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Spatters deposition on Inconel 718 laser powder bed fusion manufacturing

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Abstract
In laser powder bed fusion (PBF-LB), the detrimental effects of by-products need attention when defining a manufacturing process. One of the by-products able to modify some parts' attributes is called spatters, which consists of metal particles ejected during laser-material interaction throughout the laser trajectory. Spatters have different attributes from the virgin powder, like dimensions and oxidation level, that can change material properties and part integrity. These spatters can lead to mechanical property degradation when remelted in the part. Moreover, the build chamber gas flow configuration can play a significant role in dictating how spatter deposits along the build platform. The present study aimed to experimentally map the spatters' deposition behaviour on the build platform of a PBF-LB machine chamber when manufacturing Inconel 718 parts. To this end, the manufactured parts were centralised in the front position of the build platform near the gas inlet, while the middle and back regions were used for collecting the deposited powder and spatters. The powder samples were then examined using optical measurement equipment, and the acquired images were analysed to extract quantitative metrics of spatter deposition based on defined criteria for spatters' identification. An influence of the gas flow direction on the powder deposition along the build platform was verified. These quantitative measurements highlight the role of the gas flow behaviour in carrying these by-products along the build chamber, providing experimental indications of where they depose under the studied manufacturing conditions. Finally, understanding the spatters' deposition behaviour can be considered to better deal with by-product contamination during PBF-LB manufacturing with remarkable consistency.

metal laser powder bed fusion, Inconel 718, spatters deposition, by-products

1. Introduction

The metal additive manufacturing technology of Laser Powder Bed Fusion (PBF-LB) matches the contemporary demands of easily customized products with high mechanical properties under a manufacturing waste reduction environment [1]. In this process, the layerwise approach allows building high complex parts from metallic powder material based on laser heat source scanning. The advancements in the PBF-LB revolution over the actual manufacturing systems deal with the need to improve the properties' consistency in the process, which can be managed somehow with adequate setup. So, it is important to consider potential sources of product variation throughout the process to enhance this technology's capabilities.

Spatter is one of the most important by-products of the PBF-LB process. According to Young et al. [2] findings, there are five types of spatters with different formation mechanisms, as follows: (I) Solid spatter particles ejected by the vapour created by the laser heating before melting; (II) Metallic jet spatter derived from the liquid detachment from the melt pool depression zone during the fusion process; (III) Powder agglomeration spatters, generated from the coalescence of a liquid spatter with an unmelted powder or the collision of two liquid spatters; (IV) Entrainment melting spatters originated from the powder carried by the gas flow until de fusion region, which is fused and ejected again; and (V) Defect induced spatters formed by the laser interaction with huge preexisting defects on the previous layers. So, understanding how these units affect the process outcomes became a critical task.

Spatters' main effects on parts integrity were related to the amount of spatter contamination in previous studies [3, 4]. Moreover, the spatter deposition mechanism is affected by the protection gas flow in the build chamber [5, 6]. Dinh et al. [4] discussed that the gas flow affects the homogeneity of the products manufactured by PBF-LB, proposing that this occurs because of the different quantities of spatter deposition regarding its location on the build platform. Esmaeilizadeh et al. [7] experimentally characterised spatters when manufacturing with an Hastelloy X alloy. The authors highlighted regions of higher spatters deposition near the protection gas outlet where the parts' surface roughness was increased to a maximum of 28 µm compared to 16.8 µm in other regions [7]. So, these findings reinforce the need to manage the manufacturing conditions to enhance the repeatability of the PBF-LB technology results.

The Inconel 718 is a Ni-Fe-based alloy with remarkable mechanical performance under high-temperature environments [8]. As a result, this material is widely considered for producing structural components for high-temperature applications like gas turbines and nuclear reactors [8]. Hence, the proposed study will contribute to finding strategies to better deal with spatters' contamination during PBF-LB manufacturing of this material to improve its robustness.

The proposed study focused on quantitatively investigating the spatter deposition distribution and identifying patterns along the build platform when manufacturing Inconel 718 workpieces based on experiments. To this end, a systematic spatter particles' analysis was conducted with an optical measurement equipment Alicona followed by image analysis. Section 2 encompasses the PBF-LB manufacturing setup description and the methods used for the experimental analyses of the collected powder batches. Then, Section 3 presents the obtained results and confronts them with the literature. Finally, Section 4 highlights the main conclusions and contributions of the work.

2. Material and Methods

Gas atomised Pearl®Micro Ni718 powder (Aubert & Duval) with particles ranging from 10 µm to 53 µm was used to manufacture in an industrial PBF-LB machine, considering the chemical composition shown in table 1. The machine had a 500 W ytterbium fibre laser (1065 nm) and a roller coating system. The build chamber was protected with Argon (Ar) atmosphere. Argon flowing from the front to the back and no preheating system of the plate was used. Cuboid and rectangular samples were manufactured in the central region of the front of the 350 mm x 350 mm build platform, as schematised in figure 1. The manufacturing order followed each x-axis row along the positive y-axis, starting in the chamber front (figure 1). The main processing parameters were:

- Layer thickness of 40 µm;
- Hatching filling zig-zag path with 55 µm intervals between passes at 220 W laser power;
- Two contours with 60 µm intervals at 210 W laser power;
- Laser speed of 1.8 m/s on infill and 2.1 m/s on contours.

Table 1. Chemical composition of the Inconel 718 powder.

Element	Weight percentage/ %
Ni	50 – 55
Cr	17 – 21
Nb	4.75 – 5.50
Mo	2.8 – 3.3
Ti	0.65 – 1.15
Co	< 1.0
Al	0.2 – 0.8
Si, Mn	< 0.35
Cu	< 0.3
C	< 0.08
N	< 0.03
Fe	Balance

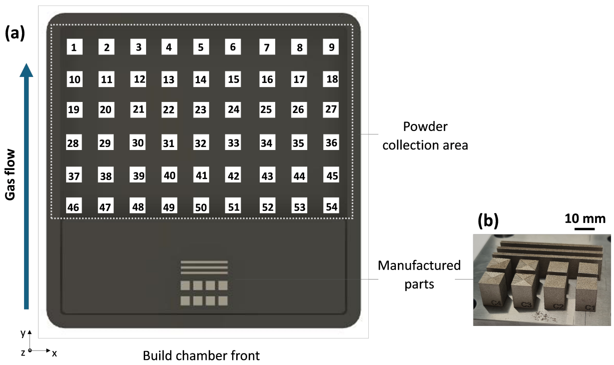

Figure 1. (a) PBF-LB build platform configuration for the experiments. White squares represent the analysed areas of collected powder and spatters. (b) Cuboid and rectangular parts manufactured by PBF-LB.

The powder was deposited only on the front part of the building plate where the parts are manufactured. This allowed 2/3 of the building plate area to be used for powder and spatters collection (figure 1). All this evaluation area had its top covered with double-sided adhesive tapes for powder and spatter collection. The protection film of the tapes was removed just after the powder bed definition on the front plates using the available glove box to avoid the raw powder from sticking to the tapes during the powder bed setup. As a result, the collected powder on the defined regions corresponded to the particles spread only during the workpieces' layers building.

2.1. Powder analysis

Figure 2 highlights potential differences that can be identified between the attributes of Inconel 718 powder particles (figure 2a) and spatters (figure 2b). It is possible to observe that spatters are visually characterised either by an agglomeration of the powder, resulting in a specific shape, or by a powder diameter greater than the manufacturer's distribution. All spatters show a change in colour due to a high temperature during their creation. Following the observed characteristics of the particles, the colour was taken as a potential criterium for quantifying the deposited spatters on the evaluated powder batches.

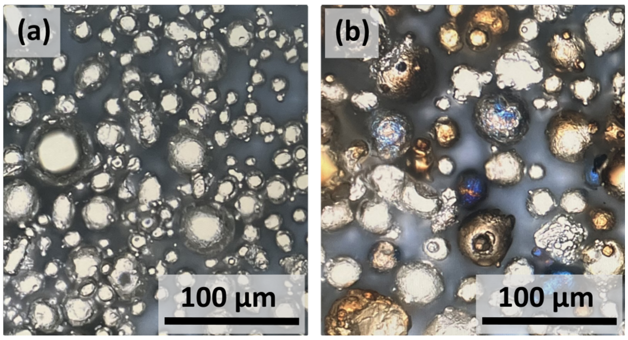

Figure 2. Powder particles, (a) raw material and (b) raw material + deposited spatters.

This way, after manufacturing, the spatters collection areas were removed from the build chamber, stored in plastic zip bags for safety reasons, and taken to the optical measurement equipment Alicona IF sensor R25HP. Fifty-four regions, represented by the white squares in figure 1 were analysed with a 5x objective magnification lens for spatter investigation. These regions were equally distributed over the powder collection area (figure 1).

The images acquired offline with Alicona equipment were then post-processed with the Color Thresholder MATLAB tool. The image was converted to the HSV colour space to obtain masked images after the thresholding, considering colour criteria. In this system, H is the hue associated with a position in the colour wheel, while S refers to the saturation and V is a value associated with the brightness [9].

As can be seen in figure 2, some regions of the image did not report robust data from the particles. These areas are related to regions with loss of definition of some particles and background, zones that were not reached by enough light, and some particles that did not reflect their colours sufficiently because of surface attributes. So, a first mask was stated to extract the dark regions in images, where no particle can be precisely defined. In this case, the HSV space specifications had full H and S ranges under a V between 0 and 0.2 for obtaining the 'area to be disregarded'. Then, two complimentary masks were structured based on the spatter characteristic colours observed in figure 2. These masks aimed to quantify the spatter fractions. The first one focused on particles within the brown and bronze palette. In this case, the H range was from 334.8º to 64.8º with S between 0.2 and 1, and V full range. The second one focused on the blue palette spatters by tuning the H range to 162.0º to 219.6º and keeping the same S and V ranges of the brown/bronze mask.

With all the masks structured, the fifty-four areas were firstly analysed with the dark mask to extract the pixels identified as 'areas to be disregarded'. Then, the remaining region of interest had the spatters quantified based on the combined results of the brown/bronze and blue masks application. Finally, the relative distributions of spatters within each analysed area could be stated. So, it was possible to investigate the spatter deposition distribution under the studied conditions.

3. Results and discussion

Figures 3 and 4 show batches of the material powder and spatters collected after the manufacturing build cycle and their respective masked images when considering the detailed colour criteria. Looking at the experimental images (figures 3a and 4a), it is possible to observe expressive differences between the two analysed regions in the number of spatters and their dimensions. The powder batch 38 located in the lateral region of the build platform had expressively fewer spatters than powder batch 14, which was positioned in the central area close to the gas outlet, straight behind the parts under manufacturing (figure 1). The powder collection area 38 located in the lateral region of the build platform evidenced bigger spatters than area 14. The spatters are ejected during the material fusion, and these findings indicate that the lighter spatter particles were more prone to be carried out far from the fusion zone, following the protection gas flow laminar behaviour. So, the differences between the powder collection regions shown in figure 3a and figure 4a also give traces of the effects of the gas flow on the spatter deposition responses.

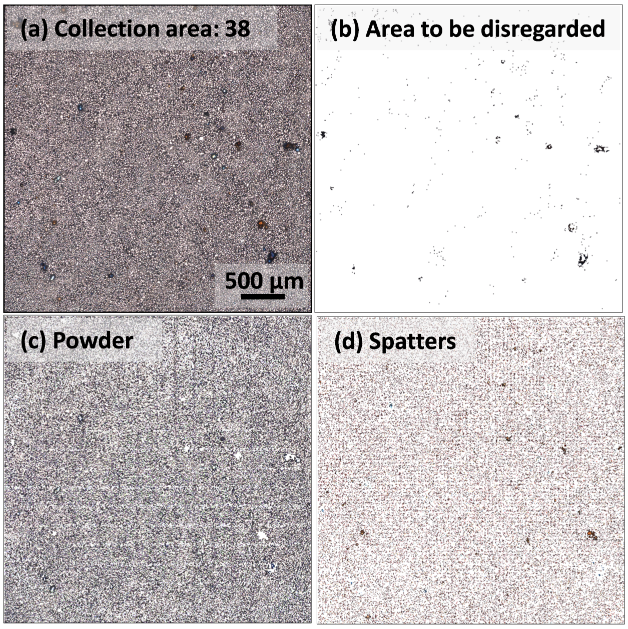

Figure 3. Examples of (a) experimental powder particles of a collection area with a low amount of spatters (b) the area disregarded by the dark mask, (c) the powder identified in the area of interest, and (d) the blue and brown/bronze masked images referring to spatters.

Despite the limitations in identifying tiny coloured particles, the proposed image analysis strategy provided a satisfactory result for estimating the deposited spatters. Concerning the overall spatters deposition, this by-product represented about 30 % of the area observed in the build platform images after the manufacturing. It is worth noting that the presence of spatters is inherent to PBF-LB manufacturing. However, higher amounts of this by-product can be detrimental to the integrity of manufactured parts, as previously discussed.

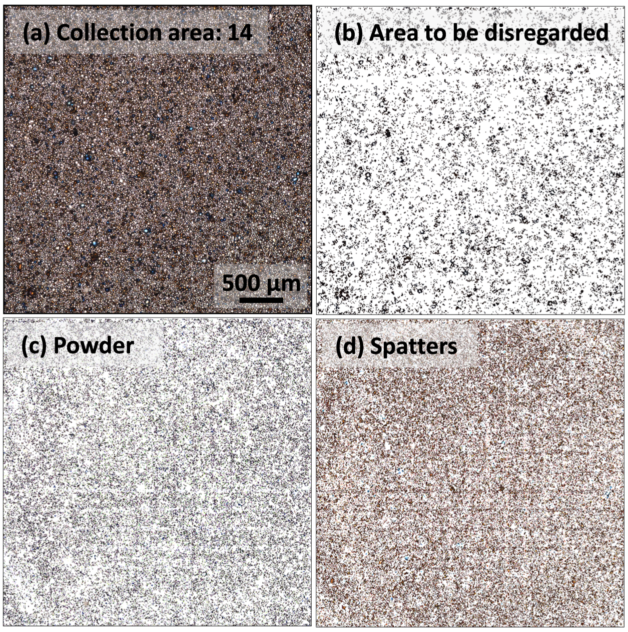

Figure 4. Examples of (a) experimental powder particles of a collection area with a high amount of spatters (b) the area disregarded by the dark mask, (c) the powder identified in the area of interest, and (d) the blue and brown/bronze masked images referring to spatters.

Figure 5 shows the relative distributions of these spatters within each analysed area regarding the gas flow. The samples were manufactured closer to the gas inlet (figure 1). Thus, the influence of the gas laminar flow direction on the spatters' deposition behaviour was signalled by the findings that almost 26 % of the observed deposited spatters were located in the central region right behind the manufacturing area, defined by a square zone limited by 31-33-49-51 areas (figure 1). When considering the y-axis entire extension in the central region (gas flow direction), expanding the observation zone to the one between the 4-6-49-51 areas (figure 1), the spatter fraction sharply increases to about 52 %, showing the effects of the spatters deposition all over the y-axis of the build platform.

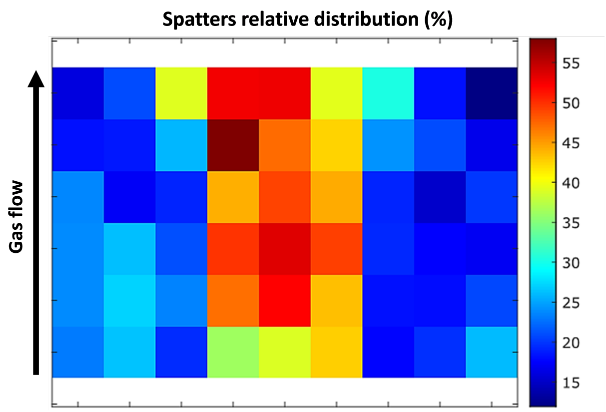

Figure 5. Relative distribution of the deposited spatters within each analysed area on the build plate, determined by the relation: spatter/(spatter + powder + area to be disregarded).

The analyses along the x-axis also supported the gas laminar flow potential in dictating the spatter deposition, taking into account that the deposition along the central positions was predominant in all rows (figure 5). The concentration of spatters in each analysed area is high in these experiments because the quantitative evaluation was performed at the end of the manufacturing, representing the accumulation of powder over the 350 layers that were built. The observation provided by figure 5 emphasises that the spatter transport was predominant along the laminar gas flow in contrast to negligible spatter deposition in other directions. Moreover, the row closer to the manufacturing area had the lowest spatter deposition regarding the x-axis. This might indicate that the particles observed in this row were mainly directly deposited with the ejection from the fusion area, considering that the gas flow seemed to favour carrying the particles away from this row in the central regions. Further investigations can be performed to validate these hypotheses.

The main findings evidenced that spatters were carried away from the manufacturing zone, mainly depositing along the protection gas laminar flow. Still, all the build manufacturing platform was impacted by the spatters generated in the manufacturing zone positioned in the front of the machine chamber. So, it is important to consider the spatter deposition behaviour when planning the PBF-LB manufacturing. Still, the observed traces of a potential gas flow role over the spatters' deposition open avenues to investigate the gas-spatters relation further. Future work will be carried out to address this subject by adding fluid simulations.

4. Conclusion

Spatter deposition distribution along the build platform upon Inconel 718 workpieces' manufacturing was investigated in the present study. Colour criteria for quantifying the spatter particles' deposition were proposed for the evaluated manufacturing conditions, considering brown/bronze and blue masks. The post-processed image analyses indicated that the central region along the y-axis in the back of the manufacturing zone encompassed about 52 % of the identified spatter particles. This way, the experiments give traces of the laminar gas flow influences on by-product deposition along the build platform.

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