Analytical study of the melt pool distortion in the Laser Powder Bed Fusion Process caused by the angle of incidence of the laser and its effect on the surface finish of the part

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Abstract: One of the factors that most affects surface roughness is the angle of incidence of the laser with respect to the platform, which varies across the platform. However, to make the L-PBF process a competitive technology, several parts must be manufactured on the same platform, using maximum building volume. Nevertheless, due to this angle of incidence, even if identical parameters and geometries are used, the surface finish of the parts varies considerably depending on the positioning of the part on the platform. Throughout this work, the effect that this angle of incidence has on the surface of parts manufactured in the different positions of the platform is presented. For this purpose, first the angle of incidence on the whole platform was determined. Then, based on these results, the distortion of the melt pool was analyzed analytically, with the aim of relating the poor surface finish, seen by different technologies such as infinite focus microscope or SEM, with the distortion of the melt pool generated by the angle of incidence.

Keywords: L-PBF, Surface roughness, Incidence angle, Position dependency, Surface finish, Melt pool.

1. Introduction

Despite the importance that L-PBF (Laser Powder Bed Fusion) technology is acquiring in recent years in different sectors, it still presents certain limitations that must be overcome to make it a useful and competitive technology [1]. For this purpose, the parts manufactured by this technology must show equal or even greater properties to those obtained by traditional technologies, such as machining.

In L-PBF technology, the final part is manufactured directly from metal powder. This powder is distributed on the manufacturing platform by a recoater, obtaining layers of uniform thickness between 20 and 60 µm. Once the layer is generated, the laser melts the area previously specified into the CAD (Computer-aided design) file. Then, the platform goes down a thickness of a layer to manufacture the next layer. The process continues until all the layers are manufactured and the final part is obtained.

One of the main disadvantages of this technology is the high roughness or poor surface finish of the parts [1]. This high roughness, considerably affects the results obtained in the fatigue tests carried out [2], since the surface defects will probably be the starting point of the crack [3]. Furthermore, this
roughness does not only affect these mechanical properties, it is also a possible focus for the proliferation of small microorganisms [4]. These microorganisms tend to accumulate in the small grooves of the surface and are more complicated to eliminate than in a perfectly smooth surface or with roughness values around 1-2 μm such as those presented by surfaces obtained using conventional technologies [5].

Several factors affect the roughness of the parts manufactured by L-PBF process [6]. On one hand, one of the main factors affecting the roughness of the part is its geometry [1] and the angle of inclination of the part surface with respect to the platform [6,7].

On the other hand, the angle of incidence of the laser with respect to the platform is also classified as one of the main causes of this high roughness by some studies [8]. This angle of incidence affects the parts roughness [9] and therefore the parts located in different positions of the platform do not reach the same surface finish. Furthermore, this angle of incidence does not only affect the roughness of the final parts, it also affects their microstructure and thickness of the thin walls [10].

Due to the scanner and optics used in the L-PBF system, depending on the positioning of the part on the platform, the laser beam impacts in the platform with a certain angle of incidence [11] [12]. Therefore this angle causes a distortion in the melt pool in the parts located away from the center, where the laser does not impacts completely perpendicular, thus increasing the roughness. However, this angle of incidence is not a factor that is studied too much in the previous literature.

Nevertheless, it should be mentioned that regardless of the positioning of the part on the platform and its geometry, the roughness also depends on the parameters used [6] and the characteristics of the powder used [13]. And even a small change in these characteristics, such as that which occurs when the powder is reused, can cause a variation in the properties of the final part [14].

Finally, and although these are not factors that have been studied extensively in previous investigations made using L-PBF technology, studies carried out using EBM (electron beam melting) technology shows how the proximity between parts or their height should also be highlighted [4]. Because when manufacturing different parts very close to each other, heat tends to accumulate between them, which facilitates the adhesion of powder particles from the powder bed to the part surface. The effect of the directionality of argon and recoater must also be taken into account [11].

In general, roughness, caused by one of the previously mentioned factors, can be classified into two main types [9,15]. On the one hand, there are the marks of solidification of the melt pool, which may be due to interactions between the material and the laser, the heat transmission or the thickness of the layers. On the other hand, partially attached particles can be found. These particles adhere to the surface due to interactions between the heat irradiated by the laser and the powder bed particles. This type of roughness depends mainly on the parameters used and the characteristics of the powder [16]. Moreover, there are two types of attached particles: The powder particles that belong to the powder bed and have a size according to the particle size distribution (PSD) and spatters that jump out of the powder bed during the melting process and are carried away by the argon stream, these spatters always show a larger size [17]. These two types of roughness can be easily distinguished, thanks to the high quality topographic images that can be obtained [18].

Throughout this study the study carried out by Sendino et al.(2020) [10] has been continued and using the tests and results obtained during this study, the angle of incidence on the whole platform has been determined and its effect on the surface finish of the part has been analyzed and explained. It was decided to continue with this study since after a review of the literature and the results seen, it seems crucial to control this angle of incidence, because only by controlling this angle it is possible to manufacture parts with similar characteristics on the same platform and make the LPBF a competitive process.

2. Methodology

2.1. Determination of the angle of incidence

To determine the angle of incidence on whole platform, the platform designed to verify the existence of the incidence angle in [10] was used. In this platform, different marks were made, radiating the laser
beam directly on the platform without a previous powder layer, in order to be able to analyze the effect of the laser radiation and its shape differences in different positions of the platform.

A Renishaw AM400 machine and the QuantAM v4 software for programming the parameters of the manufacture process were used to carry out this test. Specifically, a power of 200W, an exposure time of 200 $\mu$s and a distance between points of 900 $\mu$s were used. These parameters were optimized with the aim of analyzing each point or mark independently.

The marks were distributed throughout the manufacturing platform as shown in figure 1 (a), these marks were made in a star shapes distributed evenly throughout the platform. This shape was selected to be able to analyze the angle of incidence independently of the direction of the laser or its possible delays. After obtaining the marked platform, the geometry of the different marks was analyzed.

To analyze the geometry, some of the stars were selected, as shown in figure 1(a) and from each of them 15 marks were analyzed. Figure 1(b) and 1(c) shows two examples of the stars analyzed and the detail of two points of these stars, one of them located at the border of the platform (figure 1(b)) and the other at the center (figure 1(c)).

The Alicona MeasureSuit software of the Infinite Focus Microscope measurement system was used to measure these marks, and thanks to this system, the mayor (A) and minor axis (B) of each of the circular or elliptical marks was determined.

Once each of the points had been characterized and their position in the platform was known, the angle of incidence was determined using the procedure summarized in figure 1(d). The marks located at the center of the platform have the two axes of the same length but when the mark moves away from the center the half mayor axis A varies in size, the further away from the center the greater it is, while the half-minor axis B remains constant. It must be taken into account that these axes do not always respect the X and Y axes of the platform, because the half axis A respects the radial direction from the mark to the center of the platform.

![Figure 1.](image)

**Figure 1.** (a) Design of the platform and selection of the stars to be analysed to determine the angle of incidence (b) Star and points located in the centre of the platform (c) Star and points located in the border of the platform (d) Methodology followed to determine the angle of incidence on the platform.
Once A and B of each of the marks were measured the angle of incidence was determined using equation (1) and equation (2)

\[
\cos \alpha = \frac{B}{A} \tag{1}
\]

\[
\theta = 90 - \alpha \tag{2}
\]

where it should be noted that when B is equal to A the mark will be located at the center of the platform and therefore the angle is 0°, and this angle increases when A increases.

2.2. Effect of angle of incidence on the surface of the parts
To analyse the effect of the angle of incidence on the surface of the parts, and based on the angle determined in the previous section, a software was developed in Matlab.

![Figure 2](image)

**Figure 2.** (a) Phenomenon caused by the angle of incidence at different positions on the platform (b) Determination of the translation and rotation of each point in different positions of the platform.

To this end, the procedure summarized in figure 2 was used. The center of the platform (0, 0) was selected as origin, here the beam is completely perpendicular to the platform (\(\alpha = 0^\circ\)) and increases as the point moves away from this center. This new point is positioned at the point (\(X + XP, Y + YP\)) where XP and YP is the translation suffered by each point with respect to the coordinates of the center (X,Y) (figure 2(b)), and taking into account the transformation into polar coordinates this translation can be expressed as equation (3) and equation (4):

\[
XP = R \cdot \cos \rho \tag{3}
\]

\[
YP = R \cdot \sin \rho \tag{4}
\]

where R is the radial distance from the center of the platform to the position and \(\rho\) is the angle that has been rotated on the platform, \(\rho = 0\) is the right side of the X axis and it increases according to the right hand rule.

In addition, the inclination of each of the points has been estimated, the angle of incidence \(\alpha\) is determined according to the experimental data obtained in the previous section, and this angle is always inclined in a radial direction with respect to the center, so the inclination direction vector could be expressed as equation (5):

\[
Rotation \ direction = [\sin \rho \quad -\cos \rho \quad 0] \tag{5}
\]

Finally, in order to check the effect of the angle of incidence on the surface of manufactured parts located at different positions of the platform surface images were taken, using an infinite focus microscope and a Scanning Electron Microscope (SEM).
The parts selected to take surface images were those designed in [10] for the measurement of surface roughness. These parts were positioned on the platform at a radial distance of 0, 40, 75, 105, and 150 mm from the center. And the usual set parameter for the manufacture of Inconel 718 with a layer thickness of 60 µm was used, which is specified in [10].

These images were analyzed in order to differentiate the two main types of roughness: the roughness generated by the heat accumulation, which could cause a greater number of particles adhered to the surface and the roughness generated due to the shape of the melt pool. Thus, thanks to these images it was possible to determine what type of roughness is affected by the angle of incidence.

3. Results and discussion

3.1. Determination of the angle of incidence

To determine the angle of incidence the marks made by the laser on the platform were studied, and it was possible to see how the marks in the center always showed greater circularity, while when moving away from the center these marks lost this circularity and the A semi-axis increases.

![Figure 3. (a) Results obtained with the measurement of the angle of incidence and some of the marks analysed. (b) Diagram representing the increase of the incidence angle.](image)

After characterizing all the analyzed marks and calculating the angle of incidence of the laser in each case, it has been possible to verify how in the center, where the semi-axes of the ellipse are similar A=B, the mark is circular, which indicates that the beam is perpendicular in this part of the platform. Moreover, it was verified that the angle of incidence increases when the distance to the center increases (figure 3). Specifically, the greatest angle of incidence obtained was 31.90° at a radial distance from the center of 150 mm. Even so, it should be taken into account that this part would be outside the working area and this incidence angle was nearly 25° at 120 mm from the center, which is the limit of the working area.

3.2. Effect of angle of incidence on the surface of the parts

Figure 4 shows the same geometry manufactured in the central area of the platform, where the beam is completely perpendicular to the platform (figure 4(a)) and in an area where the beam is distorted due to the angle of incidence (figure 4(b)) (radial distance R=150 mm). In this figure, the CAD geometry of the part is shown in blue and in pink, the theoretical melt pool according to the angle of incidence obtained. As can be seen in figure 4(a), the beam is perpendicular to the platform and melts the material perpendicularly.

Therefore, all the melt pool bells are within the designed geometry and the laser does not melt any part of the powder bed if it is not specified in the CAD file. Whereas in figure 4(b) it can be seen that due to the angle of incidence the melt pool undergoes an evident distortion and therefore goes beyond...
the limit specified in the CAD file. For this reason, the wall obtained does not have a good surface finish and shows irregular marks on the surface.

\[ \text{Figure 4. Matlab study of the melt pool generated based on the experimental study and surface images obtained with the infinite focus microscope: (a) Part manufactured in the central part of the platform (b) Part manufactured on the border of the platform.} \]

In addition, figure 4 shows the surface images obtained with the infinite focus microscope after applying a color map. Figure 4(a) shows a relatively smooth surface, with roughness values of \( Sa = 4.668 \) µm, where the layers of the part can be seen in the Z-direction with some particles partially adhered to the surface due to heat transfer to the powder bed. While in the surface image shown in figure 4(b), which belongs to a part manufactured at a radial distance of 150 mm, it can be seen how the wall does not show a good surface finish, obtaining a value of \( Sa = 28.393 \) µm. Moreover, it can be seen that due to the distortion of the melt pool, many irregularities appear on the surface that do not allow to appreciate so clearly the height of the layers and the particles partially attached to the surface.

\[ \text{Figure 5. Parts surface images at different magnifications obtained by means of the SEM (X 100, X 250, X 1000) (a) Part manufactured in the central part of the platform (b) Part manufactured on the outside area of the platform.} \]
To conclude and to really check the effect of this angle of incidence, the surface images obtained using the SEM are shown in figure 5. The images obtained of the part manufactured on the central part of the platform (figure 5(a)) and the part manufactured at a radial distance of 150 mm from the center (figure 5(b)) are shown.

As can be seen, the surface finish gets worse mainly due to the effect of the solidification of the melt pool, and the increase in the number of particles adhered to the surface due to heat accumulation does not seem so evident.

In figure 5(a) it can be seen that the particles are attached to a smooth and well-finished surface. In addition, the size of these partially attached particles has been estimated with the aim of verifying that their size matches the size of the PSD of the powder, and therefore they are attached particles and not spatters. In contrast, in figure 5(b) some partially adhered particles can still be seen. However, it can be seen that these are not adhered to a well-finished or smooth surface, and the angle of incidence causes a rough surface, even without taking into account the partially adhered particles. Nevertheless, as can be seen on the wall of the part located in the central part of the platform these partially attached particles can be easily observed, while on the wall belonging to the wall located on the border of the platform these particles cannot be easily distinguished.

This phenomenon occurs because; if the beam has a certain angle of incidence, it does not penetrate completely perpendicularly into the powder bed, producing a larger melting area. Therefore, a part of the melt will stand out from the geometry specified in the CAD. However, this beam melts completely the material and its effect is not appreciated as particles partially adhering to the surface.

4. Conclusions

Angle of incidence of the laser increases from the center of the platform to the borders. Circular marks were obtained in the center of the platform, which indicate a total perpendicularity of the beam with respect to the platform, but this angle increases until reaching 32° at the farthest from the center (150 mm).

Furthermore, it has been possible to see how the surface finish of the parts, which can be quantified by roughness evaluation, worsens when the part moves away from the center. The surface analysis carried out shows an increase in roughness due to melt pool formation mechanism and its subsequent solidification, instead of particle sintering due to heat accumulation.

In conclusion, the study could be summarized in the following points:

- The angle of incidence increases to the central part of the platform where it is completely perpendicular to the platform until reaching an angle of 32°.
- The surface finish worsens as the manufactured part moves away from the centre of the platform but this increase in roughness is caused by the distortion of the melt pool and not by particles partially attached to the surface.

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