The use of non-spherical powder particles in Laser Powder Bed Fusion

Tatiana Fedina¹, Jesper Sundqvist¹, Alexander F. H. Kaplan¹

¹Luleå University of Technology, Department of Engineering Sciences and Mathematics, 971 87 Luleå, Sweden
tatiana.fedina@ltu.se

Abstract. Laser powder bed fusion (LPBF) generally involves the use of near-spherical powders due to their smooth morphology and enhanced flowability that allow for easier powder layering and laser processing. Non-spherical powders, on the other hand, are more cost-efficient to manufacture, however, the underlying mechanisms of their movement and interparticle interaction on the powder bed are still unclear. Thus, this study reports on the use of irregular iron-based powder material in LPBF, with a specific focus on particle motion and interaction behavior on the powder bed. The powder morphology, sphericity and particle size were analysed using X-ray computed microtomography and scanning electron microscopy. Based on the acquired data and by using a simplified analytical calculation, the influence of the particle shape/size on the particle movement in LPBF was established. High-speed imaging was employed to investigate the particle flow dynamics in the process zone, as well as the powder entrainment phenomenon. Particle entrainment and entrainment distances along the scanning direction were measured for near-spherical and non-spherical powders. The obtained results were compared between the powders, revealing a dissimilar particle transfer behavior. Non-spherical powder had a shorter entrainment distance partly attributed to the weaker drag force acting on these particles.

1. Introduction

Laser powder bed fusion (LPBF) is currently one of the most widely applied techniques in additive manufacturing (AM) [1]. The process offers various advantages over conventional subtractive methods, such as manufacturing parts of complex geometry, weight and material waste reduction, and processing of new materials [2,3]. Many studies on laser processing of powders in LPBF have been carried out before [4-8]. However, due to the complexity of the process, it is still challenging to understand the movement behavior of powder particles on a powder bed. In most cases, spatter ejection and particle entrainment followed by denudation are the two phenomena which cause powder motion near a solidified track [9, 10]. Spatter ejection describes the formation of spatters, originating in the melt pool [11-15]. Entrainment of particles by an induced gas flow causes the motion of particles in the vicinity of the melt pool which leads to the creation of a denudation zone. The denudation zone refers to the particle depletion area, occurring near the solidified track due to the laser beam-powder interaction [16]. The described phenomena have a direct impact on the process dynamics by activating the movement of powder particles which leads to disturbances in the powder bed [17, 18]. Therefore, it is critical to investigate the particle movement behavior and the mechanisms behind particle motion.

In AM, particle morphology plays an important role as it influences flowability and powder distribution on a build plate [19]. Powders of high sphericity and good flowability such as gas atomized
(GA) powder are normally employed in laser powder bed fusion as these powders have high packing densities and are easy to distribute over a build platform [2]. Heretofore, the movement behavior of particles in a powder system and their interaction with the laser beam have been described mainly for powders of near-spherical shape [4, 9-11, 20, 21]. The influence of laser radiation pressure on the dynamics of powder particles in the powder bed was previously investigated [22]. The authors reported that the radiation pressure can have as significant impact on the particle motion behavior as the aerodynamic forces. Furthermore, the drag force, exerted on powder particles, may dominate the radiation pressure in the vapor plume region. A simulation study by Chen and Yan [23], in which the powder particle-gas phase interaction was discussed, revealed that the metal vapor flow coupled with the vortex flow of inert gas caused spatter formation and denudation in the process zone.

The use of water atomized (WA) powder as a feedstock has hardly been investigated before [24], especially with relation to its movement behavior during laser processing. The morphology of WA powder is dominated by highly irregular particles with a tendency to agglomeration. This is due to the more rapid cooling and solidification rates during water atomization [24, 25]. However, the shape of WA powder can be altered by adjusting the process parameters or by applying thermal or mechanical post-treatment to the powder. Such a shape improvement may promote the application of WA powder in AM and, as a result, significantly decrease the cost of producing final components. Yet additional research is required to understand how non-spherical powder particles behave when the powder bed is exposed to laser irradiation.

This is addressed in the current manuscript with a special focus made on the particle movement behavior of powders of arbitrary shape. The influence of particle morphology and position on the powder bed on the process behavior of gas and water atomized low alloy powders was discussed. High-speed imaging (HSI) was utilized to measure particle entrainment distances in a radial direction for both powders and to identify variations in the powders’ behavior under changing process parameters. To evaluate the powders’ properties, X-ray computed microtomography (μCT) was employed. Based on the acquired data, the drag force, exerted on the arbitrary-shaped powder particles, was calculated.

2. Materials and methodology

2.1. Feedstock

The experiments were carried out using GA and WA 4130 low alloy steel powders with a particle size of 20-53 µm, provided by Höganäs AB. The powders’ bulk composition was analyzed by inductively coupled plasma mass spectrometry (ICP-MS). Carbon and sulphur content was measured using combustion analysis. Inert gas fusion was used to determine nitrogen and oxygen contents. The results are present in Table 1.

| Powder | Fe | C  | O  | N   | S   | Si  | Mn | Cr | Mo |
|--------|----|----|----|-----|-----|-----|----|----|----|
| GA 4130| Balance | 0.3 | 0.05 | 0.0075 | 0.0067 | 0.30 | 0.60 | 1.0 | 0.20 |
| WA 4130| Balance | 0.3 | 0.29 | 0.0030 | 0.0071 | 0.45 | 0.044 | 1.1 | 0.28 |

A Zeiss Xradia 510 Versa μCT system was employed to determine particle size distributions of the powders. To measure flowability and apparent density of the powders, the Hall flowmeter funnel method was used. Table 2 shows the powders’ properties.
Table 2. Technological properties of the 4130 low alloy steel powders.

| Powder  | Flowability (s/50g) | Apparent density (g/cm³) | Particle mean diameter D₅₀ (μm) |
|---------|---------------------|--------------------------|-------------------------------|
| GA 4130 | 22                  | 4.09                     | 37.70                         |
| WA 4130 | 30                  | 3.27                     | 27.44                         |

It can be observed that the mean particle size diameter D₅₀ of water atomized powder (D₅₀=27.5 μm) was slightly lower compared with gas atomized powder (D₅₀=37.7 μm). Moreover, prior to the experiment, to improve flowability and apparent density of the WA powder, the material was mechanically treated by the powder supplier. This treatment resulted in a slight increase of fine particle fraction in the material. The particle shape, observed using an FEI Magellan 400 extreme high-resolution scanning electron microscope, is demonstrated in figure 1, featuring various morphologies present in GA (figure 1 a) and WA (figure 1 b) powders. In addition, the particles’ cross-sections can be seen (figure 1 c, d), displaying a minor porosity that exists in both materials.

Figure 1. Morphology of GA (a) and WA (b) 4130 steel powders. GA (c) and WA (d) powder cross-sections can also be observed.

2.2. X-ray computed microtomography

The powder properties were evaluated using a Zeiss Xradia 510 Versa μCT machine with 7 W and 80 kV accelerating voltage. To hold the powders, a tube made of X-ray transparent polycarbonate with a 0.8 mm inner diameter was used. The powder specimens were located 6.5 mm from the CCD.
detector and 11.5 mm from the X-ray source. An objective lens with a 20x magnification was utilized to allow the sample analysis within an 842 × 842 µm field of view and with a 0.85 µm spatial resolution. The exposure time was between 25 to 29 s. For the powder analysis, around 950 projections of each powder sample were captured. Dragonfly 2020.1 software [26] by Object Research Systems was used for the image analysis.

2.3. Processing of preplaced gas and water amortized powders

The powder processing was carried out in a laboratory LPBF system, equipped with a continuous wave IPG Yb-doped fiber laser (with a 1070 nm laser wavelength). The laser optics had a 250 mm focal length collimator and a 150 mm focal length focusing lens which allowed a 75 µm laser beam spot diameter at the focus. To prevent back reflections that can occur during processing, the optics head was inclined at 7°. The experiment was carried out using following parameters: 33 mm/s scanning speed and 60 µm powder layer thickness. The laser power was varied between 150 and 300 W with a step of 50 W. To prevent oxidation in the process zone, a gas tube with a diameter of 20 mm was placed above the powder bed. Throughout the experiment, argon was used as a shielding gas with a flow rate of 22 L/min. The flow rate was tested prior to the laser processing to ensure a laminar flow regime in the process area. The powders were preplaced on a powder bed, dividing it into two halves. The setup details are demonstrated in figure 2.

Figure 2. A schematics of the laboratory LPBF setup, featuring the processing of individual tracks when using GA and WA powders. The red dashed line highlights the powder entrainment area. The camera is positioned with an inclination of 39° to the surface horizontal.

Depending on the system supplier, process parameters and conditions can vary. Normally, commercial LPBF machines are equipped with a scanning optics, operate at higher speeds than the value used in this study, and the processing is carried out in a sealed chamber filled with an inert gas. In the current work, despite a lower speed limit, an open linear axes laser system was utilized in order to provide more experimental flexibility and record the process with high-speed imaging. Therefore, although the powders were processed at a lower scanning speed compared to the values used in industrial LPBF systems, the authors believe the results are still consistent and representative.
2.4. High-speed imaging analysis

A Photron FASTCAM Mini UX100 high-speed imaging camera, coupled with an illumination laser CAVILUX CW (fiber-coupled outputs with a CW power of 50 W, 810 nm wavelength) provided by CAVITAR were utilized to observe the motion of variously-shaped powder particles and measure particle entrainment distances in a radial direction as shown in figure 2. To enable a clearer observation of particle dynamics in the powder bed, a 20 mm macro ring was attached to the camera lens. To remove the process light, a narrow band pass filter was used over the lens. The high-speed imaging videos were captured at 8000 frames per second (fps) and an exposure time of 80 µs. The camera was positioned with an inclination of 39° to the surface horizontal (figure 2). The HSI videos were analyzed using a Photron FASTCAM Viewer software. The particle velocity and entrainment distances for both powders were also measured based on the data acquired from the HSI camera. The velocity measurement was carried out on the GA and WA powder particles before their detachment, moving radially, on the sides of the solidified tracks.

2.5. Drag force calculation

Due to the complexity of a powder system which consists of arbitrary-shaped particles, no research has been reported on the movement behavior of such powder materials in LPBF. Nor was it needed as most of LPBF systems operate with near-spherical powders. This section interprets the physical mechanisms behind particle movement of various shape based on the drag force calculation made in this study. The drag force acting on near-spherical GA and non-spherical WA powder particles will be calculated in two regions: in the vapor jet area and in the vicinity of the melt pool.

The following assumptions were made to simplify the calculation:

1. The powder bed was assumed to be flat. No surface roughness of the outer layer was accounted for.
2. The powder motion was described only for individual particles which were not in contact with any other surfaces/particles.
3. The particle velocity was determined by HSI in the area near the edge of the melt pool in a radial direction. No particle rotation was accounted for.
4. The gas velocities were 1 m/s in the area of 250 µm from the melt pool and 150 m/s in the vapor flow region. The value was taken from a simulation study carried out by Chen and Yan [23].

To determine the drag force $F_d$, a Reynolds number $Re$ and a drag coefficient $C_d$ need to be calculated. The Reynolds number $Re$ is defined as:

$$Re = \frac{\rho_g U D_p}{\mu_g}$$  \hspace{1cm} (1)

where $\rho_g$ is the gas density; $U$ is the relative velocity between the gas flow and the particle given as $[U_g - U_p]$, where $U_g$ and $U_p$ are the gas and particle velocities, respectively. $D_p$ is the mean particle diameter; $\mu_g$ is the gas viscosity [22].

The drag coefficient $C_d$ was calculated using a formula [27] that can be applied for arbitrary-shaped particles. It is also valid in a wide range of $Re$ numbers. The coefficient $C_d$ is then defined as:

$$C_d = \frac{8}{Re^{\frac{1}{\varphi_1}}} + \frac{16}{Re^{\frac{1}{\varphi}}} + \frac{3}{Re^{\frac{1}{\varphi}}^{\frac{1}{\varphi}}} + 0.4210^{0.44(-\log \varphi)^{0.2} - \frac{1}{\varphi}}$$  \hspace{1cm} (2)

where $\varphi$ is the overall sphericity, $\varphi_1$ is the lengthwise sphericity and $\varphi_\perp$ is the crosswise sphericity. $\varphi$ refers to the ratio between the surface area of a volume equivalent sphere and that of the considered particle. $\varphi_1$ is the ratio between the cross-sectional area of a volume equivalent sphere and the difference between half the surface area and the mean projected longitudinal cross-sectional area of the considered particle. $\varphi_\perp$ is expressed as the ratio between the cross-sectional area of a volume equivalent sphere and the projected cross-sectional area of the considered particle.

Equation 3 describes the drag force $F_d$, exerted on powder particles of various morphology:
\[ F_d = \frac{1}{2} C_d \rho_g A_{p\perp} U^2 \]  

where \( C_d \) is the drag coefficient; \( \rho_g \) is the gas density; \( U \) is the relative velocity between the gas flow and the particle. \( A_{p\perp} \) is the projected cross-sectional area of the particle, subjected to the flow.

3. Results and discussion

The motion of powder particles on the powder bed is largely affected by their shape. To understand the influence of powder morphology on the particle movement in the powder bed, particle entrainment distances were measured for GA and WA powders. Figure 3 shows a correlation between the radial entrainment distances generated by the induced gas flow and the varying energy densities \( E \) defined as

\[ E = \frac{P}{U \cdot l \cdot w} \]  

where \( P \) is the laser power; \( U \) is the scanning speed; \( l \) is the powder layer thickness and \( w \) is the beam size diameter [28].

As demonstrated in figure 3, the entrainment of gas and water atomized powder particles increased with the increase of volumetric energy density. The observed behavior can be explained by the rapid increase in the pressure gradient in the process area as more energy is deposited across the laser scanned area. However, the processing of GA powder resulted in a 28% larger entrainment area compared to WA powder (1.5 mm and 1.17 mm at \( E=150 \) J/mm\(^2\), respectively). This is likely due to the difference in particle morphology between the powders. Being irregularly shaped, the WA powder has a tendency to developing contacts with neighboring particles which leads to mechanical interlocking and reduced mobility of the particles on the powder bed.

![Figure 3. Entrainment distances vs energy densities given for GA and WA powders.](image-url)

Furthermore, such behavior could also be caused by the difference in the magnitude of the drag force exerted on near-spherical GA and irregularly shaped WA powder particles. To confirm the assumption, the drag force, experienced by both powders, was calculated in two regions on the powder bed: in the vapor region (this implies in the region next to the melt, not above it as only the particle movement before its detachment was studied) and in the proximity of the melt pool, approximately 250
µm from the melt, presumably in the denudation zone. To simplify the description, let us call the mentioned regions as region 1 (vapor) and region 2 (250 µm from the melt pool). The values acquired from μCT and the study by Yan et al. [23] were used to aid the calculation. In region 1, the drag force experienced by both powders was approximately 3 orders of magnitude stronger than in the region near the melt pool. This can be explained by the strong radial drag in the vapor plume region that pulls the particles towards the melt pool.

In the region 2, as expressed in equation (1), the Re number was calculated, resulting in 4.42 and 3.37 for GA and WA powders, respectively. The drag coefficient $C_d$ was determined using equation (2) which was derived for arbitrary shaped particles by accounting for particles’ shape based on their sphericity and orientation to the gas flow. The $C_d$ calculation yielded 7.32 for GA and 10.65 for WA powders. Finally, the drag force for both materials was determined using equation (3), demonstrating a significant difference in the drag force acting on the powders. The drag force exerted on GA powder particles ($2.8 \times 10^{-8}$ N) in region 2 was 70% greater in comparison with WA powder (1.66 × 10⁻⁸ N), which supports the above mentioned assumption. This finding explains the difference in the GA and WA powder particle transfer behavior. The WA powder’s propensity to interact with nearby particles could promote agglomeration and high interparticle friction which both would lead to a development of a high counter force (s) exerted in the opposite direction to the drag force.

The movement of particles in the powder bed differs depending on the distance from the laser process area. Figure 4 highlights a sequence of images with different sizes of the particle entrainment area captured by HSI. The laser beam position was precisely between the two powder beds which allowed to study the particle motion behavior simultaneously. The red and black arrows present in figure 4 (a), (d) show the direction of particle motion. The reason for adding up the arrows only to the two snapshots (figure 4 a, d) was to improve the process visualization and, at the same time, to not distract the reader’s attention from the particle entrainment areas. The powder bed half containing GA powder exhibits a larger area of particle entrainment in comparison with the WA powder half, regardless of the surface energy density. The observed difference stems from the dissimilar morphology of the powders and their ability to flow, suggesting that a number of particles in the WA powder bed half form mechanical bonds with their neighbors and remain in their initial position.

Figure 4. A series of high-speed imaging snapshots, highlighting the areas of particle entrainment near the melt pool, created at surface energy densities $E = 125$ J/mm² (a, b, c) and $E = 150$ J/mm² (d, e, f). The active entrainment zone is encircled in red, displaying the particles next to the melt pool moving rapidly towards the powder-laser interaction area. The white dashed line divides the powder bed into 2 halves, with GA powder on the left and WA powder on the right. The red and black arrows demonstrate the direction of particle motion inside the active (encircled in red) and passive (marked with black arrows) entrainment zones.
It can also be seen in figure 4 (a-f) that regardless of the particle shape, the entrainment zone can be divided into 2 domains: the area of active entrainment (encircled in red) where the particles in the vicinity of the melt pool are rapidly entrained due to the Bernoulli effect [5] and a so called “passive” entrainment zone (black arrows outside the laser exposed area) where individual particles outside the process area are pulled in the direction of the melt pool.

It is worth mentioning that the area of particle entrainment fluctuates depending on the position of the vapor which, in turn, depends on the geometry of the melt pool.

4. Conclusions

This study has investigated the influence of powder shape on the particle movement behavior when processing near-spherical and irregular powder particles in LPBF. The following conclusions can be reported:

- Particle movement behavior changes depending on the particle morphology and position on the powder bed.
- Non-spherical WA powder particles demonstrated a restricted mobility on the powder bed which was attributed to their developed surface area and reduced flowability.
- The influence of particle shape and position on the dynamics of gas and water atomized powders was studied. The drag force exerted on GA powder particles near the melt pool was 70 % greater in comparison with WA powder. In addition, in the vapor plume region, the drag force experienced by both powders was approximately 3 orders of magnitude stronger than in the region near the melt pool.
- Regardless of the powder morphology, the entrainment of particles in a radial direction increased with the increase of surface energy density. Furthermore, when processing GA powder, the particle entrainment area was 28 % larger compared to WA powder. Such behavior is likely a combined result of the stronger drag force, exerted on near-spherical gas atomized powder particles, and the tendency of non-spherical water atomized powder to mechanical interlocking.

The results from this study demonstrate that the use of non-spherical powder particles leads to a narrower particle entrainment area compared with near-spherical powders. The observed behavior indicates that less denudation should occur around the solidified track. These findings contribute to the current limited knowledge about the application of non-spherical powder particles in additive manufacturing and their behavior.

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ORCID IDs
T Fedina https://orcid.org/0000-0003-4443-3097
J Sundqvist https://orcid.org/0000-0002-9010-1555
A F H Kaplan https://orcid.org/0000-0002-3569-6795

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