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Validation of powder layering simulation via packing density measurement for laser-based powder bed fusion

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Abstract. Powder bed fusion using a laser beam (PBF-LB/M) is considered one of the most versatile additive manufacturing methods as the parts printed have high resolution thanks to the low layer thickness used. The powder packing density (*PD*) of the powder layer has a significant impact on the density, surface roughness and other mechanical properties of the built parts. Due to the difficulty of characterizing the powder bed in situ, simulation has often been used to study the powder behavior on the powder bed. However, in order for the simulation to have practical value, there must be some way of confirming the results via experimental methods, also called validation. The aim of this study was to develop a powder packing density-based validation method for a powder bed simulation. The developed method featured a simplistic “open cup” style sample which traps powder inside for *PD* measurement. The samples were built with an EOS M 290 PBF-LB/M system using Alloy 718 (also known as “IN718” or “Inconel”) powder. Average *PD* over the five built samples was 52.4 %, with a standard deviation of 0.2 %. The method was used to successfully validate a powder bed simulation with four recoated powder layers, modelled using FLOW-3D DEM simulation software from Flow Science Inc. Similar methods for *PD* characterization were found in literature, but in many cases the method does not fully correspond to the conditions of a simulated powder bed, the scale is very small, or the reliability of the *PD* measurement is not confirmed. The method presented in this study corresponds to typical powder bed simulation conditions, while retaining high reliability and repeatability of results.

1. Introduction

Laser-based powder bed fusion (PBF-LB/M) is the most applicable of all the standardized methods of additive manufacturing (AM) in terms of industrial applications, due to its capability of fabricating complex parts with high dimensional accuracy [1–3]. The PBF-LB/M process uses a laser beam to melt thin (<0.1 mm) layers of metal powder on top of previously melted and fused layers until the required design is complete. However, building solid, accurate, and strong parts with PBF-LB/M is only possible if the powder material properties (e.g. particle size distribution or PSD [4] and particle morphology [5]), processing parameters (e.g., laser power [6], scanning speed [6], and layer thickness [7]), and post-process heat treatments [8] are carefully optimized. This is often done by practical experiments, by comparing the mechanical properties of finished parts resulting from each



combination of powder material or process parameters, which is labor-intensive, time consuming, and expensive, [9–11]. For this reason, it is an attractive proposition to replace experiments with computer simulation of the powder bed and the laser-material interaction.

Powder bed simulations (PBS) commonly use the discrete element modelling (DEM) technique which models the contact forces and trajectories of individual powder particles [12]. DEM has been used for observing powder packing behavior [13,14] as well as for creating realistic powder beds for the simulation of laser-material interaction [15]. Packing behavior is typically described with the packing density (PD) of the particles in the powder bed, which is the portion of volume in the powder bed occupied by particles. For example, a bed with a PD of 60 % consists of 60% of actual powder material and 40% empty interstitial space. As is shown in Figure 1, high PD correlates with reduced porosity in finished parts [4,16,17] and improved absorptivity of energy from the laser beam [18,19]. Higher PD also reduces the effective powder layer thickness, as the difference of powder layer volume and melt pool volume is smaller [4], which has been found to reduce surface roughness of parts [20].

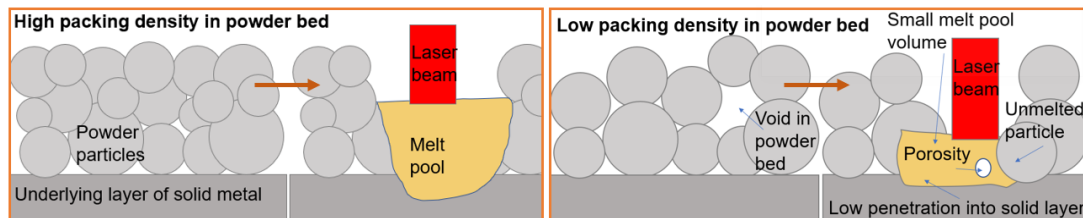


Figure 1. Effect of powder packing density in PBF-LB/M, adapted from: [20], and data in [18].

It is therefore important that PBS models accurately represent the powder packing behavior. This can be confirmed by a validation experiment, where the powder packing density is measured from the real powder bed and compared to the packing density of the simulated powder bed, these validation methods are referred to as “ PD -based validation” in this study. Such validation experiments have been developed across many studies conducted by various authors [11, 13, 22, 23, 25]. In [21] the “staircase” method, which was developed in [22], was used to validate a DEM recoating simulation. In this method, a 10 x 25 mm rectangle is built to a height of about eight layers, and the build continues with five zones of stepped height increase incremented by one layer height, creating an object resembling a staircase. Powder was removed from around the staircase, and the single layer of powder left on the second “step” of the staircase was weighed to find its packing density. The thickness of this single powder layer was measured using a high depth of field digital microscope, enabling the calculation of PD . In [23] the PBF-LB/M process was used to build one layer tall 15 x 15 mm rectangular enclosures in three lines along the length of the build platform. The surrounding powder was removed, and the sampled powder inside the enclosures was weighed to determine PD . This style of sample is referred to as an “open cup” sample in this study. Both of these PD -based validation methods investigate a small area and single layer of powder. Such a small sample volume increases the relative impact of measurement error, and cannot be considered a representative sample of the whole powder bed. This is problematic if a DEM-simulated powder bed is intended to be used as a “digital twin” representation of the actual powder bed of an PBF-LB/M system.

Simulations of powder packing behavior are also sometimes validated with other parameters, e.g. the angle between the build platform and the powder pile during recoating, the dynamic repose angle (DRA) [24], or the slope angle of a powder pile formed under gravity, the angle of repose (AOR) [24,25], or by visual comparison between the simulated and real powder bed [13]. More research is needed to confirm if parameters not based on PD can be used to validate a powder bed simulation of powder packing behavior.

There are also multiple methods developed for measuring PD , which are not intended for validation, but could be applied for validation purposes. A non-exhaustive list of these methods include the closed container samples [26], open cup samples [22,27–29], the sample picker device [30], impact

penetration into the powder bed [31], or light-curable liquid polymer to extract powder bed samples [32]. The sample picker, impact penetration test and liquid polymer methods require purpose-built equipment, and have a seemingly high risk of measurement error (e.g. the sample picker is hand-held). The closed container method was found in preliminary tests to be difficult to perform repeatably, in addition to the relatively large amount of material waste and long build times, making the method expensive. The high powder column also does not correspond to the simulated thin powder beds. Therefore, only the open cup sample was chosen for further development. In this study, a *PD*-based validation method which uses a large area open cup sample was designed. Five samples were built and measured to confirm the repeatability of the method. Sources of uncertainty were recognized and quantified. The method was used to validate a PBS model based on *PD*, and the significance of uncertainty in the validation method was compared to inherent uncertainty in the simulation.

2. Aim and purpose of study

Simulation of powder packing and especially the validation of these simulations form a modest portion of total research on PBF-LB/M simulation, as is shown in Figure 2. This figure shows the number of yearly publications between the years 2003–2023 with keywords related to the topic of this study, which were extracted from the Elsevier SCOPUS database in May 2023. Unless otherwise mentioned, all terms are separated by AND, and were searched in all article fields.

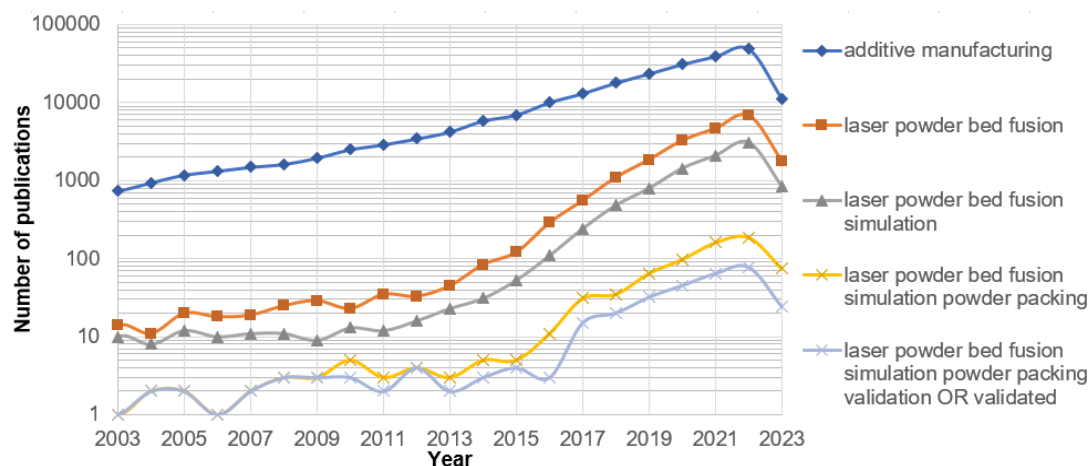


Figure 2. Yearly publications for search terms related to PBF-LB/M, simulation, and validation.

The total number of articles containing “additive manufacturing” was over 230 000, and over 20 000 for “laser powder bed fusion”. Adding “simulation” yields nearly 9 300 results, and adding “simulation powder packing” and “simulation powder packing (validation OR validated)” yields 701 and 312 results respectively. Though simulation is a relatively popular topic in research related to PBF-LB/M, less than 10 % of it is related to the powder packing behavior despite it being crucial for building a realistic base for simulating the laser-material interaction. Of the studies on simulation of powder packing behavior, less than half mention validation by definition. One possible reason is the expense of testing a validation method for PBS. Furthermore, the lack of well-established standardized powder characterization routines and tests during and pre- or post-PBF-LB/M processing also makes validation of PBS models less popular in literature.

This study aims to develop a repeatable, simple, and inexpensive validation method which corresponds to the conditions of a typical PBS model; low powder layer thicknesses and high repeatability. The scientific relevance of this study is the new understanding of the significance of uncertainty in the validation method compared to uncertainty in the simulation model. Also, the inexpensive and repeatable *PD*-based validation method can enable the accurate validation of PBS models which increase the understanding of powder packing behavior in PBF-LB/M. The industrial

relevance of this study is that the presented large area open cup sample is well suited for validating PBS models which are extrapolated to the entire build area. PBS has potential for replacing expensive experiments, but only if the models can be reliably validated. The presented validation method can also be used as a method for characterizing PD during PBF-LB/M processing.

3. Experimental setup and procedure

3.1. Experimental setup

An EOS M 290 PBF-LB/M system by EOS GmbH (Germany) was used to build the open cup samples. The powder material was the gas-atomized EOS NickelAlloy IN718 (Alloy 718). The powder PSD is between 22-50 μm , and particles are mostly spherical with occasional satellites, see supplier specification in [33]. Alloy 718 was chosen for this study as it is commonly processed with PBF-LB/M in industry [34,35] and its behavior in PBF-LB/M is well documented [36]. A validated parameter set could be provided by EOS, which reduced the risk of error from build defects. The samples were weighed using a Mettler Toledo ICS425 (Switzerland) scale (measuring accuracy 0.1 g). The length and width of the open cup sample were measured with a Mitutoyo 500-173-30 Absolute Digimatic (Japan) caliper (measuring accuracy 0.01 mm). The height of the open cup walls was measured using a Mitutoyo ID-C112X Absolute Digimatic (Japan) depth gage (measuring accuracy 0.001 mm). The simulation model of the powder bed was created with FLOW-3D DEM software by Flow Science Inc. (USA).

3.2. Experimental procedure

Only the topmost powder layers are affected by the laser-material interaction, so the sampled powder bed should be relatively thin, but still multiple layers thick to reduce the impact of measuring error. Of the build platform area, only the central region near the dispenser would be sampled, because the edges and the end of the powder bed may have higher variation in PD due to the possible segregation of different sized particles [32] and the unlikely possibility that the recoater does not pick up enough powder from the dispenser. Thus, the sample should be shallow and follow the shape of the platform, but it should be centered and placed near to the dispenser, as seen in Figure 3.

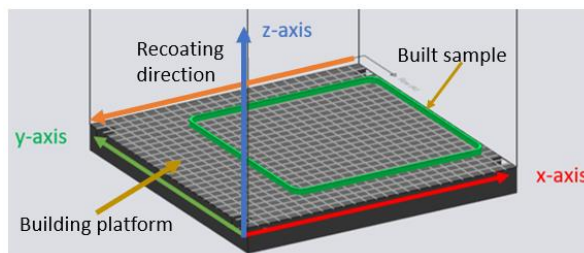


Figure 3. A 3D-model of the “open cup” PD validation sample (green) on the build platform of an EOS M 290. The recoater picks up powder from the dispenser at end of x-axis, and spreads the powder over the building platform towards the origin, i.e., right to left.

The outside width of the sample is 178 mm. The corners were rounded with a 10 mm radius to ease the removal of powder from the open cup sample. The height was 5 mm and wall thickness was 2.5 mm. Both values could still be lower, though this will make it more difficult to remove surrounding powder without disturbing the sampled powder. The samples were built using the 40 μm layer height Alloy 718 process for the M 290 [33]. After printing, powder outside the sample walls was removed with a paint brush, and the build platform with the sample was weighed as seen in Figure 4 A. This weighing yields m_{full} which is the mass of the platform, sampled powder, and any powder residue left on the platform after initial brushing. After this, the sampled powder was moved from the walled area into a plastic bag with a scoop and paint brush, and weighed. The weight of the bag was tared. This gives the minimum mass of sampled powder, $m_{\text{powder-min}}$. Then, the sample area inside the wall was cleaned with a cloth, but the area outside the wall was left untouched, as is seen in Figure 4 B. After this the build platform was weighed, yielding m_{emptied} which was deducted from m_{full} to find $m_{\text{powder-measured}}$ which is the likely most accurate value for mass of sampled powder.

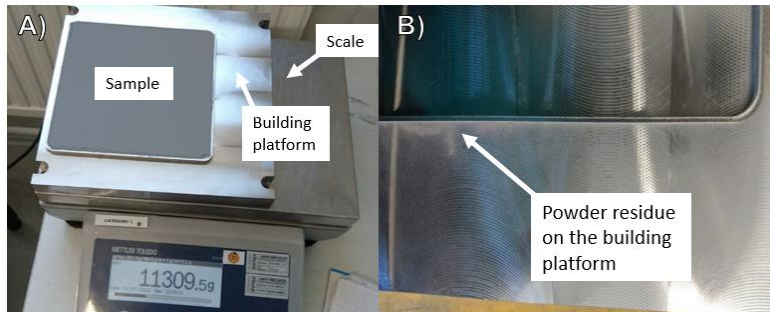


Figure 4. The open cup sample during initial weighing (A) and after emptying the sampled powder (B), where the arrow indicates powder residue outside the sampled area.

Measuring $m_{\text{powder-measured}}$ this way results in a value where only the mass of sampled powder is included and the mass of residual powder outside the sampled area is excluded. Finally, the entire platform was vacuum cleaned and wiped with a cloth and isopropyl alcohol, including the bottom side and the screw holes. After this the platform was again weighed, yielding m_{cleaned} , which was deducted from m_{full} to find $m_{\text{powder-max}}$, which is the likely maximum value for mass of sampled powder. After this weighing procedure, the inner width and length of the sample rectangle were measured at three locations (at midpoint and both edges) and averaged. Wall height was measured at the midpoint of each rounded corner and averaged. Sample volume V_{sample} was calculated based on the average width w , average length l , and the average height h , using Equation 1. The rounded corners were assumed perfectly round with a 10 mm radius r .

$$V_{\text{sample}} [cm^3] = \frac{(w-2r)*l*h + \pi*r^2*h + (l-2r)*2r*h + r^2*\pi*h}{1000} \tag{1}$$

Next, the volume occupied by powder particles was calculated for each three powder mass values with skeletal density ρ_s of particles (measured by supplier according to ASTM B923-22), using Equation 2.

$$V_{\text{powder}} = \frac{m_{\text{powder}}}{\rho_s} \tag{2}$$

With V_{powder} and V_{sample} , it is possible to calculate PD using Equation 3.

$$PD = \frac{V_{\text{powder}}}{V_{\text{sample}}} \tag{3}$$

In addition, a nominal PD (PD_{nominal}) is calculated using the nominal volume of the CAD model and $V_{\text{powder-measured}}$ (the volume of powder calculated from $m_{\text{powder-measured}}$). As is shown in Figure 5, a PD value was calculated for each measured powder mass (min, measured, max) and their calculated powder volumes, using the measured sample volume V_{sample} .

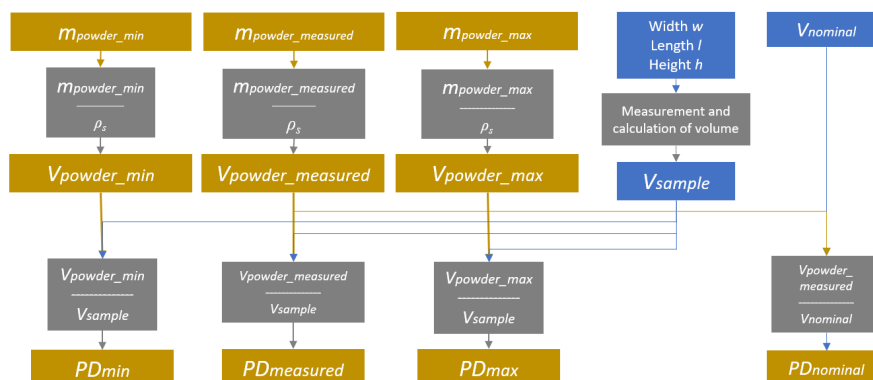


Figure 5. Different PD values and their calculation logic.

3.3. Simulation model

The model has approximately 260 000 particles recoated in four 40 μm layers. The shape of recoater and recoating speed were the same as in the real M 290. The total simulation area including the dispenser was 17.5 x 1.5 mm, of which the powder bed was 6.5 x 1.5 mm. The simulated PSD was based on data from dynamic image analysis (ISO 13322-2) and particle density on pycnometry results (ASTM B923-22), both done by the powder supplier. Friction coefficients were approximated as 0.3 and 0.6 for particle-particle dynamic and static friction respectively and 0.4 for particle-wall friction, based on rheometry experiments done according to standard ASTM D7891. A suitable particle stiffness was found by calibration as 10 N/m, and the coefficient of restitution was approximated from [37] as 0.6.

The PD of the simulated powder bed was measured in three ways, since the choice of method has significant effect on the result. Measuring the fraction of volume occupied by particles from a sampling volume completely embedded in the powder bed will yield higher PD than if the sampling volume is defined by the extents of the powder bed. The former measurement in this study is referred to as $PD_{\text{max-sim}}$ and the latter $PD_{\text{min-sim}}$. A measurement taken between these two is $PD_{\text{measured-sim}}$. PD was sampled from both the full length of the simulated powder bed and a central stable area, where the thickness of the powder bed did not vary. The “stable area” measurement is considered more useful, as varying powder bed thickness distorts the PD measurement. The simulation was then repeated with identical parameters to quantify the effect of randomized particle generation pattern on PD .

4. Results and discussion

4.1. Results of validation experiment

The PD_{min} , PD_{measured} , PD_{max} results of each sample as well as their mean and standard deviation are shown in Table 1. The samples are labeled OL (Open cup, Large area) and numbered in build order.

Table 1. Measured and calculated PD of all samples.

PD	OL1	OL2	OL3	OL4	OL5	Mean	Standard deviation
PD_{min}	51.9 %	51.9 %	52.2 %	52.6 %	52.5 %	52.2 %	0.29 %
PD_{measured}	52.2 %	52.2 %	52.3 %	52.6 %	52.6 %	52.4 %	0.20 %
PD_{max}	52.2 %	52.2 %	52.3 %	52.7 %	52.7 %	52.4 %	0.22 %
PD_{nominal}	54.0 %	52.4 %	53.0 %	52.8 %	53.5 %	53.2 %	0.56 %

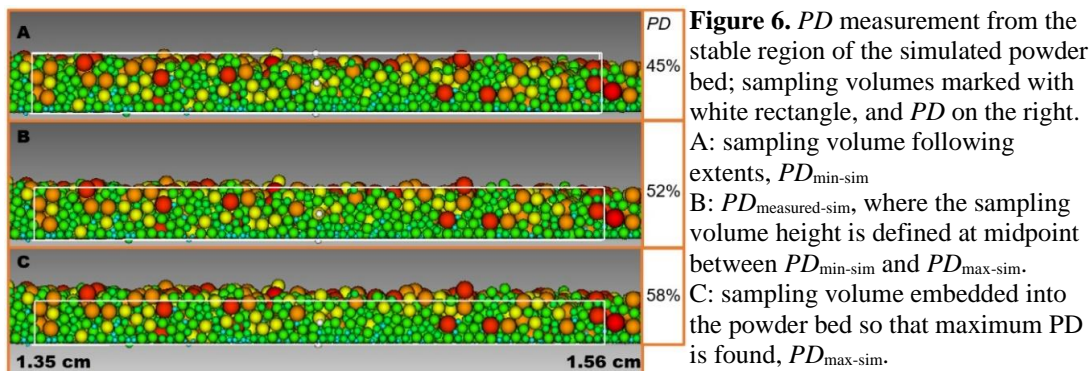
As it can be seen in Table 1, there is slight variance between the PD values, but all values of PD_{min} , PD_{measured} , and PD_{max} are between 51-53 %. PD_{measured} is considered the most accurate measurement since the values of PD_{min} and PD_{max} are likely lower and higher than the true PD respectively, and are not intended as a characterized value, but only for quantifying uncertainty from the cleaning method. The mean value of PD_{measured} was 52.4 %, and it is considered the definitive PD value characterized with this method. The PD_{measured} is very uniform across samples, with a standard deviation of 0.20, likely due to the large mass of sampled powder which reduces the relative significance of small measurement errors. The only variation in PD_{measured} is a slight increase between the second and fourth samples, after which there is no change between OL4 and OL5. This could be due to increasing proficiency in sample handling, leading to less sampled powder being lost before weighing. This increase is not present in PD_{nominal} , which alternates between 52.4-54 % without a clear trend. No correlation between PD_{nominal} and other PD values was found, which indicates that variations in sample volume which are not accounted for in the sample measurement (e.g. variation in the surface of the build platform or the build wall) do not impact PD and are not a significant source of uncertainty. The built parts were slightly taller (0.02-0.18 mm taller) than the nominal CAD model, which was unexpected as PBF-LB/M-built parts with a short z-dimension are typically slightly shorter than nominal due to instability of layer thickness in the first ~10 layers [38]. This is possibly due to the

manually coated first layer being slightly thicker than the nominal layer height. For this reason, PD_{nominal} is always slightly higher than PD_{measured} or PD_{max} .

The PD_{min} and PD_{max} values were measured to quantify the variation resulting from different sample cleaning methods or error in sample cleaning. Greatest difference between PD_{min} and PD_{measured} values was in samples OL1 and OL2, with a difference of 0.3 percentage points. The PD_{max} values have at most 0.1 percentage point difference to PD_{measured} values, indicating that the samples have low error due to residual powder and other debris on the build platform, and that the error from accidentally removing residue from outside the sampled area before weighing is lower than the error caused by trying to remove only the sampled powder by brushing and scooping. Therefore it is better practice to e.g. vacuum clean the sample and entire build platform before weighing. Overall, the results show that the used cleaning method is an insignificant source of uncertainty regardless of the used technique.

4.2. Application of validation method to simulation

As seen in Figure 6, the method of measuring PD from the simulation has significant effect on the PD .



The sampling volume heights for the extent-following $PD_{\text{min-sim}}$ and fully embedded $PD_{\text{max-sim}}$ were 150 μm and 210 μm respectively, with the $PD_{\text{measured-sim}}$ being defined as the midpoint between these extremes (180 μm). The nominal powder bed thickness was 200 μm . $PD_{\text{measured-sim}}$ measured at a stable region of the powder bed, between 1.35-1.56 cm of simulated volume (full length of powder bed being 1.1-1.75 cm of the total volume) is considered the best analogue to the measurement method in the validation experiment, which also sampled a central stable region. $PD_{\text{measured-sim}}$ was 52 %, which agrees with the validation experiment. $PD_{\text{min-sim}}$ and $PD_{\text{max-sim}}$ were 45 % and 58 % respectively, which means the choice of measurement method is a significant source of uncertainty, much larger than any uncertainty associated with the validation method.

The $PD_{\text{min-sim}}$, $PD_{\text{measured-sim}}$, and $PD_{\text{max-sim}}$ measured from the full length of the simulated powder bed (1.1-1.75 cm) were 37 %, 49 %, and 58% respectively. The lower results were expected due to lower powder bed thickness at the end of the bed resulting in more empty volume being included in the sampling volume. However, $PD_{\text{max-sim}}$ was identical in both measurements, which is significant since $PD_{\text{max-sim}}$ is fully embedded in the simulated powder bed and thus should not be affected by any variation in powder bed thickness, indicating that as long as the sampling volume is equally embedded in the powder bed, its size and thus the change in wall-powder interface area does not affect the PD result. If the length of the sampling volume affected PD , a change in $PD_{\text{max-sim}}$ should have been seen.

The results of a repeated simulation run were nearly identical, except $PD_{\text{measured-sim}}$ in the stable region of the repeat run was 53 % compared to 52 % in the first run. This is not a sufficient sample size to make conclusions, but it demonstrates that the randomized particle generation is a potential source of uncertainty, though further research on the effect of randomized particle generation on the variance of PD is needed to quantify how significant a source of uncertainty it is, and to confirm that the variation in PD observed in this study is not an outlier.

The open cup PD -based validation method can be considered sufficiently repeatable and precise for the purposes of validating DEM simulations of powder bed recoating. The validation result matching the carefully parametrized simulation indicates that the sampled powder bed in the open cup method is not significantly compressed by gravity compared to the simulation despite being about 50 times taller, and that the PD of a $\sim 9 \text{ mm}^2$ sampling area of the simulation is comparable to the average PD of the entire center area of the build platform.

5. Conclusions

The aim of this study was to develop a powder packing based validation method which matches the typical conditions of a powder bed simulation and is suitable for their validation. Uncertainties related to the measurement process were identified and quantified. The results of the validation experiment and its sources of uncertainty were compared to a powder bed simulation model and the sources of uncertainty related to it. The main conclusions of the study are:

Multiple validation methods based on different powder bed parameters exist in literature, as well as many methods for measuring PD for other purposes. The presented open cup PD -based validation method with Alloy 718 powder material had a mean value of PD_{measured} over five samples of 52.4 % with a standard deviation of 0.20 %. Despite the sample being orders of magnitude larger, the PD result is a good match to a simulated powder bed, which was carefully parametrized by practical experiments, literature review, and calibration. The sources of uncertainty quantified from the simulation are more impactful than those of the validation method, making the validation method sufficiently accurate and reliable for validating powder bed simulation models.

6. Future work

The validation model built in the scope of this research could be utilized as a basis to develop a thermomechanical CFD/FEM model of laser-material interaction as an initial step in the PBF-LB/M simulation methodology. In addition, the powder bed model could be a part of a powder characterization sequence. Traditional powder characterization for PBF-LB/M includes the characterization of PSD, particle morphology, packing density, and flowability. With the rapid development of simulation software, it is a natural progression that simulation of the powder bed in the build chamber becomes a part of the powder characterization sequence.

7. References

- [1] Godéc D, Gonzalez-Gutierrez J, Nordin A, Pei E and Ureña Alcázar J 2022 *A Guide to Additive Manufacturing* (Cham: Springer Nature)
- [2] Gibson I, Rosen D, Stucker B and Khorasani M 2021 *Additive Manufacturing Technologies* (Cham: Springer International Publishing)
- [3] Willkomm J, Kuhlbach K, Merget D, Wagner M, Reich S, Ziegler S and Schleifenbaum J H 2021 Design and manufacturing of a cylinder head by laser powder bed fusion *IOP Conf. Ser.: Mater. Sci. Eng.* **1097** 012021
- [4] Spierings A B, Herres N and Levy G 2011 Influence of the particle size distribution on surface quality and mechanical properties in AM steel parts ed D Bourell and B Stucker *Rapid Prototyping Journal* **17** 195–202
- [5] Guzmán J, de Moura Nobre R, Rodrigues Júnior D L, de Moraes W A, Nunes E R, Bayerlein D L, Falcão R B, Sallica-Leva E, Oliveira H R, Chastinet V L and Landgraf F J G 2021 Comparing Spherical and Irregularly Shaped Powders in Laser Powder Bed Fusion of Nb47Ti Alloy *J. of Materi Eng and Perform* **30** 6557–67
- [6] Kumar P, Farah J, Akram J, Teng C, Ginn J and Misra M 2019 Influence of laser processing parameters on porosity in Inconel 718 during additive manufacturing *Int J Adv Manuf Technol* **103** 1497–507
- [7] Nath S D, Gupta G, Kearns M, Gulsoy O and Atre S V 2020 Effects of layer thickness in laser-powder bed fusion of 420 stainless steel *Rapid Prototyping Journal* **26** 1197–208

- [8] Al-Maharma A Y, Patil S P and Markert B 2020 Effects of porosity on the mechanical properties of additively manufactured components: a critical review *Mater. Res. Express* **7** 122001
- [9] Aversa A, Marchese G, Saboori A, Bassini E, Manfredi D, Biamino S, Ugues D, Fino P and Lombardi M 2019 New Aluminum Alloys Specifically Designed for Laser Powder Bed Fusion: A Review *Materials* **12** 1007
- [10] Asnafi N 2021 Application of Laser-Based Powder Bed Fusion for Direct Metal Tooling *Metals* **11** 458
- [11] Budinoff H D and Shafae M 2022 Connecting part geometry and cost for metal powder bed fusion *Int J Adv Manuf Technol* **121** 6125–36
- [12] Zohdi T I 2018 PART II—Discrete Element Method (DEM) Approaches: Dynamic Powder Deposition *Modeling and Simulation of Functionalized Materials for Additive Manufacturing and 3D Printing: Continuous and Discrete Media: Continuum and Discrete Element Methods* Lecture Notes in Applied and Computational Mechanics ed T I Zohdi (Cham: Springer International Publishing) pp 83–119
- [13] Shaheen M Y, Thornton A R, Luding S and Weinhart T 2021 The influence of material and process parameters on powder spreading in additive manufacturing *Powder Technology* **383** 564–83
- [14] Lee Y S, Nandwana P and Zhang W 2018 Dynamic simulation of powder packing structure for powder bed additive manufacturing *Int J Adv Manuf Technol* **96** 1507–20
- [15] Tian Y, Yang L, Zhao D, Huang Y and Pan J 2020 Numerical analysis of powder bed generation and single track forming for selective laser melting of SS316L stainless steel *Journal of Manufacturing Processes* **58** 964–74
- [16] Spierings A and Levy G 2009 Comparison of density of stainless steel 316L parts produced with Selective Laser Melting using different powder grades *Proceedings for the 2009 International Solid Freeform Fabrication Symposium 20th Annual International Solid Freeform Fabrication Symposium* (Austin) pp 342–53
- [17] Pleass C and Jothi S 2018 Influence of powder characteristics and additive manufacturing process parameters on the microstructure and mechanical behaviour of Inconel 625 fabricated by Selective Laser Melting *Additive Manufacturing* **24** 419–31
- [18] Boley C D, Khairallah S A and Rubenchik A M 2015 Calculation of laser absorption by metal powders in additive manufacturing *Applied Optics* **54** 2477–82
- [19] Pal S, Gubeljak N, Bončina T, Hudák R, Toth T, Zivcak J, Lojen G, Leben N and Drstvenšek I 2021 The effects of locations on the build tray on the quality of specimens in powder bed additive manufacturing *Int J Adv Manuf Technol* **112** 1159–70
- [20] Shi X, Ma S, Liu C, Chen C, Wu Q, Chen X and Lu J 2016 Performance of High Layer Thickness in Selective Laser Melting of Ti6Al4V *Materials* **9** 975
- [21] Wu S, Lei Z, Jiang M, Liang J, Li B and Chen Y 2022 Experimental investigation and discrete element modeling for particle-scale powder spreading dynamics in powder-bed-fusion-based additive manufacturing *Powder Technology* **403** 117390
- [22] Wischeropp T M, Emmelmann C, Brandt M and Pateras A 2019 Measurement of actual powder layer height and packing density in a single layer in selective laser melting *Additive Manufacturing* **28** 176–83
- [23] Chen H, Wei Q, Zhang Y, Chen F, Shi Y and Yan W 2019 Powder-spreading mechanisms in powder-bed-based additive manufacturing: Experiments and computational modeling *Acta Materialia* **179** 158–71
- [24] Xiang Z, Zhang M, Yan R, Yin Q and Zhang K 2021 Powder-spreading dynamics and packing quality improvement for laser powder bed fusion additive manufacturing *Powder Technology* **389** 278–91
- [25] Cao L 2019 Study on the numerical simulation of laying powder for the selective laser melting process *Int J Adv Manuf Technol* **105** 2253–69

- [26] Jacob G, Donmez A, Slotwinski J and Moylan S 2016 Measurement of powder bed density in powder bed fusion additive manufacturing processes *Meas. Sci. Technol.* **27** 115601
- [27] Liu B, Wildman R, Tuck C, Ashcroft I and Hague R 2011 Investigation the effect of particle size distribution on processing parameters optimisation in selective laser melting process *Proceedings for the 2011 International Solid Freeform Fabrication Symposium 22nd Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference (Austin)* pp 227–38
- [28] Haferkamp L, Haudenschild L, Spierings A, Wegener K, Riener K, Ziegelmeier S and Leichtfried G J 2021 The Influence of Particle Shape, Powder Flowability, and Powder Layer Density on Part Density in Laser Powder Bed Fusion *Metals* **11** 418
- [29] Rogalsky A, Rishmawi I, Brock L and Vlasea M 2018 Low cost irregular feed stock for laser powder bed fusion *Journal of Manufacturing Processes* **35** 446–56
- [30] Lampitella V, Trofa M, Astarita A and D’Avino G 2021 Spreading of Powders in Powder Bed Additive Manufacturing: an Experimental Approach *ESAFORM Proceedings 2021 24th International Conference on Material Forming (Liège)*
- [31] Li J, Gao G, Zhang S and Du Y 2019 Calibration and Measurement Study on Density of Selective Laser Sintered 3D Printing Powder Bed *Journal of Physics: Conference Series* **1267** 012072
- [32] Ali U, Mahmoodkhani Y, Imani S, Esmacilizadeh R, Liravi F, Sheydaeian E, Huang K, Marzbanrad E, Vlasea M and Toyserkani E 2018 On the measurement of relative powder-bed compaction density in powder-bed additive manufacturing processes *Materials & Design* **155** 495–501
- [33] EOS GmbH 2023 EOS NickelAlloy IN718 Material Data Sheet. Available from: <https://www.eos.info/en/3d-printing-materials/metals/nickel-alloys> [Accessed 10 May 2023]
- [34] Kelkar R, Andreaco A, Ott E and Groh J 2018 Alloy 718: Laser Powder Bed Additive Manufacturing for Turbine Applications *Proceedings of the 9th International Symposium on Superalloy 718 & Derivatives: Energy, Aerospace, and Industrial Applications* The Minerals, Metals & Materials Series ed E Ott, X Liu, J Andersson, Z Bi, K Bockenstedt, I Dempster, J Groh, K Heck, P Jablonski, M Kaplan, D Nagahama and C Sudbrack (Cham: Springer International Publishing) pp 53–68
- [35] Caiazza F, Alfieri V, Corrado G and Argenio P 2017 Laser powder-bed fusion of Inconel 718 to manufacture turbine blades *Int J Adv Manuf Technol* **93** 4023–31
- [36] Sanchez S, Smith P, Xu Z, Gaspard G, Hyde C J, Wits W W, Ashcroft I A, Chen H and Clare A T 2021 Powder Bed Fusion of nickel-based superalloys: A review *International Journal of Machine Tools and Manufacture* **165** 103729
- [37] Li X, Dunn P F and Brach R M 1999 Experimental and numerical studies on the normal impact of microspheres with surfaces *Journal of Aerosol Science* **30** 439–49
- [38] Chen H, Cheng T, Li Z, Wei Q and Yan W 2022 Is high-speed powder spreading really unfavourable for the part quality of laser powder bed fusion additive manufacturing? *Acta Materialia* **231** 117901

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