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Influence of the processing parameters on the dimensional accuracy of In625 lattice structures made by laser powder bed fusion

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Abstract
Lattice parts made in Inconel 625 with laser-powder bed fusion (L-PBF) process have been manufactured with a variation of processing parameters, namely laser power and scanning speed, in order to determine their influence on the dimensional accuracy of the lattices' structure. Four combination sets of laser power and scanning speed have been chosen, and three parts per set were manufactured for repeatability. Then, the lattice structures have been scanned by X-Ray Computed Tomography (XCT), and the dimensions of the struts as well as the volume of the parts were measured using VGStudioMax on the XCT images. While the vertical struts are thinner than the nominal value, the horizontal struts are thicker, and no correlation to the processing parameters was possible due to the roughness of the struts. However, the volume measurements showed an increase with the energy density, i.e. the ratio of the power over the speed, and thus the average thickness of the struts increases accordingly.

Dimensional accuracy, Laser Powder Bed Fusion, Metrology, Metal, X-Ray Computed Tomography, Lattice

1. Introduction

Metal additive manufacturing and especially Laser Powder Bed Fusion (L-PBF) utilization is increasing in the industrial field since the last decade, partly thanks to its ability to produce parts with very complex geometries, such as lattice structures. Lattices are widely investigated for their interesting weight to mechanical properties' ratio and energy absorption in the industry [1], or bone and tissue reconstruction in the medical field [2].

However, if the mechanical properties have been well described in the literature [3], it is less the case for the dimensional accuracy of those parts, which remains difficult to master and control. In addition, lattice structures cannot be machined afterwards to make up for the deviations observed, contrary to fully dense parts. The issue is that the deviations can alter the properties of the part (mechanical properties, weight, porosity…) if the overall dimensions of the struts differ from the designed part.

Nevertheless, some work can still be found in the literature about the dimensional accuracy of lattice structures, with either different processes or materials. For example, Yan et al. [4] showed that the strut size was higher than the designed value for gyroid lattice structure made with a 316L steel alloy. Qiu et al. [5] demonstrated that the deviations in strut dimensions increased with the laser power due to the increase of the melt pool width on AlSi10Mg. About the influence of the nominal dimension, Sufiiarov et al. [6] found that the minimum deviations were observed for strut sizes between 0.35 mm and 0.45 mm, on a range of dimensions that vary from 0.1 mm to 0.9 mm. Finally, regarding geometrical properties, Ameta et al. [7] managed to evaluate flatness of lattice structures' top surface, using the theory of supplemental surfaces.

The point of the research presented here is to determine the influence of the linear energy density (LED), laser power and scanning speed on the dimensional accuracy of lattice structures, by studying the size of the struts and the volume of the whole lattice structure. Laser power and scanning speed's influences on the dimensional accuracy are first order parameters, which is why they have been chosen for the study. The characterization is performed by X-Ray tomography (XCT).

In this article, the experimental method will be presented first, followed by the results and discussion on the measurements.

2. Experimental methodology

2.1. Parts' fabrication

The lattice structures have been manufactured in Inconel 625 with a 3DSystems ProX DMP320 L-PBF machine, equipped with a polymer scraper and an Ytterbium fiber laser and its spot diameter has been measured to be 70 µm. The cell type used for the lattice parts is a simple orthogonal cell, with a strut thickness of 300 µm, and a cell size of 2 mm (Fig 1a).

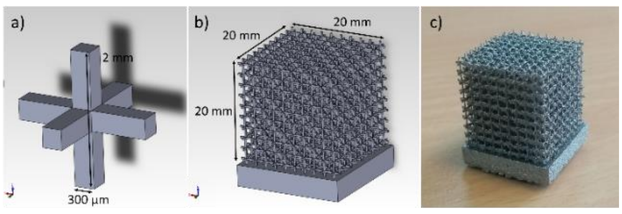

Figure 1. Illustration of a) CAO design of the lattice cell, b) CAO design of the full lattice structure, c) a manufactured lattice part

This cell type has been chosen to make it easier to characterize. The cell is repeated in order to have a lattice structure with a cubic shape of 20 mm per side (**Figure 1** b and c). The design has been made with Solidworks.

Table 1. Set of parameters investigated

Set of parameters	Power (W)	Scanning speed (m/s)	LED (J/m)
1	250	1.85	135
2	250	1	250
3	400	1.6	250
4	350	1	350

The different processing parameters are recorded in the **Table 1** and concern only the filling step. The chosen parameters are ordered by increasing the LED, which is defined by:

$$LED = \frac{P}{v} \text{ in J/m} \qquad (1)$$

where P is the laser power in W and
v the scanning speed in m/s .

This ordering has been chosen to determine the influence of the LED on the dimensional accuracy. The second set of parameters is the one that is recommended by the constructor and the third set has the same LED, but with higher laser power and scanning speed.

Three lattice samples are manufactured per set of processing parameters for repeatability. There is one contour step with a laser power of 180 W, and a scanning speed of 1.9 m/s, which are both kept constant for all of the parameters. The hatching space is 100 µm, and the layer thickness is 60 µm. The scanning strategy consists of back and forth trajectories with a rotation of 66° between each layer. No downskin or upskin is performed, and the contour step occurs before the filling step. Supports are used to remove easily the parts from the build tray.

Regarding the software used, 3DExpert has been used to prepare the fabrication (position, supports, scanning strategy) and DMPVision has been used to set the power and scanning speed parameters, as well as for the launching of the fabrication.

2.2. XCT scanning of the parts and measurement protocol

The parts have been scanned with an X-Ray computed tomography system, METROTOM by ZEISS, with a voltage of 200 kV, a current of 135 µA and a voxel size of 30 µm. Then the calliper tool from the software VGStudioMax is used to perform dimensional measurements of the struts.

Concerning the measurements, two planes are considered: the XY plane, parallel to the building plate, in blue in the Figure 2 1a), and the XZ plane perpendicular to the building, in green in the Figure 2 2a). It is assumed that the XZ and YZ planes are equivalent. In the XY plane, the dimensions of the struts are measured in the x direction, red circles in the Figure 2 1b). In the XZ plane, struts are measured in the Z and X directions, respectively blue and red circles in the Fig 2 2b). The struts in the Z direction refer to the vertical struts while the struts in the X direction refer to the horizontal struts. Also, struts in the X direction are measured on both the XY and XZ planes in order to take into account the asymmetry for the horizontal direction.

There are three measurements per analysed strut with the calliper tool. Moreover, to have values that are relevant of the whole structure, measurements are performed on the corner and on the center of the observed plane, and this for the top, middle and bottom rows of the lattice structure (Figure 2). Thus, in total, twelve horizontal struts and six vertical struts are measured per sample. The volume are determined via VGStudioMax after removing the base of the part, and applied on the whole lattice structure.

Concerning the analysis of the results, the values displayed are relative errors in percent: $\frac{Measured\ value - Nominal\ value}{Nominal\ value} \times 100$. The error bars on the graphs represent the standard deviations among all of the measurements, struts or volume, for the three samples per set of parameters.

3. Results

3.1. Struts' dimensions

The results of the horizontal and vertical struts dimensions are respectively recorded in the Figure 3 and the Figure 4. The first remark that can be done is the fact that the vertical struts' are thinner than the nominal value, while the horizontal ones are thicker, regardless of the processing parameters used.

However, the size of the error bars make it impossible to compare the results, even though a trend is visible. Firstly, it appears that the errors on the vertical strut dimensions are around 20 % lower than the nominal value, and that the recommended processing parameters do not display the lowest deviations. The same can be said for the horizontal struts, which

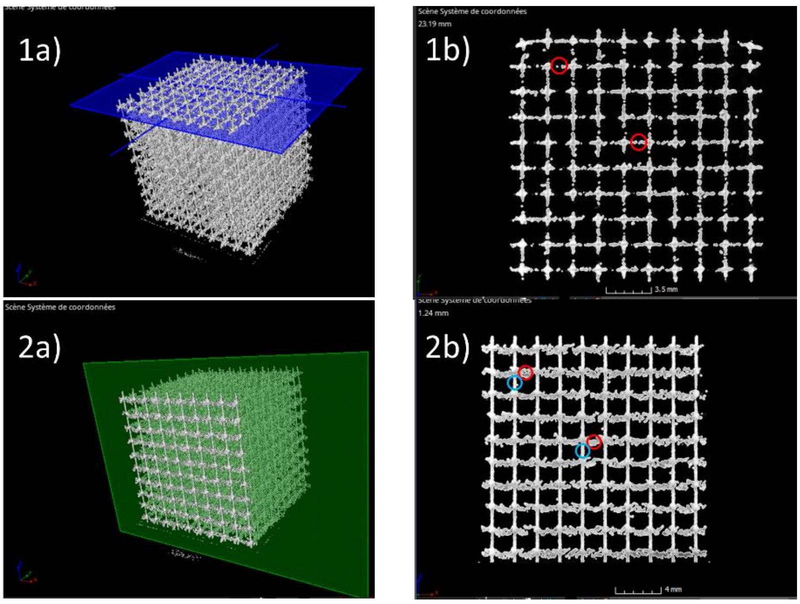

Figure 2. Tomography images of a lattice structure: 1a) 3D visualisation of the lattice top row in the XY plane; 1b) measured struts in the XY plane for the top row; 2a) 3D visualisation of the lattice top row in the xz plane; 2b) measured struts in the XZ plane for the top row

have relative errors going from 7 to 69 %, with higher variation following the parameters used and higher disparity of the results.

It seems that the size of the strut increases with the LED, which results in decreasing deviations for the vertical struts, and increasing for the horizontal struts. However, there seems to be differences for the dimensions of lattices' struts between the parts that have the same LED. The parameter sets with higher laser power seem to grant bigger dimensions for both directions, even if the difference is thin for the vertical struts.

3.2. Volume

The relative errors on the volume of the overall lattice structure are displayed in the Figure 5. It appears that the LED has a great influence on the volume of the lattice structure. The lower LED has almost 25 % less volume than in theory, while the higher LED is 12 % bigger.

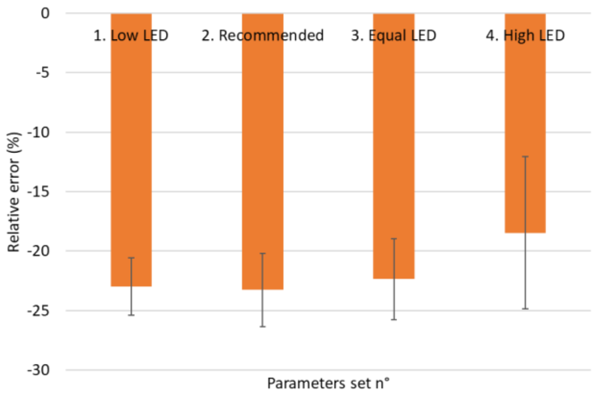

Figure 3. Relative errors for lattices' vertical strut dimensions with different processing parameters

The recommended parameters allow -5 % of error on the volume, and the third set of parameter, which has the same LED, has a dimensional error under 3 %. Thus, it appears that there are differences for two processing parameters with the same energy density but with different laser power and scanning speed. Indeed, the second set is under the theoretical value, and the third one is above.

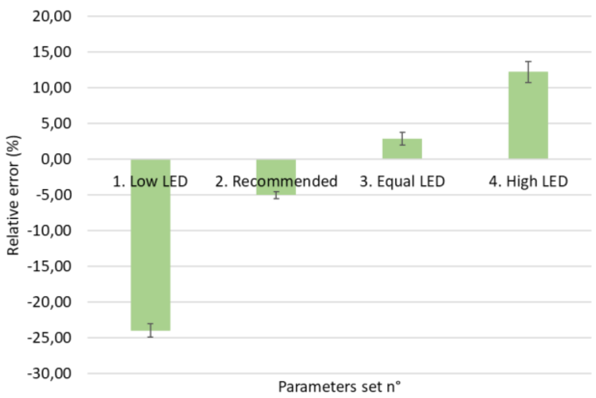

Figure 5. Relative errors for the lattice structures' volumes

4. Discussion

The results on the dimensions of the lattices' struts are difficult to analyse due to the important error bars' values. It is important to note that the measured values for the struts dimensions were consistent from one lattice to another for a given set of processing parameters. This means that the error bars come from the disparity among the struts from each lattice structure.

Concerning the vertical struts, it seems that the processing parameters have little influence on the dimensional accuracy. On the other hand, the values of the horizontal struts' dimensions show clear variations for the different parameters, but the error bars are too important to conclude anything quantitative.

These error bars can be explained by the asymmetry on the horizontal struts. As seen in the Figure 2 1a) and 2a), there is a clear difference between the size of the struts in the x direction as seen from above (XY plane) and from the side (XZ plane). Moreover, it is difficult to measure the horizontal struts' dimensions in the XZ plane, due to the bad surface roughness (Figure 6). This non-smooth surface roughness on the horizontal struts is due to their orientation.

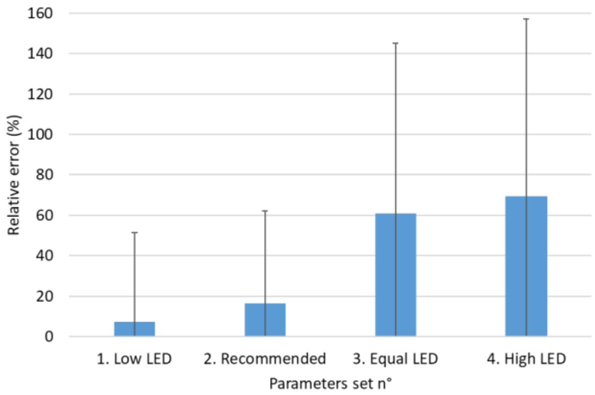

Figure 4. Relative errors for lattices' horizontal strut dimensions with different processing parameters

The overhanging horizontal struts, that would in theory need supports, overheat during the melting due to the bad thermal conduction provided by the underlying powder, leading to an agglomeration of neighbouring powder. Moreover, the powder is not dense enough to support the recoil pressure resulting from the laser-matter interaction during the scanning. This causes a collapse of the melt pool during the scanning, explaining the severe surface roughness observed [8]. This phenomenon also explains the differences of dimensional accuracy between the horizontal and vertical struts. What can also be said is that the measurements on the horizontal struts are not representative on a dimensional perspective, and this could require another method of measurement to characterize the dimensions in order to take into account the surface roughness for example.

When looking at the volume measurements in Figure 5, it is clear that an increase in the LED induces an increase in the volume. If the strut measurements did not enable to conclude about the influence of the LED on the dimensional accuracy due to the error bars, they managed to provide better understanding. The increase in volume attests of the increase in dimensions of the struts. The origin of this increase with the LED certainly come from the increase of the melt pool width which also increases with the LED [9]. From the graph, it is also possible to observe a difference of volume between the two parameters with equal LED. This highlights the fact that one parameter has more influence over the dimensional errors than the other. It would be interesting for further research purpose to perform a design of experiment to determine this.

By observing the volume measurements of the processing parameters n°2 and 3 with low relative errors < 5 %, one could conclude that these parameters offer good dimensional accuracy. Yet, the volume measurements should not be considered without the measurement of the dimensions of the struts, as neither the vertical nor the horizontal struts display such accuracy, due to the reasons mentioned above. In addition, since the vertical struts are thinner than in theory, and the horizontal struts thicker, a compensation effect at the scale of the volume distorts the results. Finally, the internal porosity has not been considered and surely can affect the results.

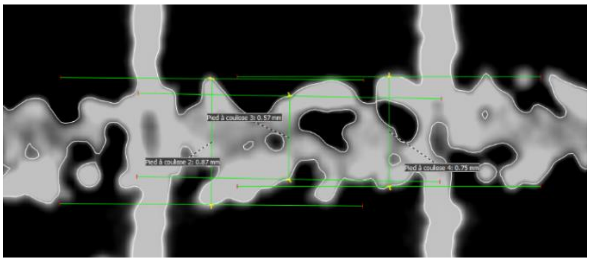

Figure 6. Example of measurement of the dimension of a horizontal strut with bad surface texture

5. Conclusion

In this study, four processing parameters with different laser powers and scanning speeds have been used to determine their influence on the dimensional accuracy of lattice structures, made by L-PBF with Inconel 625 as a material. The measurements obtained by XCT allowed the determination of the dimensions of the struts and of the volume of the lattice structures.

These results show several interesting facts:

Firstly, the quantitative analysis of the dimensions of horizontal struts is not possible due to the important roughness, which disturb the dimensions' measurements. The origin of the roughness comes from the build orientation of the whole lattice causing the struts to overheating due to the bad thermal conduction, and the melt pool to collapse due to the recoil pressure, not supported by the powder.

All of the processing parameters caused the vertical struts to be about 20 % thinner than the design, while the horizontal struts display asymmetrical and thicker struts dimensions.

Even if the evaluation of the dimensions of the struts did not enable the comparison, the volume measurement indirectly showed an increase of the struts' size with the linear energy density (LED). The increase in the struts dimensions is correlated with the melt pool width, which also increases with the LED. Although, there is a difference in the strut's size for a similar LED with higher laser power and scanning speed.

This difference in dimensional accuracy for similar LED should be the object of future work, by the mean of a design of experiment, allowing the understanding of potential interactions between the laser power and scanning speed, or the eventual prevalence of one parameter over the other on the dimensional errors.

Further investigation will focus on the establishment of a more representative measurement method, which could take consideration of the roughness impact. This could be done using volume measurement for the struts for example.

Finally, it will be interesting to study the influence of other processing parameters such as the orientation, the layer thickness or the scanning strategy on the dimensional accuracy of lattice structures.

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