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Comparative Study of Particle Size and Shape Effects on Powder Packing Densities

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ABSTRACT

Uncertainties in powder spreading in powder bed-based additive manufacturing (AM) have posed challenges in the quality and repeatability aspects of manufactured parts. These challenges result in high porosity due to voids existing between the powder bed particles. This work focuses on identifying the uncertainty induced by particle size distribution (PSD) on powder flowability using SS316L as a model material. Various sizes of particles, ranging from 10 µm to 100 µm, as well as spherical and satellite-shaped particles with a bimodal ratio of 70:30, were analyzed. The tapped density, apparent density, and Hausner ratio of each sample will be determined using USP 616. Smaller particle sizes have been shown to reduce both bulk and apparent density. Meanwhile, the shapes of particles also contribute to the packing ability between the powder particles. Satellite powder has been proven to increase the diameter of the powder, consequently enhancing the bulking density of the powder particles. Moreover, bimodal particles have been shown to increase both bulk and tapped density, whereas smaller powder is not able to fill the voids that exist between the larger particles. However, the bulk density decreases as the size ratio between the powder particles increases, indicating that smaller powder is capable of filling the gaps between the particles. When comparing the powder particles in terms of Hausner ratio value, bimodal particles have been shown to cause the poorest flowability with a value of 1.19856. This is due to the fact that the smaller particles between the larger particles increase the friction between the powders. Therefore, this study illustrates how particle size and shape influence powder packing densities, which is crucial for optimizing material design and processing techniques

Keywords: Powder packing density; tapped density; bulk density; loosening effect; satellites; spherical powder

INTRODUCTION

Materials from metals and polymers seems to be used as powder feed materials of AM (Aripin et al. 2022; Foudzi et al. 2020a). One of the most popular AM processes is Selective Laser Melting (SLM) Process. One of the major advantages of SLM is that this process are useful in producing tough material and machinery equipment by using titanium (Buhairi et al. 2022). In SLM or another name for it which is Laser Bed Powder Fusion (LBPF), laser beam was used to melt the powder materials layer by layer to produce 3D part (Gao et al. 2015; Low et al. 2001; Meier et al. 2019; Wang & Chen 2015; Yap et al. 2015).

However, the major challenges in producing less porosity part is to control the porosity of the powder bed (Averardi et al. 2020). This challenge will lead in producing high porosity due to voids exists in between the particles in the powder bed. The voids will eventually lead to gas porosity where the gases molecules were entrapped between the particles (Aripin et al. 2023). Few factors such as particle size and shapes play vital roles in the quality and repeatability of powder spreading in powder bed. Besides, uncertainty of powder size distribution (PSD) due to variation of powder size leads to poor spreading quality (Gong et al. 2017; Grasso & Colosimo 2017; Mehdipour & Khayat 2017).

Several investigation were carried out by researchers to understand the impact of variation in PSD on the material properties: Leung et al. 2019; Miracle et al. 2003; Young et al. 2022); decreasing in powder flowability results in poor powder packing density, and (Miracle et al. 2003); increasing in radius ratio between two particles will improve the packing efficiency of the powder due to less friction between particles. However, this will lead to problems such as poor packing density and loosening effect in powder distribution. Besides, previous results also mentioned that homogeneity of powder could affect the powder flowability, which affected the powder packing density of the product (Brika et al. 2020; Young et al. 2022). (Marczyk & Hebda 2023) also stated that spherical particle promotes better packing density which allow better densification process. A study on different powder particles size by Haferkamp in 2021 (Haferkamp, Spierings, et al. 2021) found out that finer powder particles results in higher powder layer densities. Smaller particles have better packing densities due to their ability to fill in the voids between larger particles.

(Hassun et al. 2021) revealed that increased in packing density led in improving green density and allow faster sintering process compared to less dense powder. In his study, less dense pack compact powder required more times to reach theoretical density of 4.25 g/cm^3. It also can be seen that the density part is 95.64 % for loose pack while high pack powder is 98.57 %. Powder packing density also show the same trend where the use of bimodal powder increases the powder's packing density up to 8.2%. It also has been found out that bimodal particles also increase the flowability of the powder to 10.5% and reduce the sintering shrinkage to 6.4 %. Lastly, the final density parts for binder jetting found out to be increase by 4.0 %.

Besides bimodal mixture, particle distribution also plays a huge role in sintering parts. A research work by Mostafaei in 2019: wide samples with range between 16-63 μm in PSD will results in finer pores and higher powder packing density. The printed part density for 16-63 μm is way higher compared to powder sample with smaller range which is 16–25 μm and 53–63 μm (Mostafaei et al. 2019). This indicates that larger range of powder size distribution will allow the smaller powder particles to fill in the gap between larger particles for higher sintering density.

To minimize the porosity percentage in the SLM parts, most of the study have focused on the processing parameter such as laser power, scanning speed and others (Foudzi et al. 2020b) (Zhang et al. 2017). However, powder characteristics, including size, shape, and particle size distribution, can also influence the development of pores in the finished parts (Mazlan et al. 2023).

(Averardi et al. 2020) also agrees that blending various particle size and shape eventually will increase the packing density. Nevertheless, problems such as segregation and separation also might occur. Thus, in this study, a bimodal mixture with ratio of 70:30 was performed to determine the packing density in order to evaluate the effectiveness of bimodal ratio as an alternative measure by using fine particle. The objective of this study is to minimize the production costs associated with generating ultra-fine particles during laser processing.

METHODOLOGY

POWDER CHARACTERIZATION

In this experiment, seven different types of powders with various sizes and shapes were used. The powders were categorized into three sets of satellite-shaped particles: 30 μm, 50 μm, and 100 μm, and four sets of spherical particles with size ranges of 10 μm, 30 μm, 50 μm, and 100 μm. The focus of this investigation was on the powder prepared by Changsha Tijo Metal Material Co. Ltd., and its shape was meticulously examined through Scanning Electron Microscopy.

The bulk density and tap density measurement is crucial for assessing the flow properties of a powder, offering valuable insights into its handling and processing characteristics. In the first method, 50 grams of the powder was weighed and then transferred into a cylinder by using a Carney funnel. The volume occupied by the powder in the cylinder was recorded as the bulk volume. This method provides a measure of the powder's density under normal gravitational conditions. The second method involved tap density testing. 50 grams of the powder was accurately weighed and transferred into a graduated cylinder from a fixed height of 200 mm using a Carney funnel. The initial volume of the powder in the graduated cylinder was recorded as the bulk volume. Subsequently, the graduated cylinder was subjected to repeated mechanical taps at a frequency of 5 Hz until no further change in volume was observed. The volume of the powder after tapping was then recorded as the tapped volume. The Hausner ratio, calculated as the ratio of tapped volume to bulk volume, was then determined using Equation 1. A lower Hausner ratio, ideally close to 1, signifies improved flow properties of the powder.

$$Hausner\ Ratio = \frac{Tapped\ density}{Bulk\ density} \quad (1)$$

BIMODAL MIXING

The bimodal powder mixtures were created by using two different batches of powder for each mixture. This is to investigate the effects of particle size distribution on the overall characteristics of the powder blends. The chosen ratio for larger to smaller particle sizes was consistent across all mixtures, with 70% of larger powder particles and 30% of smaller powder particles. For the first bimodal mixture, the composition included 70% of 100 µm powder particles, and 30% of 50 µm powder particles. The second mixture comprised of 70% 100 µm particles which combined with 30% of 30 µm particles. Lastly, the third mixture consisted of 70% of 100 µm particles and 30% of 10 µm particles. To ensure a homogeneous blend, each mixture was mechanically stirred at a speed of 240 rpm for a duration of 1 hour.

RESULT & DISCUSSION

POWDER CHARACTERIZATION

Their particle size distribution (PSD) was measure by using Horiba Laser Scattering Particle Size Distribution Analyzer LA-960. As provided by the supplier, the powders particle has two different shapes which is one is homogenously spherical, while the others are spherical with the presence of satellite. The particles shape factors were measured by using Field Emission Scanning Electron Microscope (FESEM) Brand Zeiss, model Merlin Compact from German. Figure 1 depicts the SEM images of those different powder samples shapes.

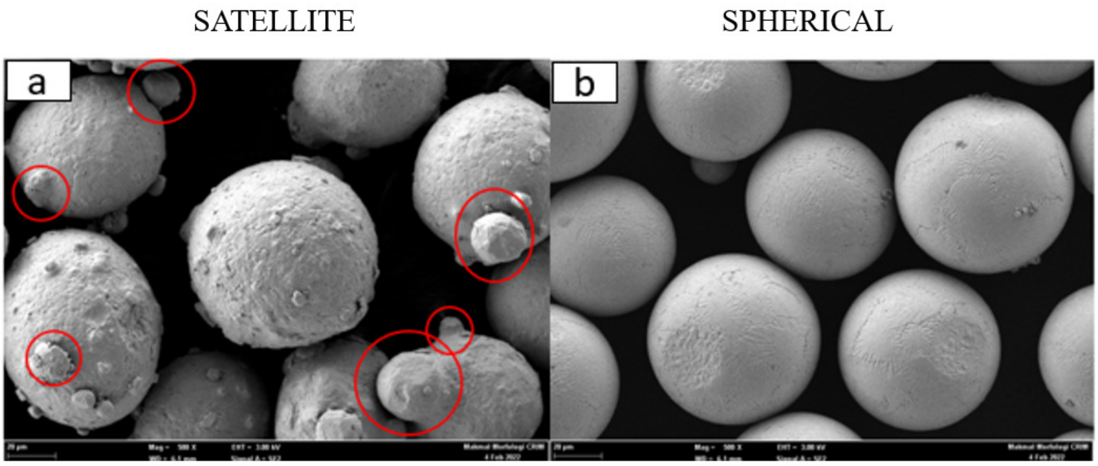

FIGURE 1. SEM images of (a) spherical satellites (b) spherical particles

The corresponding PSDs are displayed as shown in Figure 2. Figure 2 (a), (e), (f) and (g) has more uniform distribution compared to spherical powder with satellite at Figure 2(b),(c) and (d). According to Luo et al. satellite particles is one of the common defects in gas atomization process. In gas atomization process, to produce spherical powder, a stream of liquid metal is sprayed with high-velocity gas stream. During this process, the sprayed liquid metal will form droplets. Then the droplets will cool down and produces spherical powder. However, satellite particles formed when there is difference between the velocity of the gas and droplet at the starting of the atomization process. The velocity of droplets depends on the size of the droplets. Smaller droplets will have faster droplet velocity and faster cooling rate. This smaller droplets will fall faster and attached to the bigger droplets and attach to the surface of bigger droplets during the atomization process (Luo et al. 2021). The unused powder was reused to alter the powder properties.

This non-uniform shape will eventually affect the particle size distribution and powder packing density. Table 1 exhibits the particle size distribution for three spherical with satellites and four smooth spherical. As provided by the manufacturer, powder sample I and V, II and VI, and III and VII are supposed to be the same size of 30 µm, 50 µm, and 100 µm, respectively. However, as shown in Figure 1, satellite powder has larger diameter compared to spherical powder. This is due to the fact that satellite powder particles have non-uniform shapes. The larger structure occurred due to the combination of central particle and the adhering satellites. In fact, the actual diameter measurement, however, refers to the size of the central particle, with the smaller particles influencing the visual impression of the ensemble.

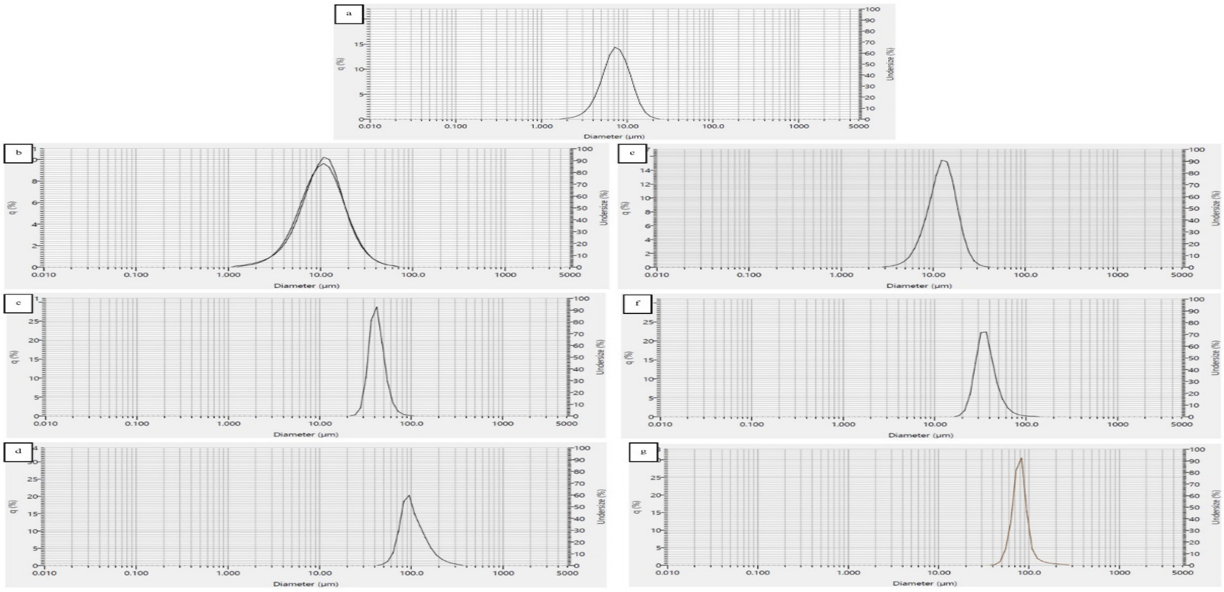

FIGURE 2. Particle size distribution for (a) 10 µm spherical (b) 30 µm satellite (c) 50 µm satellite (d) 100 µm satellite (e) 30 µm spherical (f) 50 µm spherical (g) 100 µm spherical

TABLE 1. Particle size distribution for SS316L

Powder Sample	Particle Shape	Particle Size Distribution		
		D_{10}	D_{50}	D_{90}
I	Spherical with satellites	4.9	10.6	21.2
II		33.1	41.6	54.9
III		72.3	99.0	161.0
IV	Spherical	4.5	7.4	11.8
V		7.7	12.6	19.3
VI		26.6	35.5	50.7
VII		61.7	79.0	100.6

BULKED AND TAPPED DENSITY

Figure 3 shows the graph of bulk density for the satellites, spherical and bimodal powder. This figure revealed the larger those particles size, the smaller the bulked and tapped density value. This study has been in line with (Coe & Pasebani, 2020), (Haferkamp, Liechti, et al. 2021), and (Montero-sistiaga et al. 2018). It can be seen that for both satellite and spherical unimodal, larger particle have more efficient packing density than smaller particles. At 100 µm size of powder, the bulk density is 4.56 g/mL^3 while the tapped density is 5.01 g/mL^3. As the particle size decreases, the bulked and tapped density also decreases. However, insignificant differences was observed for 30 µm and 10 µm powder particles size, the bulk density and tapped density. This is because of the particle size distribution IV and V is very small as shown in Table 1. According to (Theodoridis & Kraemer, 1998), bulk density will lead to less packing resistance compared to smaller particles which had larger surface area that could lead to high resistance in packing.

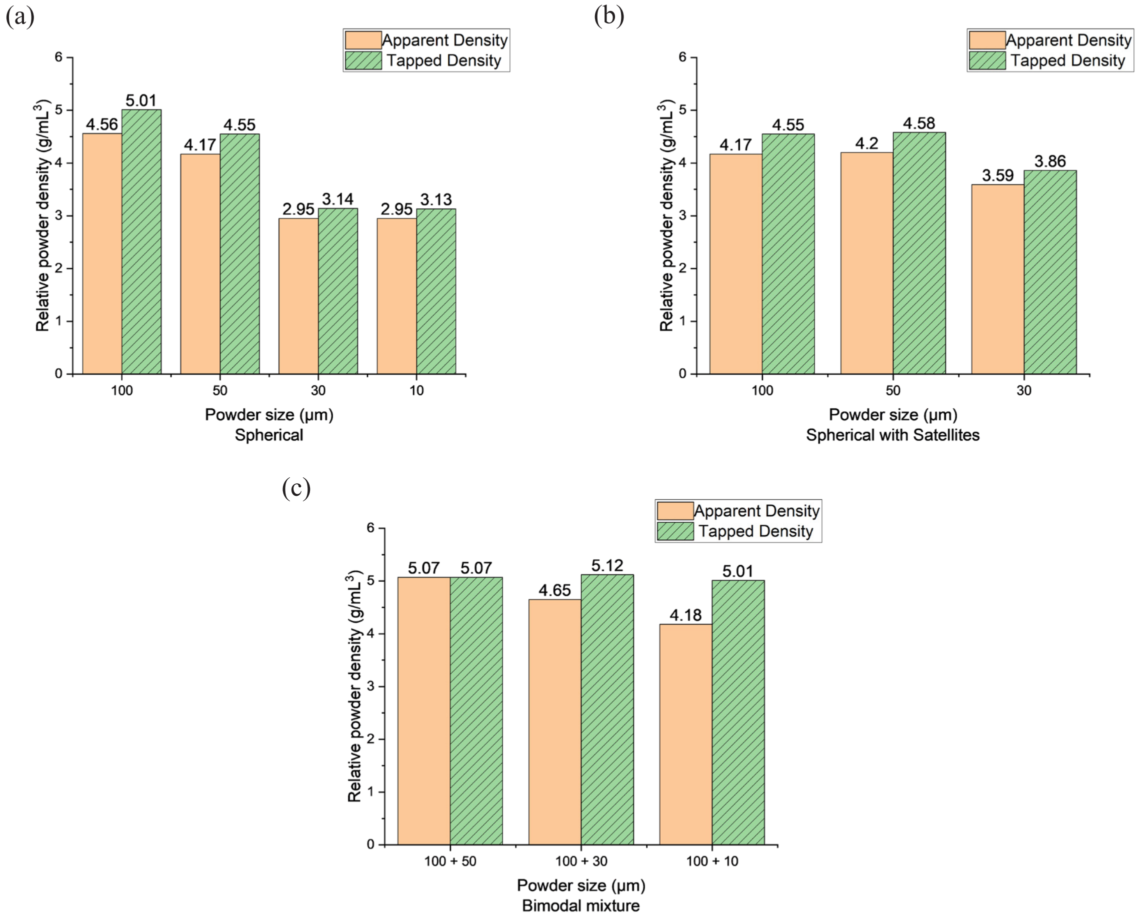

FIGURE 3. Particle size distribution for (a) 10 µm spherical (b) 30 µm satellite (c) 50 µm satellite (d) 100 µm satellite (e) 30 µm spherical (f) 50 µm spherical (g) 100 µm spherical

It also can be proven when comparing both satellite and spherical powder, where the satellite powder has smaller surface area as shown in Table 1. Bulk density decreases as the particles become less spherical (Theodoridis & Kraemer, 1998). In general, as the particles of a material become less spherical and more irregular in shape, the void spaces between the particles tend to increase. Irregularly shaped particles do not pack together as efficiently as spherical particles, resulting in a greater volume for a given mass. From Figure 2, the difference of bulk and tapped density for larger particles such as 100 µm and 50 µm are small. However, the difference become highly significant when comparing with both satellites and spherical of smaller particles. For spherical powder of 30 µm, the bulk density is 2.95 g/mL^3 while the tapped density is 3.14 g/mL^3. Meanwhile, for satellites powder with the same size of 30 µm, the bulk and tapped density is slightly higher. This is because as can be seen in schematic diagram in Figure 4(b), satellite powder has smaller particles attached on the surface which allow the powder to have multiple contact point, therefore increasing the friction between the particles. By this, the spherical with satellites particles to be more difficult to rearrange.

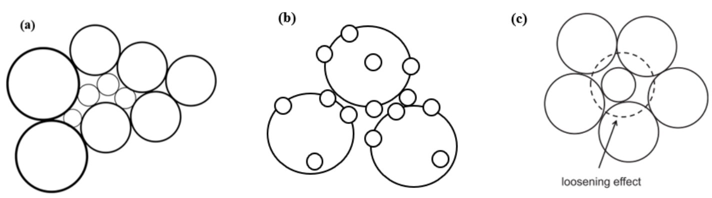

FIGURE 4. Schematic diagram (a) spherical (b) spherical with satellites powder particles (c) loosening effect (Ye et al. 2018)

Meanwhile, for bimodal particles, the bimodal particles have larger bulk and apparent densities compared to unimodal particles. Bimodal mixtures in this experiment shows poor packing density due to obvious particle size differences between first and second powder diameter. According to (Gopinath et al. 2017) (Ye et al. 2018), when the difference between the bimodal particles is small, it causes loosening effect as shown in the schematic diagram in Figure 4(c). However, as the secondary particles size decreased in the bimodal mixtures, decreasing trend can be observed with the bulked and tapped density. When the size ratio is 1:2, the tapped and bulk density is 5.07 g/mL^3. When the ratio is 1:3.333, the bulk density and tapped density is 4.65 g/mL^3 and 5.12 g/mL^{3,} respectively. Lastly, the bulk and tapped reduce to 4.18 g/mL^3 and 5.01 g/mL^3 when the ratio of the powder is 1:10. This indicates that, reduce in powder ratio size will improve the powder packing density, as it will allow the smaller particles to fill in the void between larger particles. The smaller particles are not small enough to fill in the void between the larger particles. Instead, it creates bigger space between the particles. Therefore, when the secondary particles decrease for the bimodal mixture, the bulk and tapped density also decreases.

HAUSNER RATIO

Meanwhile, Figure 5 shows the measured Hausner Ratio for unimodal and bimodal mixture. For both satellite and spherical unimodal powders, the Hausner ratio increasing as the particles size increase. This indicates that larger powder has poor flowability. Meanwhile, for bimodal mixture, bimodal size with the smallest secondary powder shows poor flowability. As stated by (Pleass & Jothi, 2018), increasing Hausner ratio indicates poor flowability. Poor Hausner ratio will cause the powder to be difficult to distributed onto the powder bed due to high friction. Hence, this will cause difficulties in preparing sample especially for compaction of powder bed distribution in SLM.

However, when comparing Hausner ratio of bimodal and unimodal, bimodal show the highest Hausner ratio value. At powder ratio of 1:10, the Hausner ratio value is the highest which indicates that the powder has poor flowability. (Coe & Pasebani, 2020) stated that low apparent density in bimodal powder size will eventually result in poor flowabilities. The presence of smaller particles between larger particles will eventually increase in friction and affect the particles rearrangements. This will lead to problems in SLM powder bed distribution.

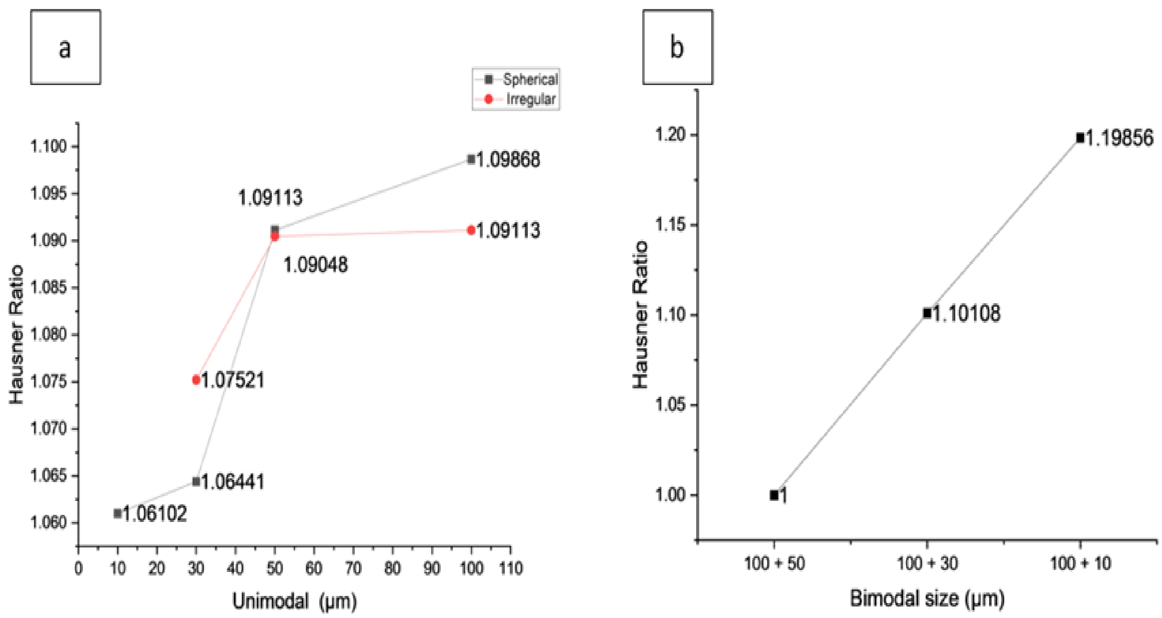

FIGURE 5. Hausner ratio (a) unimodal particles (satellites & spherical) (b) bimodal particles

According to (Fitzpatrick, 2013), for unimodal particles, the flowability of the powder is still considered excellence. However, for 1:10 bimodal powder ratio, the flowability of the powder is considered as fair only as it exceeds the value of 1.19.

CONCLUSION

In conclusion, the experimental findings emphasize the substantial influences of particle size and shape on powder packing characteristics. Smaller particle sizes were consistently associated with lower bulk and tapped density, attributed to heightened surface area causing increased interparticle friction. The superior packing efficiency of spherical particles, owing to their symmetrical nature, was evident in higher bulk and tapped density values. Contrarily, the introduction of bimodal particle distributions yielded no significant impact on powder packing density. However, this lack of significance translated into poor flowability, emphasizing the intricate interplay between particle size, shape, and distribution in shaping the overall behaviour of powdered materials. These perceptions contribute to a deeper understanding of the factors influencing powder packing, which is vital in diverse industrial applications where efficient handling and processing of powders are dominant.

In the quest for optimizing the properties of bimodal mixtures, this study explores two strategic adjustments: increasing the size ratio between particles and modifying the mixture ratio. By augmenting the size ratio, a more pronounced distinction between larger and smaller particles was introduced, with the intent of refining packing arrangements and, consequently, enhancing overall mixture characteristics. Simultaneously, the manipulation of the mixture ratio offers a targeted approach to influencing the blend's behaviour, specifically by increasing the proportion of one particle size. This approach aims to afford a nuanced control over the interplay between differently sized particles in bimodal mixtures, facilitating a deliberate tailoring of properties to meet specific application requirements. The experimental framework involves systematic adjustments in size and ratio, offering valuable understandings into the particulars of bimodal mixtures and providing a foundation for informed optimization strategies in powder processing applications.

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DECLARATION OF COMPETING INTEREST

None.

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