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SURFACE ROUGHNESS DEPENDANT FACTORS IN METAL POWDER BED FUSION PROCESSES

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Abstract
Powder bed fusion (PBF) is a promising Additive Manufacturing technology that allows to manufacture very complex parts. However, not all the parts distributed in the platform, despite having the same geometry, have the same surface roughness. There are different parameters that could affect the surface roughness.
In order to study these parameters, two different platforms were designed and analyzed with a Surface Roughness Tester. The results show which parameters affected principally the surface roughness, and these results suggest a dependency of surface roughness on the part position in the build chamber. Based on this study, the effect of the laser beam incidence angle hypothesis is presented in this paper.

Roughness, Selective Laser Melting, laser beam, incidence angle, downskin

1. Introduction

PBF processes (Powder bed fusion), are one of the most promising techniques for additive manufacturing (AM) [1] [2] and are based on the direct manufacturing of parts from metallic powder, fusing the material layer by layer, as specified by a CAD file. These parts show advantages over others manufactured by other technologies, such as the great complexity in its design [3] [4] and the possibility of combining thin walls, hollow areas or lattice structures. This complexity enables the reduction of the weight of many parts, for that is a technology with a special interest for the aeronautical and healthcare sector [5] [6] [7].
However, this technology still has some limitations in comparison of other traditional processes. One of these limitations is the poor surface finish that lead to the need of a final postprocessing stage of the parts [8]. This high roughness is an important parameter that affects the resistance to fatigue of the part [9]. The high roughness of the parts manufactured using PBF technology is due to different factors [4] [10]:
The heat accumulation is an important factor, because of that, the particles of the powder bed can adhere to the part surface. These adhering particles are partially molten, increasing the roughness [11].
The heat accumulation can be due to different reasons. One of the reasons is when the parts are very close to each other, the heat of melting the nearby parts will affect the parts roughness. Another reason is the height of the pieces. In the highest parts in which the laser have to melt more layers, more heat will accumulate. As a consequence, the higher parts present a higher roughness than lower parts [12]. In addition, platforms usually have more molten area in the lower part than in the upper part, only the highest parts will reach the highest layers.Because of that in the lower layers the manufacturing time is longer than in the upper layers. Consequently, the roughness is not the same in the upper part than in the lower.

Another determining factor in the roughness will be the geometry of the melting surface and the angle it forms with the horizontal [12] [13]. There are different types of surfaces, for the study of roughness two will be defined:
- Upskin: It is the area that does not have an upper layer on top, it can be seen schematically in figure 1 (a).
Downskin: As shown in Figure 1 (b) is the area that does not have a lower layer. In general, the laser melting a layer transmits energy to the lower layer as well, thereby obtaining a poor finish, as shown in Figure 1 (c).

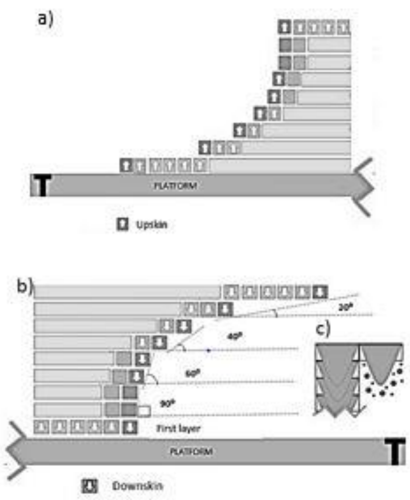

Figure 1: Downskin and upskin zone scheme

If it is an upskin surface, with molten material underneath, the roughness will tend to be smaller than downskin surfaces those have the non-melted powder bed under them. These downskin

surfaces will be the roughest of the geometry, since when melting the layer that only has powder under it is possible to partially melt powder from the bed that does not belong to that layer, increasing the roughness [14] [10].
Two other factors can increase the roughness. On the one hand, the wiper, which is responsible for dragging powder on the platform from the back of the platform to the front, repeat the same movement for each layer, and it may not distribute the powder full homogenously, being able to affect for these small differences to the roughness [10]. On the other hand, the manufacturing will take place in an inert argon atmosphere. This argon stream enters to the chamber from one side and exits from the other, creating gas streams in the building chamber. The stream drags the spatter and oxide formations to one side of the chamber, for that the parts one this side of the platform are rougher than the parts on right side [10].
In conclusion, many parameters may affect the roughness of the part. This work will verify the main factors related with the roughness of the parts in order to find new parameters that may intervene in the surface finish.

2. Equipment and material used

The tests were made on the Renishaw AM400 powder bed additive manufacturing machine, using the Inconel 718 as material. The Inconel 718 is a nickel-chromium-molybdenum alloy designed to withstand corrosive environments and high temperatures. These properties make it a very suitable material for the aeronautical sector [2].
The powder used for the tests is Renishaw house powder and was reused several times after sieving it to remove the damaged and oxidized powder particles after manufacturing.
For the roughness analysis, different geometries were designed to check effect of different factors. For the manufacture of these parts, the following volume parameters were used (Table 1):

Table 1: Parameters used in the manufacturing process.

Hatch distance (mm)	0,9
Power (W)	200
Point distance (µm)	70
Exposure time	80

Once the parts were made to analyze them the SV C3200H4 Surface Roughness Tester of mitutoyo house was used, under the ISO 1997 standard and using the following parameters: profile R, shortest cut-off λC 0,8mm and longest cutoff λs=2,5mm. The cut-off is wavelength at which the filter becomes effective.
The surface was also analyzed using an Alicone confocal microscope model Control ServerFP G1 Vf2, to analyse the particles that are partially fused on the surface and that could be the cause of the high roughness.

3. Procedure

For the analysis of the different effects, two different platforms were designed with different pieces:

3.1. Analysis of the effect of the wiper and the argon

For this study, a first platform with different cubes placed on each edge of the platform was designed.

3.2. Analysis of downskin parts

The downskin analysis was performed on a second platform. Based on previous studies, the downskin will be the surface with the worst surface finish. To analyze this effect, an inverted octagonal pyramid was designed, with the faces oriented 55° from the horizontal, placed on each side of the platform.

3.3. Analysis of the effect of heat accumulation

In that second platform a group of geometries was designed to analyse the effect of heat accumulation due to the height of the parts, as well as the parts closeness between them [11].
To this end, four rectangles were designed at different heights and distributed at different points on the platform, thus being able to verify the effect of the wiper and argon, seen in the first platform, as well as studying the heat accumulation due to the height and proximity of the parts.

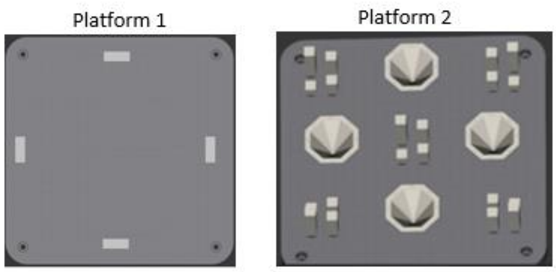

Figure 2: Design of the first and second platform

Figure 2 shows the geometries designed and their distribution on the second platform.

4. Results and discussion

4.1. Analysis of the effect of the wiper and argon

The four surfaces of each square, designed in the platform 1, were measured, taking eight measurements on each face, to minimize the effect that a partially molten particle could have on the surface.
The values of Ra are around 4µm in the central geometry of the platform, and it moves away to values of 23µm in the pieces placed on the edges of the platform. These results are shown in Figure 3.
That demonstrated that the least rough part is the central one, besides this piece shows a uniform roughness in all its faces. Moreover, the pieces placed on the edge show a very different roughness on each of their surfaces, always showing the highest roughness on the outside surface of the piece.
This shows that the most significant effect on the roughness is not due to the wiper or argon, because the roughest piece is not always the left of the platform or on the front.

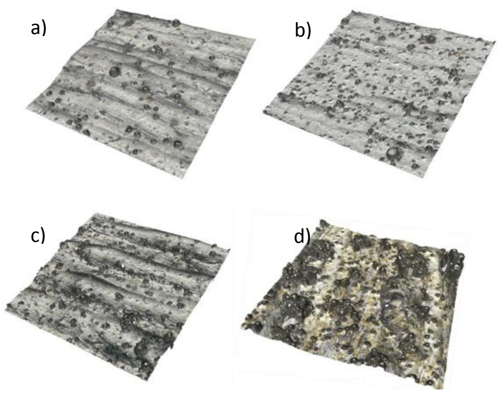

Figure 3: Results of the first platform to analyse the effect of the wiper and argon stream.

One of the possible causes of this high roughness at the edges of the platform could be the angle of incidence of the laser. Since the laser, placed in the center of the platform, could incise completely perpendicular to the center of the platform, but create a small angle at the edges.

4.1. Analysis of downskin parts

In the case of the octagons designed for this purpose, as in the previous geometries, each surface was measured eight times to minimize the effect of the particles adhering to the surface. Both the exterior and the interior face were measured (downskin and upskin), obtaining 16 measurements per octagon.

As expected, the roughness in the downskin always is higher than the upskin. The roughness is increased by 50% between the face of upskin to downskin. These results are shown graphically in Figure 4. This effect of upskin and downskin can also be clearly seen in the case of Rz.

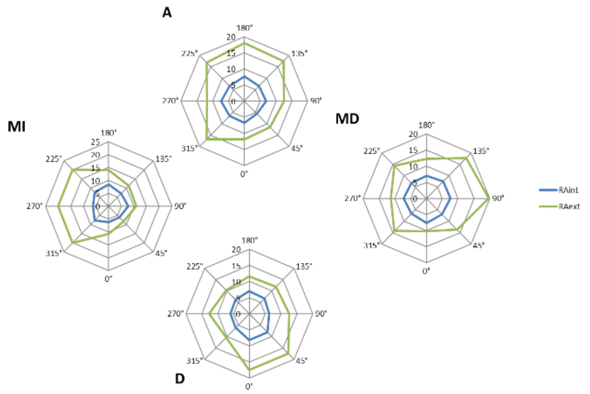

Figure 4: Results obtained studying the downskin parts.

In these geometries the effect seen in the previous platform could also be checked, in which the roughness increased in the edge of the platform possibly due to the lens.

This effect of the bad result on the outside can also be seen at first sight. The downskin face that is on the outside of the platform always shows a brown color with more stuck powder than on the inside of the platform. This effect can be seen in Figure 5, where is a photograph of a face downskin oriented towards the central part of the platform next to another oriented towards the outside.

Figure 5: First sight of a downskin part with different orientation.

In addition, to verify the existence of those partially fused particles on the surface, surface images were taken by confocal microscopy. The upskin has the smallest number of particles stuck on the surface, as is shown in Figure 6. Images were also taken of one of the vertical surfaces that already showed some more stuck particle, but not too many as the downskin surface. In the case of downskin, images were taken of both the exterior and the interior, with a greater number of particles on the exterior faces.

Table 2: Roughness value of different zones of the parts

SURFACE	Ra (µm)
Upskin	6,547
Vertical surface	6,967
Edge Downskin	19,346
Centre Downskin	10,082

Table 2 shows the results obtained after measuring the different surfaces with the roughness tester. The roughest zone is the downskin, especially the outside-orientated downskin, due to the partially molten particles.

Figure 6: Analysis of the partially pelted particles in different surfaces: a) Upskin, b) vertical face, C) downskin oriented to the centre of the platform, d) downskin oriented to the platform edge.

4.3. Analysis of the effect of heat accumulation

•Effect of height

In the case of the highest test specimens, the roughness was analysed throughout the specimen to analyze the roughness depending on the height. Specifically, it has been analysed the central test specimen, avoiding the effect of the other parameters. In these specimens, a measurement was made in three dimensions, measuring 38mm on the X-axis to measure the entire height of the specimen and 7mm on the Y-axis to measure the entire face. There were taken 700 measurements on the Y axis and 3800 on the X axis. The results obtained graphically are shown in Figure 7.

When analyzing the test parts, it was found that the roughness increased up to 15% in case of analyzing the upper 10mm of the test part or the lower ones, the roughness increased for Sa=4,78 µm in the lowest part to Sa=5,57 µm in the highest.

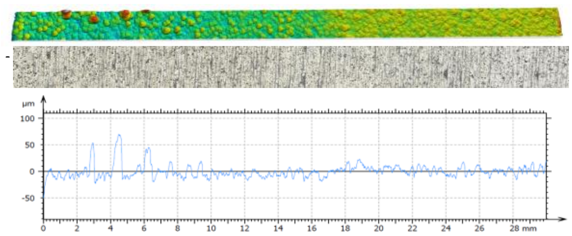

Figure 7: Analysis of the roughness through the test specimens

So that, with these measurements it has been possible to verify that due to the heat accumulation in the upper part of the specimen, the roughness could vary.

•Proximity between the pieces:

To verify the effect that the proximity of the parts can have, the rectangular parts manufactured in the center of the platform have been used, to avoid other parameters that could affect the roughness.

These specimens should show a higher roughness on the faces close to other parts. However, when analyzing the specimens it has been seen that the difference in roughness between the surfaces that were far from the rest of the parts and those close to them did not vary considerably.

After analyzing all the parameters that could affect the roughness it has been seen that not all have the same importance.

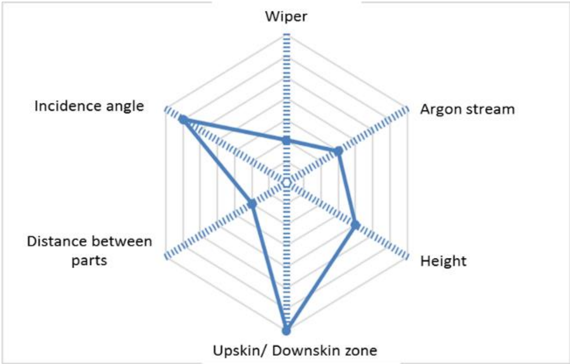

Figure 8: Influence of different parameters.

Figure 8 shows schematically the importance of each of the factors. As could be seen, it has been determined that the factors that most affect the roughness are the area of the geometry, whether it is an upskin face or downskin and the position of the part on the platform.

5. Conclusions

The roughness may be due to different factors, but after this study, it has been demonstrated that the rougher parts are always the downskin surfaces of the platform.

However, the experimental results have shown that the roughness of the parts manufactured by PBF does not only depend on the geometry or manufacturing parameters. It has been verified that it also depends on the position of the on the platform, the pieces situated in the edges always have higher roughness than in the centre.

It has been determined that the factors that most affect the roughness are the geometry of the part and its zone (upskin and downskin areas) and the incidence inclination of the laser.

This angle could vary in the different areas of the platform. The scanner is located in the central part of the building chamber and this position could affect the laser focus and cause a certain incidence angle at the edges of the platform. Due to this incidence angle, a powder of the bed could be molten partially.

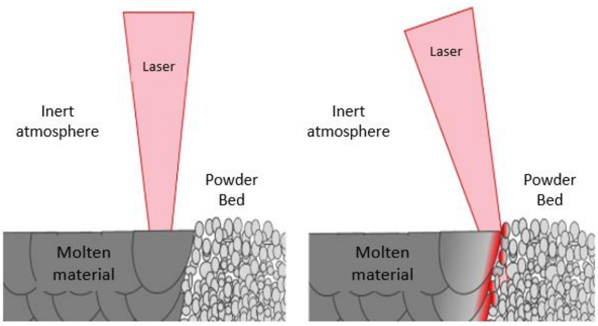

Figure 9: Effect of the incidence angle in PBF parts

In addition, this laser beam not perpendicular to the platform will have a lower energy density than the perpendicular one, causing a higher roughness. For that, it could melt more material than the specified in the CAD file, as shown in Figure 9, in addition because of the lower energy density, these particles were only molten partially increasing the surface roughness.

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