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# Measurement of powder spreading dynamics in additive manufacturing 

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#### Abstract

In this work, we examine the effect of the state of the pre-processing powder bed in powder-based additive manufacturing, particularly in metal laser powder bed fusion (PBF-LB). The spreading of the powder layer has been identified as a critical but underresearched stage of the PBF-LB process; the existing literature on PBF-LB predominantly focuses on overall process parameters and the properties of the powder feedstock. Here, we investigate powder spreading dynamics by measuring spread powder surfaces using optical measurement technologies, primarily fringe projection. Measurement technologies are investigated to determine which can be used to provide valuable data about the state of the powder bed. Powders can be immobilised to improve the ease of measurement; in this work, immobilisation is achieved by adhering it to the base of a petri dish, and different adhesives are investigated. Most adhesives used create inhomogeneous surfaces where the texture is determined by the adhesive, as opposed to the powder, and therefore they provide minimal utility in analysing the powder. Experiments are also performed with a machine containing the build surface and powder spreading components used in PBF-LB. Powder is spread across the build surface, as during the PBF-LB process; the resulting unprocessed powder surface is then measured using a fringe projection system. The resulting point cloud is then used to generate a digital surface representing the powder surface, which can be further analysed. This work investigates the measurement of spread powder layers using optical measurement techniques. The method of adhering powders to a base does not provide satisfactory results as the adhesive dominates the surface texture; however, it is possible to measure loose powder insitu using fringe projection and therefore analyse the surface texture of the powder bed. This analysis can be used to indicate the performance of the powder spreading process.


Keywords: Metrology, additive manufacturing

## 1. Introduction

Additive manufacturing is a process whereby parts are created by joining smaller component material pieces to form the desired shape as defined by 3D model data, typically a layer at a time [1]. Powder bed fusion (PBF) is a process whereby a powder feedstock is spread across the build surface and an energy source, commonly a laser [2], is used to fuse the powder particles into the desired part geometry. PBF-LB is a technology with promising industrial applications, but uptake is still limited; an improved understanding of the process can be used to optimise and implement control measures which improve the quality of parts produced [3].
The powder spreading stage of the PBF-LB process has been identified as crucial but is under-researched [4,5]. In this paper, we aim to develop understanding of powder spreading by investigating optical surface measurement technologies to assess powder spreading. Two experiments are conducted regarding measurement of spread powder surfaces. Powders are adhered to a petri dish for ease of measurement without the risk of powder becoming airborne. In the second experiment, powder is spread using PBF-LB apparatus and measured in situ using a fringe projection system. These experiments provide data to demonstrate the utility of different methods of measuring powder, which can be used to analyse powder spreadability and improve the PBF-LB process.

## 2. Powder-based additive manufacturing

Previous research on powder-based additive manufacturing, especially PBF-LB, has focused on process parameters, mainly concerning the laser used and the powder feedstock, and how these parameters relate to the mechanical properties of the finished parts [6]. Several powder parameters affect the particle dynamics of the powder spreading stage of the PBF-LB process [4,5]. The powder spreading behaviour determines the state of the powder bed, which is here defined as the overall condition of the powder bed, including the powder packing density, the surface roughness of the powder bed, and the variation of these qualities across the entire powder bed. In turn, the state of the spread powder bed influences the melting stage and the quality of the finished part. Other process parameters, such as the laser parameters, also have a significant effect but are considered out of the scope of this paper. Literature has also shown that the speed and form of the spreader arm affect the powder bed, with a higher spreading velocity creating a lower powder bed surface roughness and certain form factors performing better [7].
Regarding shape, spherical particles are preferable, as these provide better flowability and more uniform powder layers [6,8]. Powders with a wider particle size distribution containing a larger concentration of fine particles have been found to reduce bulk powder flowability [9], likely due to fine particles forming agglomerates and increasing inter-particle forces. However, a wider particle size distribution can increase powder packing
density, as finer particles fill voids between larger ones [6]. Ideally, the powder layer density is higher and homogenous across the entire build surface; an inhomogeneous powder layer can cause defects in the finished part. A lower powder bed density can also reduce the stability of the melt pool, which can cause defects in the finished part [6].

It has been found that powder with higher flowability forms a more homogenous powder layer during the spreading process [6]. A low flowability may cause the power to fail to form a complete powder layer. Powder spreadability is distinct from powder flowability, and most existing research focuses on flowability. While the two characteristics are closely related, they are separate; conclusions about flowability do not necessarily follow for spreadability and assumptions made for flowability do not apply to powder spreading. Powder flowability typically occurs in large bulks and is mainly controlled by gravity, while spreadability is controlled by shear forces and occurs within smaller layers, where the particle size may be on the same order of magnitude as the layer size [4]. Many powder characteristics affect the powder spreadability, with higher flowability and powder packing density being ideal [4,5]. A more regular spherical shape improves spreadability, while powder size distribution is more complex; a wider distribution containing more fine particles may have a better packing density but a poorer flowability due to a higher tendency towards agglomeration [5].

## 3. Powder adhesion

To measure a powder, it must be contained within a suitable vessel or environment. While loose powder may sometimes be measured, this powder may become airborne, which presents a safety risk for the operator due to inhalation and a contamination risk to the equipment used. While powder may potentially be measured through a transparent medium, this method will not work for all optical measurement technologies and will provide an additional source of error. Alternatively, powder may be adhered to a surface, which prevents powder from becoming airborne, but the surface topography of the adhered powder may be different to a freely-spread powder layer.

In this work, we conducted an experiment in which methods of adhering metal powder were tested. A quantity of $\mathrm{AlSi}_{10} \mathrm{Mg}$ powder, with particle sizes ranging between $(20-63) \mu \mathrm{m}$, was deposited on several Petri dishes and adhered to the inner bottom surface. A spatula was used to spread the powder around the dish manually. All stages using loose powder were carried out under fume extraction to ensure any powder particles that became airborne were removed. The exact immobilisation procedure varied for different adhesives; for double-sided tape, a section was cut to the length of the dish and powder was spread atop it. For the aerosol spray adhesive used, separate samples were made with adhesive applied prior to the powder, adhesive applied atop the powder, and with both. For PVA glue, super glue and epoxy, a quantity of the adhesive was deposited onto the base of the dish and spread across it, then powder was spread atop the adhesive immediately afterwards. As several adhesives required time to set fully, the dishes were left undisturbed for twenty minutes. After the adhesive had set, a pressurised air jet was used to remove any powder that had not adhered to the dish surface; minimal force was applied to avoid breaking powder adhesion. Samples were also prepared in which the powder was not affixed to the base. The resulting powder samples are shown in figure 1.

Each powder sample was measured using a GOM ATOS Core 300 fringe projection system [10]; the sample was placed on a
rotational stage with several marked points. The sample was then measured from different angles using the rotational stage, and the GOM Scan software utilised the markers to stitch these measurements into a single point cloud. Each adhered powder sample was measured with the lid removed, as the transparent plastic adds a source of error to the measurement due to having different optical properties to air, such as a higher refractive index. As the powder remained adhered to the base, there was no significant safety or contamination risk to consider. However, the dishes containing loose powder were measured through the transparent plastic lid; the risk of powder becoming airborne and being inhaled by the operator or contaminating equipment was considered too significant, and fume extraction was unavailable.
The point clouds generated by the fringe projection measurements were then exported in the .stl file format and analysed using MountainsMap software [11]. This software was used to extract a surface from the point cloud, generating a virtual surface which represented the physical surface of the powder. This then allowed for quantitative and qualitative surface texture analysis.


Figure 1. Powder samples affixed using; a) adhesive tape; b) spray adhesive; c) super glue; d) PVA glue; e) epoxy; and f) not affixed.

All forms of adhesion had a significant effect on the structure of the powder and therefore hold little to no utility for assessing powder spreadability. The adhesion processes created highly inhomogeneous surfaces, where the texture was dependent on the adhesive as opposed to the powder spreading process. However, for the adhesive tape, a thin and relatively homogenous layer, with some small powder clusters, forms, as shown in figure 2; while the texture present is still determined by the shape of the tape and the layer is thinner than desired, the powder is not occluded in any way. The fringe projection system has insufficient resolution to identify individual powder particles, however, the powder-on-tape surface may provide some utility when measured with a system having a sufficiently resolution. This method would allow for identification and analysis of individual powder particles, and more detailed characterisation of the powder clusters formed. The spray adhesive also created a relatively homogenous surface; however, the pressure of the aerosol disrupted the powder; future work could attempt to create a "less intense" delivery mechanism, which may preserve a powder surface with less disturbance.

## 4. Powder spreading

This experiment examines powder spreading in an environment that more closely resembles industrial usage. An AconityMIDI+ PBF-LB machine was used [12], which allows for the lower
chamber containing the build surface and powder spreading mechanism to be separated from the upper chamber containing the laser; only the lower chamber was used here, which provides easier access to the powder. The system includes a powder reservoir and a build surface consisting of metal plates that are initially level with the main surface but can alter their $z$-heights via motor control.


Figure 2. A section of powder immobilised using double-sided tape, measured by fringe projection. Visualisation generated using MountainsMap 9 software [11].

### 4.1. Powder spreading methodology

An excess quantity of 316 stainless steel powder was deposited in the powder reservoir of the MIDI+. The reservoir was then raised above the main surface level while the build surface was lowered below this level. The spreading arm was moved across the length of the main surface at a constant velocity, spreading powder across the build surface. The fringe projection measurement system was then used to acquire topography measurements of the powder layer formed. The
fringe projection system was positioned adjacent to the MIDI+ system, and the build chamber door was opened to allow clear line of sight for the fringe projection process; this setup is shown in Figure 4. The system was then reset, with the spreading arm returning to its initial position and all powder removed from the build surface and the surrounding main surface under fume extraction. This process was repeated using a carbon brush spreading arm and a silicone spreading arm. Both spreading arms consist of a long solid implement, covering the whole width of the build area that is moved by motor control to mechanically spread the powder across the build surface; the silicone blade uses a long length of silicone material, while the carbon brush uses a length of metal with shorter carbon fibre bristles attached. Prior to talking measurements, the fringe projection system was calibrated within the same room, and the exposure time was adjusted manually.


Figure 4. The experimental setup including the GOM fringe projection unit positioned to measure the powder bed of the Aconity PBF-LB unit.

a)

b)


## C)

Figure 3. Filtered surface measurements of; a) the base plate without any powder; b) a powder layer spread using the carbon brush spreader arm; c) a powder layer spread using the silicon spreader arm.

### 4.2. Data analysis

The measured surfaces were automatically converted into point clouds by GOM Scan software and then exported in the .stl file format. These files were imported into MountainsMap 9 software [11] and converted into height maps, 2D images of the surface topography in which $z$-height is represented using a colour scale, with point spacing ( $0.8725 \times 0.8731$ ) mm . The height map was filtered via a series of operations; first, an area of $(100 \times 100) \mathrm{mm}$ was extracted. Then, an S -filter was applied with a value of 2.7 mm , approximately equal to the size of 3 pixels. The surface was levelled by subtraction of a least squares plane. An L-filter of 99.7 mm was then applied to remove underlying waviness larger than the overall measurement area from the surface. The resulting surface was then analysed; surface parameters per ISO 25178-2 [13] were calculated by the software, specifically $S q, S s k, S k u, S p, S v, S z$ and $S a$. The same processing was duplicated on the other measured surfaces, and images and parameters were created. The final filtered surfaces can be seen in figure 3, and select surface parameters are tabulated in table 1.
The filtered surfaces in figure 3 show distinct textures. Surface a) shows the texture of the empty build surface. Three measurements were taken of each powder surface; for each, a virtual surface was generated, and parameters were calculated, as seen in table 1. For both powder surfaces, the repeat measurements show only minor variations in the surface texture parameters. Both powder surfaces show a relatively successful spreading attempt as there is complete powder coverage of the build area; however, there are features visible which may cause issues with the melting and part formation process. In the carbon brush surface, several depressed lines can be seen. Conversely, a wider raised line can be seen on the silicone surface. Both of these features show significant inhomogeneity in the powder surface caused during the spreading process.

Table 1. Surface texture parameters for the build surface and the two different powder surfaces. Confidence intervals computed at $95 \%$ confidence on three repeat measurements.

| Surface | Sq $/ \boldsymbol{\mu m}$ | Sku | Sz $/ \boldsymbol{\mu m}$ | Sa/ $\boldsymbol{\mu m}$ |
| :--- | :--- | :--- | :--- | :--- |
| Carbon | 16.28 | $7.14 \pm 0.38$ | $178 \pm 17$ | $11.66 \pm 0.31$ |
| brush | $\pm 0.36$ |  |  |  |
| Silicone | 28.05 | 3.18 | $173 \pm 13$ | $21.90 \pm 0.14$ |
|  | $\pm 0.23$ | $\pm 0.031$ |  |  |

The surface parameters compiled in table 1 provide a quantitative analysis of the surface texture. These also show a difference between the surfaces; the powder surface spread by the silicone spreading arm shows larger deviations from the nominal plane than that of the carbon brush. For example, the average $S a$ value of the carbon brush surfaces is ( $11.66 \pm 0.31$ ) $\mu \mathrm{m}$, while the average $S a$ value of the silicone surfaces is ( $21.90 \pm 0.14$ ) $\mu \mathrm{m}$.

## 5. Discussion

The results included in this paper show that fringe projection is a valid technique for determining powder spreadability by assessing the success of a spread powder layer. Fringe projection possesses a sufficiently large measurement area to include a significant area of powder in a single measurement and sufficient resolution to resolve the features formed in powder surfaces. Further research is required to examine what features can be determined and what quantitative parameters are useful; specifically, which of these features and parameters significantly correspond to the quality of the finished AM part. As per the
results of this paper, future work may use fringe projection as the primary measurement tool.
There was limited success in powder adhesion, as no methods immobilise powder without causing significant disruption to the powder surface. Further research may be conducted regarding different optical measurement techniques and whether adhered powder surfaces are useful with these technologies.
The literature shows that powder parameters affect the spreading process in powder additive manufacturing. In this paper, we have demonstrated that different spreading implements have a notable effect, creating different features and differing surface roughness. Future work can examine this variation further and attempt to correlate it to quality parameters of finished parts.
In this paper, we have demonstrated techniques of measuring powder surface texture to assess powder spreadability. Future work may build upon these results to determine the ideal parameters for evaluating powder spreadability and link these to finished part quality. Additionally, these parameters may be measured within the PBF-LB process and utilised for in situ control.

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