velocities, the optimised blade outperformed the roller.

Nan et al. (Nan, Pasha, & Ghadiri, 2020) used DEM-CFD simulations to study effect of gas drag during spreading with a roller spreader. The impact of gas and particle interaction during spreading with a roller has been analysed and quantified in terms of both powder bed properties and the particle flow in the heap. The gas drag force has a deleterious impact on the powder bed quality due to the lower convection and circulation of particles within the heap. Higher gas drag as a result of higher roller speed, causes lower particle fraction in the powder bed. Increasing the inter-particle adhesion forces between particles (higher particle surface energy) surprisingly counteracts the adverse effect of gas drag and hence improve the quality of the powder bed.

3.4.2.3. Powder bed's porosity and packing fraction. Desai and Higgs (Desai & Higgs, 2019) reported on the spread layer porosity, which increased with the roller's translational speed. The simulation findings showed that when the roller's rotating direction changed from anti-clockwise to clockwise, the layer porosity increased.

When spreading speed was raised in the low range (50–100 mm/s), tiny patches on the powder bed were detected by Chen et al. (Chen et al., 2020). Significantly larger empty patches on the powder bed were created at spreading speeds ranging from 100 to 300 mm/s. The powder bed's relative packing fraction steadily decreases with an increase in the spreader's velocity from 10 to 500 mm/s (Chen et al., 2020). It should be noted that, the powder bed relative packing fraction was very low at spreader velocities larger than 300 mm/s. One of the purported advantages of using a counter-rolling-type powder spreader is greater pressure on the powder bed surface, which may raise the packing fraction of the powder bed. However, this study (Chen et al., 2020) demonstrated the opposite result, whereby increasing spreader's pressure by increasing the spreading speed was unfavourable for the packing quality of the powder layer. Yao et al. (Yao et al., 2021a) used DEM to investigated the effect of spreader velocity on the “volume of pore space around the particle” in the powder bed. The powder bed has larger “volume of pore space” when spreader velocity increases. The packing density of the powder bed, composed of Co–Cr particles with D_{50} of 52.08 μm, fell by roughly 5% when the spreader velocity increased by 5 times (Lee et al., 2020).

Fouda and Bayly (Fouda & Bayly, 2020) used DEM simulation to investigate the effect of vertical blade spreader speed on packing fraction reduction due to shear induced dilation of titanium alloy (Ti6AlV4) powder. The powder has spherical, mono-sized and non-cohesive particles. The 5 tested blade velocities were 10, 30, 50, 80 and 100 mm/s. The gap size between the blade and powder bed was kept constant at 200 μm. A fall in packing fraction with increasing spreading velocity was reported. Meier et al. (Meier et al., 2019) also reported that higher spreader speed leads to a lower mean layer thickness and packing fraction. Yao et al. (Yao et al., 2021a) employed DEM to investigated the effect of spreader velocity on the packing fraction (uniformity) of the powder bed by using 316 L stainless steel. The results also showed that higher blade speed resulted in lower bed quality.

Yan et al. (Yan et al., 2017) employed DEM to investigate the effect of rake spreader speed (between 0.03 m/s to 0.15 m/s) on relative packing fraction of the powder bed. In their simulation, they used spherical particles with diameters ranging from 30 to 50 μm and attempted to produce a Gaussian distribution. At lower translational speed, rake shape does not affect the powder bed packing fraction. As spreader speed increased, the packing density of powder beds dropped. They have also experimentally studied the effect of spreader vibration on the powder bed packing fraction. The rake speed controls the vibration, which in turn influences the powder distribution. Furthermore, Schiochet Nasato et al. (Schiochet Nasato, Briesen, & Pöschel, 2021) investigated the effects of vibrating recoating mechanism for the deposition of polyamide 12 powders using DEM and evaluated the porosity of the powder layer. It was found that a small frequency and amplitude with lower spreader velocities resulted into a reduction of the powder bed's porosity. However, excessive vibrational energy loosened the powder bed due to vibro-fluidised particles. The negative effects of larger spreader velocities were mitigated using the vibrating mechanisms, which lowered the porosity of the powder layer (Schiochet Nasato et al., 2021). Furthermore, Angelidakis et al. (Angelidakis et al., 2023) also stated that the quality of the Polyamide 12 spread layer with respect to the layer density and surface roughness could be improved through efficiently utilising a vibrating spreader mechanism. The application of vibration on the spreading of non-spherical, cohesive particles was also investigated using discrete element method, where similar to Schiochet Nasato et al. (Schiochet Nasato et al., 2021), small frequency and amplitude with lower spreader velocity created denser powder beds with reduced porosity (Angelidakis et al., 2023). It is therefore imperative to efficiently choose the vibration conditions in combination with specific translational spreader velocity so as to create optimal powder beds with low porosity and high packing fractions.

Chen et al. (Chen et al., 2022) conducted a series of single and multi-layer powder spreading tests to investigate the role of spreader velocity in laser powder bed fusion. They agreed with previous literature that the layer packing density decreases with an increase in spreader velocity but interestingly stated that in multilayer processes the high spreader velocities were successful in producing defect free layers and ultimately parts with enhanced mechanical properties. The reduction of defects such as pores with an increase in spreader velocity was mainly attributed to the reduced cooling time between layers (Chen et al., 2022). Habiba and Hebert utilised a computational approach to assess the quality of multi-layers in laser powder bed AM (Habiba & Hebert, 2023). They investigated the effects of spreader velocity on the layer porosity and packing fraction. They also stated that the reduction in the spreader velocity resulted into lower layer porosity and enhanced packing fraction as powders had sufficient time to settle accordingly under the spreader (Habiba & Hebert, 2023). Additionally, they further explained that the porosity of the powder bed decreased significantly at the start of the spreading for the first two to three layers and continued to decrease along the spreading direction. This was due to the direct interaction of particles within the first layer with the effects of the build plate (Habiba & Hebert, 2023).

3.4.2.4. Powder bed uniformity. Powder bed uniformity as a powder layer characteristic is used alongside packing fraction and surface roughness to assess the quality of spread layers (He, Gardy, Hassanpour, & Bayly, 2020 a; Wu et al., 2023b). Yao et al. (Yao et al., 2021a) investigated the influence of various process parameters such as blade velocity on the quality of the spread layer in terms of the layer uniformity. They stated that an increase in blade velocity worsened the structure uniformity of the powder bed due to reduced particles packing and void filling. They further quantified the uniformity of the powder bed by the variation coefficient (ρ_{VC}) as expressed by Equation (6) below:

$$\rho_{VC} = \frac{\rho_{st}}{\overline{\rho}} \tag{6}$$

Where ρ_{st} was the standard deviation of the packing density and $\overline{\rho}$ was the average value of the packing density (Yao et al., 2021a). Yao et al. (Yao et al., 2021b) numerically studied the spreading behaviour of 316 L stainless steel powders where the effects of blade velocity on the quality of the powder bed was examined. The local uniformity of the powder bed as a powder bed quality was investigated using the contact force network of the local structure and the corresponding coordination number (CN) distribution of particles. They concluded that lower blade velocities led to an enhanced spread layer uniformity (Yao et al., 2021b).

Moreover, Wu et al. (Wu et al., 2023b) researched on how to improve the spreadability of Ti6Al4V powders by characterising powder layers in uniformity through parametric studies, where they concluded that an increase in blade velocity resulted into loose and non-uniform powder layers. They further stated that spreading powders at low spreader velocities and greater gap sizes would facilitate dense and uniform powder layers but would restrict rapid fabrication required in AM (Wu et al., 2023b). Furthermore Si et al. (Si et al., 2021) numerically investigated the effects of process parameters such as blade velocity on the spreading behaviour of Polyamide 6 powders, where the packing density and layer uniformity was utilised to assess the quality of the spread layer. They stated that the lower blade velocity can improve the packing density and layer uniformity, however, poses limitations on the production efficiency.

3.5. Spreader type and material

There are different types of spreaders in AM such as flexible silicone, rigid steel, ceramic blades and rollers (Snow et al., 2019). Snow et al. (Snow et al., 2019) gathered that the coverage on the build plate mostly depends on the spreader material rather than spreader velocity. They suggest that silicone blades provide better percentage of spread for powders with higher angle of repose (reduced flowability), whereas using rigid steel blades resulted in better coverage for powders with lower angle of repose (high flowability) (Snow et al., 2019). Moreover, Haeri et al. (Haeri et al., 2017) stated that a roller had a better performance compared to a blade on the quality of the spread layer at the same operating conditions. This was due to the blade having less contact with the powder bed resulting into particle dragging and consequently lowering the layer quality. Utilising a roller provided a much larger contact area with the bed, allowing efficient particle rearrangement and a higher powder bed density (Haeri et al., 2017). In their further publication, the conducted study distinguished between two spreader types, a roller and an optimised blade; where a conventional blade was modified geometrically to produce a super elliptic profile (Haeri, 2017). It was shown that the optimised blade had better performance at high translational speeds generating smoother layers compared to a roller (Haeri, 2017). Furthermore, Beitz et al. (Beitz et al., 2019) investigated the effects of blade geometry on the surface roughness of PA12 powder layers in SLS, they observed significant effects on the surface quality and packing bed density (Beitz et al., 2019). They concluded that the flat-bottomed blade produced the lowest layer surface roughness compared to sharp and slightly rounded blades. This was due to the compression induced by greater horizontal contact zones between the bed and blade, which led to a more uniform and dense powder bed (Beitz et al., 2019). Notably, the effect of spreader geometry on the quality of spread layer is minimised during lower translational velocities (Yan et al., 2017).

Budding and Vaneker (Budding & Vaneker, 2013) studied the effect of different spreader shape (blade, forward and backward rotating roller and the combination of roller and blade) on the powder bed density of gypsum powder. When spreading a single layer with both the roller and blade shapes, the powder bed quality improved. The powder bed density increased by either an increase in the roller diameter or using a forward rotating roller. However, using a forward-rotating roller causes the cohesive gypsum powder to stick to the roller and hence surface quality reduces.

Salehi et al. (Salehi et al., 2023) investigated two recoater blade geometries including a flat “nose” spreader with a larger cross-sectional area and a tapered, sharp-edge spreader with a lower cross sectional area. They concluded that the recoater with a flat “nose” resulted in an increase in the relative packing fraction of the spread layer compared to the tapered, sharp-edge spreader. The flat “nose” geometry applied a downward force on the particles as they spread under the blade, which enabled the particles to settle into uniform and even layers (Salehi et al., 2023). Furthermore, Reijonen et al. (Reijonen, Revuelta, Metsä-Kortelainen, & Salminen, 2024) investigated the effects of hard (steel) and soft (rubber) recoater blades on the porosity and processability of thin walls and overhangs in laser powder bed AM. It was mentioned that when constructing bulk material without any complex characteristics, both the hard and soft recoater resulted in good processability with extremely low porosity values less than 0.001%. However, when producing more complex geometries substantial difference was observed with the difference in spreader types. Soft (rubber) recoater blades resulted into lower layer porosities while the hard (steel) recoater blade generated higher layer porosities as the interaction between the hard blade and thin feature created severe disturbances on the powder bed that resulted into local variations of the effective layer thickness and consequently increased porosity (Reijonen et al., 2024).

Yao et al. (Yao et al., 2021 a) used DEM to investigate the effect of blade inclination angle on the packing fraction (uniformity) of the powder bed. The results showed that the packing density of the powder bed increased when the blade spreader angle was 15° in the flow direction. This behaviour is due to powder bed being compressed by the inclined angle during spreading as opposed to the vertical blade. This impact from the inclined blade is similar to the impact reported by Haeri et al. (Haeri et al., 2017) for the super-ellipse type spreader, which produced a higher powder bed density than both non-inclined blade and roller spreader.

Wang et al. (Wang, Yu, Li, Shen, & Zhou, 2021) comprehensively studied the effects of spreader geometry on powder spreading processes using discrete element method. They investigated six spreader geometries and their individual influence on spread layers in terms of spreading efficiency and powder layer homogeneity. Fig. 8 below represents the different spreader types with their respective top and side spread layer profiles. The simulation results suggested that the round blade, Fig. 8(f), deposited the largest amount of powder followed by the inclined blade, Fig. 8(a). They concluded that the powder layers spread by a roller, Fig. 8(e), demonstrated the worst homogeneity while the round blade spreader, Fig. 8(f) generated the best spread layer in terms of

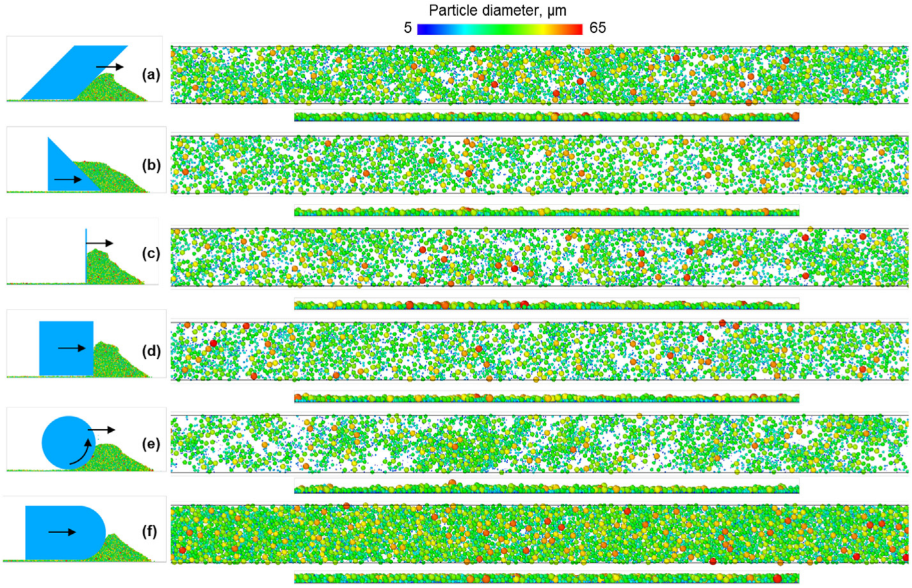

Fig. 8. Top and side profiles of powder spread layers with different spreader geometries: (a) inclined blade; (b) declined blade; (c) vertical blade; (d) wide blade; (e) roller; (f) round blade (Wang et al., 2021).

spreading efficiency and powder layer homogeneity (Wang et al., 2021).

Furthermore, Wu et al. (Wu et al., 2022) investigated the effects of modifying the bottom side of the blade on the quality of the Ti64 powder spread layer in terms of the particle deposition behaviours and the packing properties. They investigated the underlying mechanisms of the evolution of packing quality of the vertical blade, intact-arc blade (Haeri, 2017) and half arc blade (Wu et al., 2022) as demonstrated in Fig. 9 below. They concluded that the layer packing fractions increased with the modifications to the vertical blade bottom, where the particle deposition behaviour improved after the introduction of the intact-arc bottom, Fig. 9(b), whereas the newly designed half-arc blade, Fig. 9(c) facilitated superior packing properties compared to the other blades (Wu et al., 2022).

3.5.1. Powder bed's surface roughness

As stated previously, Haeri et al. (Haeri et al., 2017) reported that the application of blade spreader causes larger surface roughness compared to a roller. This was attributed to the fact that a large contact area with the powder bed was attained with the roller spreader. This allows a gradual particle rearrangement over the powder bed during spreading. The blade shape spreader interacts with the powder bed at a single point. This causes particles in the

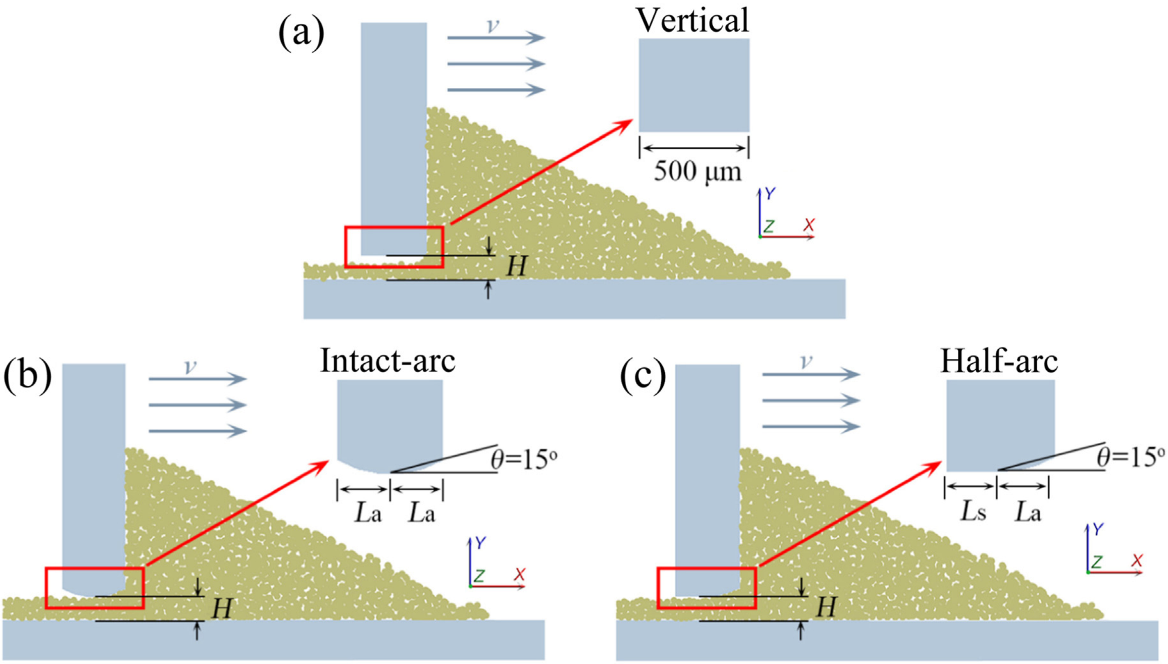

Fig. 9. Blades utilised in simulation: (a) vertical blade; (b) intact-arc blade (Haeri, 2017); (c) half-arc blade (Wu et al., 2022).

powder bed to be dragged when the blade spreads the powder. In another study, Haeri (Haeri, 2017) compared surface roughness of powder beds obtained by using roller and elliptical shape blade spreaders. In comparison to the use of roller spreaders, the results demonstrated that the elliptical shape blade spreader provides a powder bed with lower surface roughness.

Beitz et al. (Beitz et al., 2019) stated that using a flat bottom blade shape spreader produced the lowest arithmetic surface roughness. This was explained as due to the higher compression attained by using this blade shape. However, on the other hand, spreading powder with either sharp and round blade shape spreaders produced a powder bed with a larger surface roughness due to lower “effective vertical compression”. Meier et al. (Meier et al., 2019) reported that using a recoating blade with a lower adhesive force enhanced the layer characteristics of very fine powders, but not the coarse powders.

Moreover, Salehi et al. (Salehi et al., 2022) developed a “spreadability tester” to measure the quality of the spread layer in terms of the powder bed surface roughness using a novel shadowgraphy technique. They employed two different blades, i.e. one with higher cross-sectional area and flat “nose” and another one tapered recoater with the smaller cross-sectional area and sharp edge. They stated that spreading polymer powders with flat nosed recoater resulted in slightly higher surface roughness than the sharp edged recoater, at a gap size $2*D_{90}$ (Salehi et al., 2022).

3.6. Environmental conditions affect spreading behaviour: temperature, humidity and flow behaviour

Temperature as an environmental factor significantly influences the spreading behaviour of powders in layer based additive manufacturing. There is limited reported work in the literature on the effect of temperature on the spreading behaviour of powders. Zinatlou Ajabshir et al. (Zinatlou Ajabshir, Hare, Sofia, Barletta, & Poletto, 2024 a) investigated the effect of temperature on polymer powders spreading behaviour in powder bed fusion additive manufacturing, where they observed that an increase in temperature resulted in a decrease in the layer packing fraction due to an increase in particle cohesivity, which caused the formation of agglomerates in the spread layer. They also concluded that the shear stresses in front of the blade increased at higher temperatures due to the higher interparticle forces between particles. It has been reported that elevating the temperature increases the kinetic energy and cohesive inter-particle forces (Ruggi, Barrès, et al., 2020; Ruggi, Lupo, et al., 2020) due to higher plastic deformation under cohesion conditions in contact points, resulting into an increase in shear stresses (Nan, Rahman, Ge, & Sun, 2023).

Humidity as an environmental condition also plays a key role in the spreading behaviour of AM powders as it can impact both their chemical and physical characteristics. Although humidity is controlled in the chambers during the spreading and sintering phase, it can be less controlled during powder handling, transportation and packaging, hence, conditioning of powders is imperative for repeatable results (Cordova, Bor, de Smit, Campos, & Tinga, 2020; Nguyen et al., 2017). Haydari (Haydari, 2021) conducted a study on the spreading behaviour of stainless steel powder for additive manufacturing, where two samples exhibited similar flowability characteristics but very different spreading behaviour due to the impact of humidity. Furthermore, Haydari et al. (Haydari et al., 2024) expanded on their study, where the changes in the spreading dynamics of the two samples was a result of small yet significant difference in chemical composition and its consequent effect on moisture adsorption. They stated that the spreading behaviour significantly improved after drying in either the vacuum oven or a freeze dryer (Haydari et al., 2024).

Although humidity may act as a lubricant and conductor to dissipate electrostatic charge and facilitate flow in some conditions, its absorption on the surface of powders typically results in increased cohesivity and at high humidities, liquid bridges, which leads to agglomeration that consequently generates poor flow and lower packing density (Armstrong, Brockbank, & Clayton, 2014; Emery, Oliver, Pugsley, Sharma, & Zhou, 2009; Nguyen et al., 2017; Slotwinski & Garboczi, 2015).

3.7. Defining spreadability as a bulk powder characteristic in AM

Although there has been considerable research within literature regarding the spreading of AM powders, to date there is no general consensus that agrees upon the definition of the term “spreadability”. Different authors have introduced their own definition of the term spreadability which is mainly based on the packing efficiency and flowability (Snow, 2018). More detailed analysis of the spread layer has also been proposed. He et al. (He et al., 2020a) developed and demonstrated a digital spatial discretisation method for investigating spread layer structure distributions, including methods for identifying pores within the spread layer. For thin, quasi-2D layers, Roy et al. (Roy, Xiao, Angelidakis, & Pöschel, 2024) used a Voronoï-based method to quantify local variations in the surface morphology and packing structure of cohesive systems.

Some researchers have explicitly defined the term spreadability as a metric for powders in AM, while others refer to various measured parameters in relation to spreading behaviours. We have summarised these examples of in Table 2 and Table 3.

Based on the flowability-approach, Snow et al. (Snow et al., 2019) defined the spreadability of powders where they compared flowability measurements to the spreading behaviour of powders using an in-house spreading rig. Moreover, there are other flowability-based approach studies available within literature (e.g. Akib, Marzbanrad, Ahmed, & Li, 2022; Clayton et al., 2015; Jacob et al., 2018; Muñiz-Lerma et al., 2018; Nan & Ghadiri, 2019; Shi et al., 2004; Spierings et al., 2015).

Layer surface roughness as a measure of spreadability has been investigated by Beitz et al., (Beitz et al., 2019), and has been investigated in various studies as an important factor characterising the quality of spreadability (e.g. Haeri, 2017; Haeri et al., 2017; Mussatto et al., 2021). Parteli and Pöschel (Parteli & Pöschel, 2017) developed a DEM numerical tool to simulate powder coating using multi-sphere models. They quantified the spreadability of powders in terms of the surface roughness (Parteli & Pöschel, 2017).

Packing density and its uniformity are significant terms regarding the measure of spreadability within literature. Ahmed et al. (Ahmed et al., 2020) investigated formation of empty patches and the manifestation of particle jamming and expressed the powder layer uniformity as a measure of spreadability. Their experimental work involved manual spreading of the powder heap, which may result into user-dependent errors such as inconsistent speed at which the cutter is moved across. There are other uniformity-based studies available in literature (e.g. Muñiz-Lerma et al., 2018; Nan et al., 2018; Shaheen et al., 2019).

Yan et al. (Yan et al., 2017) stated that relative packing density would be an appropriate index to evaluate the powder spreading as more compacted powder bed would be normally desirable for the fabrication quality. Van den Eynde (Van den Eynde, 2018) measured the packing ratio (layer density over tapped density) for the spread layer and correlated that with the powder properties. Later, Haydari (Haydari, 2021) proposed that the results of spreadability could be better evaluated using the ratio of spread layer bulk density to the initial bulk density of powders. In her work, this ratio was defined as the “spreadability index”. The ratio of the layer bulk density to the initial bulk density of powders could be a useful index to assess

Table 2
Explicit definition of the term spreadability.

No.	Author	The term spreadability is explicitly defined as:
1	Snow et al. (Snow et al., 2019)	Percentage coverage on the built plate, the powder deposition rate and the rate of change of the avalanching angle. • Flowability of powders was used to define the spreadability of powders. • An exhaustive approach was implemented in correlating different flowability techniques to the spreading behaviour of powders in regard to the percentage coverage and powder clumping. • Some of the flowability techniques utilised did not represent the real spreading process in additive manufacturing.
2	Ahmed et al. (Ahmed et al., 2020)	The ability of powder to be spread uniformly as a thin layer of a few multiples of particle size without; the formation of any empty patches; presence of agglomerates; or rough surfaces. • Frequency of the formation of empty patches and their size is used to define the spreadability, which are a manifestation of particle jamming during the spreading process. • The proposed techniques measured the spreading of the powders at different gap sizes which replicates the spreading behaviour. The experimental outcomes were related well with Discrete Element Method simulation of the same system which provides a further development in assessing spreading behaviour of powders. • Experiments involved manually spreading which may be dependent on the user. Manually controlling the speed and movement at which the powder is spread may impact the spread layer.
3	Drake et al. (Drake, 2018)	"Ability of the powder to spread over itself, its interaction with build plate material, its interaction with the spreader blade or roller, as well as its interaction with partially built parts within the build chamber." • Particle characteristics to be used for quantifying spreadability. • The degree to which spreadability is affected by each of the above factors need to be thoroughly researched to accurately characterise the quality of AM powders. Mapping spreadability to the influence of each of the particle characteristics can allow a better understanding of powder performance.
4	Desai and Higgs (Desai & Higgs, 2019)	A quantification through the spread layer properties such as mass of spread layer, spread throughput, porosity of deposited layer and roughness of the spread layer. • Mass of powder in the sampling region and the porosity of the spread layer was used to quantify spreadability that is based on the ease at which the powder spreads. • The study shed light on the significant influence of spreader velocity on powder bed qualities such as layer roughness. These insights contributed to further understanding the importance of powder properties on the quality of spread layer. • Their worked focused on the quality of a single layer.
5	Jacob et al. (Jacob et al., 2018)	A correlation is established between the powder characteristics such as apparent density, flowability and powder bed density by considering different locations of powder spread on the built plate. • Powder flowability and properties such as particle size and size distribution are used to quantify spreadability. • The study applied different characterisation techniques to correlate flowability of different powders to the spreading dynamics. • This experimental work focused on the quality of a single layer rather than multi-layer analysis.
6	Beitz et al. (Beitz et al., 2019)	The ability to form a smooth powder bed during application. • Powder bed surface roughness is used to quantify the spreadability of powders with different particle size distributions. • The study utilised three blade shapes along with various characterisation techniques such as X-ray micro computed tomography (XMT) and confocal laser scanning microscope (LSM) to analyse the surface qualities. • The analysis of the spread layer is based on the surface roughness of a single powder bed layer.
7	Muñiz-Lerma et al. (Muñiz-Lerma et al., 2018)	A measurement based on powder flow and uniformity of the spread layer. • Powder flowability and spread density were used to quantify spreadability. • Their work compares properties of 3 a.m. powders to identify the minimum required acceptable feedstock using conventional powder characterisation as well as powder spread density, moisture sorption and work of cohesion. • The experimental work was compared to simulation results provided in literature, where free flowing spherical spheres were assumed, and the effects of surface energy and particle-particle interaction were not considered.
8	Haydari (Haydari, 2021) and Mehrabi et al. (Mehrabi et al., 2023)	The ratio of powder spread layer density over its natural bulk density • The spreadability index which is the ratio of the bulk density of the spread layer to the bulk density of the powder was used as an indicator for spreadability. • The work investigated powder flowability and spreadability, where they revealed that none of the flow test techniques utilised provided a correlation between the dynamic powder flow and powder spreadability. Therefore, caution is necessary when correlating powder flow behaviour with spreadability. • The experimental work investigated the quality of a single layer rather than multi-layer analysis.

the behaviour of powder before and after spreading or in other words, this index may be a viable metric to measure how much the packing of powders is affected by different parameters during the spreading process. The value of spreadability index is generally a value between 0 and 1, while, a value over 1 indicates an over packed or compacted layer which in powder bed system may not be desirable due to possible prevention of laser penetration through compacted layer (Haydari et al., 2024). This index was also used by Mehrabi et al. (Mehrabi et al., 2023) for the evaluation of Ti6Al4V powders spreadability. Moreover, there are further studies correlating the packing density to the quality of the spread layer (e.g. Cordova et al., 2020; Fouda & Bayly, 2020; Salehi et al., 2023; Shaheen et al., 2019; Van den Eynde, 2018).

Overall, existing metrics regarding spreadability in literature revolve around flowability, surface quality and packing, however, no general agreement can be found in the literature regarding the term "spreadability" in an additive manufacturing context. Therefore, defining a standard spreadability metric with respect to process parameters is essential in additive manufacturing. Moreover, the measurement of spread layer density in parallel with process parameters is lacking within literature.

4. Discussion on the technical and knowledge gaps and future development prospects

Various authors have attempted to define the term spreadability as an important parameter in additive manufacturing. However, to date there is no consensus regarding the definition of spreadability. The absence of standard and agreeable spreadability metrics is a notable gap within research, as there are no powder characterisation techniques to predict this behaviour within the powder feedstock (Snow, 2018). Lack of correlation between flowability and

Table 3
Indirect definition of the term spreadability.

No.	Author	Spread behaviour was investigated as:
1	Fouda and Bayly (Fouda & Bayly, 2020)	Established as a correlation between packing fraction and spreading behaviour. • Packing fraction of the layer was used to quantify the spread behaviour of powders. • DEM simulation was used to investigate the effect of process parameters such as the vertical blade speed and gap size on the layer packing fraction such that the former reduces the packing fraction while the latter increases it. • The work utilised mono-sized spherical particles and the inter-particle cohesion was not taken into account.
2	Nan et al. (Nan et al., 2018)	Spreading was investigated in terms of particle dynamics and transient jamming. • Particle jamming, and the formation of empty patches was used to understand the spreading behaviour of powders. • Their DEM simulation investigated the effects of process parameters such as spreader velocity and gap size on the powder spreading behaviour. This provided a great insight in the quality of the spread layer with the changes in process conditions. • The analysis of particle jamming, and the formation of empty patches was on a single spread layer.
3	Haeri (Haeri, 2017)	Spreading was measured in terms of void fraction and volume fraction. • The surface roughness of the layer and void fraction was used to assess the spreading behaviour of powders. • They investigated the effects of process parameters such as spreader velocity, geometry and type of spreader on the volume fraction and roughness of the layer. • The simulation analysed the surface roughness and void fraction of a single spread layer rather than multi-layers.
4	Haeri et al. (Haeri et al., 2017)	Spreading was measured based on the effect of particle shape and operating conditions on the bed quality. • The powder bed density and surface roughness of the layer was used to further understand the spreading behaviour of powders. • The effect of particle characteristics such as particle shape and process parameters including spreader type and velocity was used to further understand the spreading dynamics. This study provided insight into how new powders would perform in terms of their size, length and aspect ratio. • Their study investigated the powder bed density and surface roughness of a single layer rather than a multi-layer analysis. Understanding inter-layer dynamics provides an indication on the overall quality of the manufactured part.
5	Nan et al. (Nan & Ghadiri, 2019)	Spreading was investigated via the dynamic behaviour of powder spreading related to powder properties, machine design and operation conditions i.e. gap size and speed of spreading. • Particle flow was used to quantify the spreading process in terms of the shear band and mass flow rate through the gap size. • The effects of gap size and spreader velocity on the spreading process was examined using simulation by applying realistic physical and mechanical particle properties. • The simulation analysed the effects of particle flow in terms of the mass flow rate and shear band of a single spread layer.
6	Shaheen et al. (Shaheen et al., 2019)	Spreading was measured through layer characteristics such as density and layer uniformity. • Layer density and uniformity was used to quantify the spread behaviour using parameter variations such as cohesion, sliding and roller friction. • In addition to studying the effects of friction on layer homogeneity, they further investigated the effects of humidity and spreader type on the layer density and homogeneity. • The simulation was beneficial for qualitative observations where more particles were required to quantify the effects on layer homogeneity. Additionally, parametric studies in terms of surface energy and inter-particle friction would have been beneficial in understanding spreading dynamics as irregularity on powders impact the effective surface energy.
7	Van den Eynde (Van den Eynde, 2018)	Spreading was measured based on powder packing ratio (spread layer density over tapped density) and qualitative powder bed roughness. • Powder packing ratio and qualitative observations were utilised to further understand the spreading dynamic of powders. • The research focused on development of a screening methodology with a focus on power flowability in order to facilitate the introduction of new polymers to the laser sintering market. The extensive research focused on different flowability measurements and a correlation to the spreading dynamics was attempted. • The experimental work studied the spread of a single layer, while a multi-layer analysis may be beneficial to further develop metrics to characterise the spreading dynamics.

spreadability has proven to be a challenge in predicting the ability of powders to be uniformly spread across the build plate (e.g. Ahmed et al., 2020; Haydari et al., 2024; Mehrabi et al., 2023; Snow, 2018; Zinatlou Ajabshir, Sofia, Hare, Barletta, & Poletto, 2024 b). This work endeavoured to establish a comprehensive review of the literature regarding the effects of powder characterisation and process conditions on the quality of spread layer and the final part. The effect of particle size and size distribution has had considerable attention in the published literature. Moreover, studies on the morphology of powders mainly revolve around spherical and irregular particles, while there is limited discussion regarding their mixtures. Furthermore, whilst the surface properties of powders had significant study via DEM simulation, experimental investigations of the effects of surface energy and adhesion of powders on the final product is limited. The effects of gap size and spreader velocity as process-induced parameters on the quality of spread layer have been investigated to some extent. However, spreader type, multi-layer spreading and environmental conditions such as humidity and temperature are some important areas that require more attention so as to define a regime map for quantifying the quality of spreading in additive manufacturing.

This review suggests that individual powder characteristics may not be sufficient to provide optimal measures of powder spreadability. Since, a single characterisation method cannot fully represent the powder behaviour under spreading conditions, a combination of different methods and correlation of the analysis is imperative to establish an understanding of the spreading dynamics. Despite efforts and extensive research to define and measure spreadability using conventional flowability techniques, a significant mismatch exits between these standardised tests and the actual spreading behaviour. Hence, some of the literature regarding the spreading dynamic of powders in AM, have been critically reviewed to compare the effects of different parameters and/or their combination on the quality of the spread layers or the final manufactured part. This has been compiled in a table (see Supplementary Data (Appendix A)) facilitated with a traffic light system to navigate through, where the green and red colours, respectively, represent the positive and negative impacts of the mentioned parameters on the quality of spread layer and final part.

Supplementary Data in Appendix A consists of both powder and process induced effects on the attributed quality of the layer and/or the sintered part. Each paper was extensively reviewed where the methodologies, parameters and key findings were categorised accordingly.

Powder-induced parameters that had a significant effect on the attributed quality of the layer (i.e. layer porosity, layer surface roughness and layer packing density) and/or sintered part included in Supplementary Data (Appendix A) are.

- Particle shape and size distribution (PSD)
- Bulk and tapped density
- Morphology: aspect ratio (AR) and sphericity
- Particle surface properties: surface energy, adhesion, porosity and roughness
- Bulk flow behaviour: Hausner ratio, angle of repose, avalanche angle, flow function, basic flow energy/specific surface energy and qualitative flow behaviour.

The process-induced parameters that were covered in the summary of literature included in Supplementary Data (Appendix A) are.

- Gap size
- Spreader velocity
- Type of spreader: blade, roller, material and geometry
- Sintering/melting speed
- Laser power
- Environmental factors: temperature, humidity and ambient gas.

For example, referring to the study by van den Eynde (Van den Eynde, 2018) in Supplementary Data (Appendix A), the red colour indicated a negative impact from irregular morphologies on the quality of the spread layer and final part. Moreover, upwards arrow (↑) shows that an increase of Hausner ratio and avalanche angle has a negative impact on the quality of the final part, while the downward arrow (↓) indicates a decrease in the flow function results into a negative impact on the final part. However, an increase or decrease of some parameters poses a positive impact on the attributed layer quality and final part, which is presented by the colour green.

Supplementary Data (Appendix A) provides a comprehensive summary of research papers regarding the spreading behaviour of powders, which maps out the individual parameters associated with the respective research, as well as their overall effect on the quality of the layer or sintered part. As it can be seen, there is limited research work that reports a comprehensive investigation of the influence of all powder properties and process parameters on the quality of spread layer and/or sintered part. For example the studies by Mussatto et al. (Mussatto et al., 2021), Yusuf et al. (Yusuf, Choo, & Gao, 2020) and Clayton et al. (Clayton et al., 2015) report on the effects of powder and process properties on spread layer quality and its consequent effect of the quality of final sintered part. While the study by Yusuf et al. (Yusuf et al., 2020) reports on the influence of single particle properties on spread layer quality and consequently on the final sintered part, no direct measurements of bulk powder flowability nor spread layer packing density were conducted. Mussatto et al. (Mussatto et al., 2021) addressed the significant influence of powder morphology, spreading velocity and the thickness of the layers on the uniformity of the powder bed and the quality of sintered part by utilising AISI 316 L stainless steel powders. They conducted a series of experiments by employing a laser powder bed fusion printer where powder layers were spread systematically. They concluded that increased surface uniformity of the spread powder layer is achieved with finer powders and under lower spread velocities which leads to higher surface uniformity of the sintered layer. However, spread layer packing density and the sintered part density have not been evaluated and correlated with particle morphologies. Moreover, Clayton et al. (Clayton et al., 2015) conducted a review where four case studies were used to demonstrate the limitations of single parameter characterisation using a range of virgin and used powders. Powder rheology was a technique employed to observe any change within powders that could have an impact on the overall AM process, however no actual examples of AM processes were presented or discussed in detail.

In terms of powder flow behaviour, an increase in the Hausner ratio and avalanche angle and a reduction in the flow function often results into poorer flow behaviour which may result into lower quality of spread layers and/or end parts. However, recent studies by Haydari et al. (Haydari et al., 2024) and Zinatlou Ajabshir et al. (Zinatlou Ajabshir et al., 2024 b) shows lack of correlation between some flow measurements and powder spreadability.

5. Conclusion

This review underscores the pivotal role of spreadability in additive manufacturing, advocating for a holistic approach to its characterisation and highlighting avenues for future exploration.

Spreadability is a critical factor in layer-by-layer additive manufacturing, as powder dynamics have a substantial impact on the quality and integrity of printed structures. Despite substantial research efforts to define and measure spreadability using traditional flowability evaluations, a significant mismatch exists between these standardised measurements and the actual behaviour of powders.

Furthermore, the interaction between the influence of powder characteristics and process parameters and its influence on the powder spreading and consequently the manufactured part, highlights an important knowledge gap. Existing research mostly examines these aspects in isolation, ignoring the complex interplay between material qualities and process conditions. This mismatch highlights the critical need for extensive research that bridge the gap between powder characterisation and process optimisation, allowing for more informed decision-making for additive manufacturing users and machine manufacturers. Understanding the complex link between spreadability and process factors brings up new opportunities for innovation in materials science. Researchers can improve printability and broaden the spectrum of materials suitable with additive manufacturing methods by customising powder formulas to have optimal spreadability properties.

Lastly, incorporating sophisticated spreadability characterisation techniques into current process workflows facilitates the construction of closed-loop feedback systems. Manufacturers may achieve exceptional levels of process control and reproducibility by continually monitoring and modifying printing settings in response to real-time spreadability data. This not only reduces the danger of faults and rework, but also allows for quick iteration and optimisation of print designs, speeding the rate of innovation in additive manufacturing.

CRediT authorship contribution statement

Fatemeh A. Talebi: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Zobaideh Haydari:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Hamid Salehi:** Formal analysis, Investigation, Methodology, Writing – original draft. **Mozhdeh Mehrabi:** Data curation, Writing – review & editing. **Jabbar Gardy:** Formal analysis, Supervision, Writing – review & editing. **Mike Bradley:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Andrew E. Bayly:** Conceptualization, Supervision, Writing – review & editing. **Ali Hassanpour:** Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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