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Efficient process parameter optimisation procedure in Laser Powder Bed Fusion

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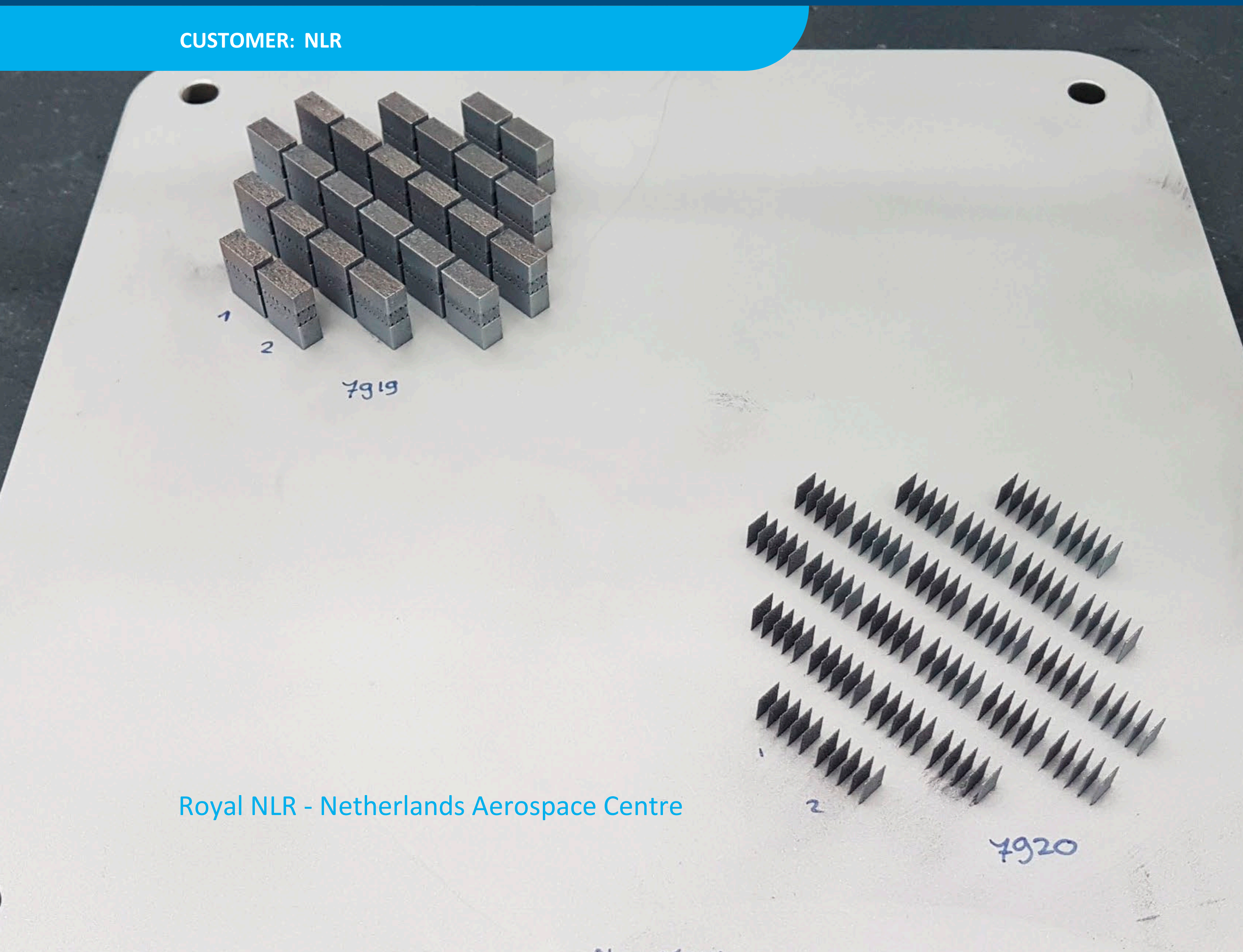

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EXECUTIVE SUMMARY

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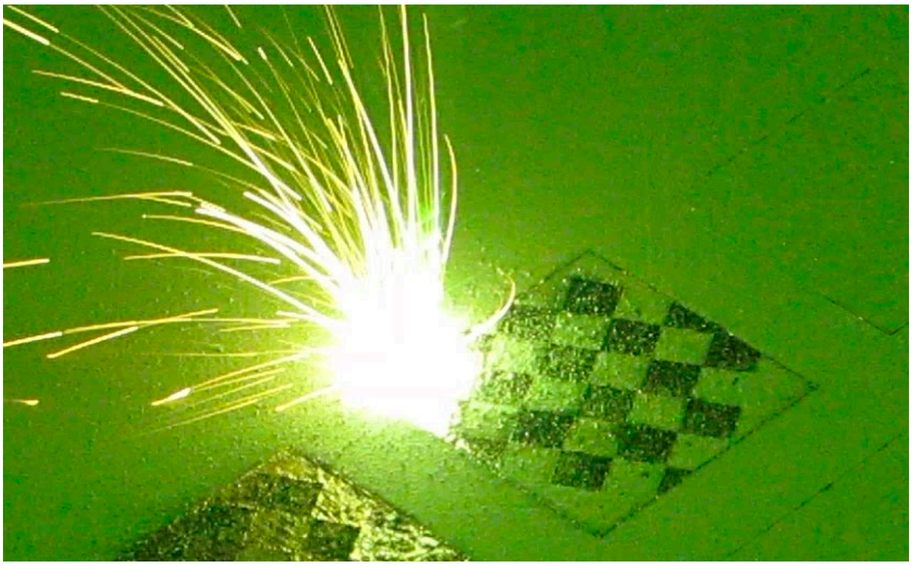

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DESCRIPTOR(S)
Additive Manufacturing
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Process parameters
AlSi10Mg

Problem area

Process parameter optimization is a time-consuming step in the introduction of new alloys for Laser Powder Bed Fusion (L-PBF) technology. An efficient way of performing the process parameter optimization needs to be developed and this was the objective of this work.

Description of work

In this work, three optimisation routes have been investigated: contour, hatch and interface parameter optimisation. The first is carried out by printing several thin walls with varying laser power and scan speed, and then evaluating the roughness, porosity and wall thickness. For the hatch, blocks with varying hatch distance within a layer are printed and evaluated based on the porosity. Lastly, in order to optimise the interface, blocks with a tilted hatch pattern are printed in order to created a varying interface distance and the porosity is measured.

Results and conclusions

The following conclusions are drawn from this work:

- The proposed method reduces drastically the number of samples that needs to be printed and characterised, and hence the time.
- This methodology allows an efficient optimisation for the contour, hatch and interface parameters.
- The contours can be optimised by building thin walls and evaluating the porosity, roughness and thickness measured from cross-sections.
- The optimum hatch parameters are selected from cross-sections of blocks built with varying hatch spacing.
- The offset between the hatch and the contour is a challenging parameter. With the proposed method of rotating the hatch, a varying offset is created, which reduces significantly the number of samples to be printed.
- Although not investigated in this work, the contour-hatch method could allow the evaluation of different laser modes, since they influence the start/stop of the tracks.
- Up-skin and down-skin parameters are also important for the final part quality. An efficient optimising methodology should still be investigated for these parameters.

Applicability

Almost all Additive Manufacturing (AM) processes are based on digitally creating a path that is later used for creating the 2D component. In addition, the parameters used for scanning this pre-defined path need to be optimised for every new material and every machine. Therefore, the proposed methodology can be applied in many AM technologies in order to drastically reduce the process parameter optimisation time.

GENERAL NOTE
This report is based on a presentation to be held at European Powder Metallurgy Congress & Exhibition (EuroPM2021), virtual, 18-22 October 2021.

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Summary

Important properties such as porosity, microstructure and surface roughness of metal parts produced by Laser Powder Bed Fusion (L-PBF) are largely determined by process parameters including laser power, scan speed, distance between scan lines and layer thickness. L-PBF parameter optimisation methods are now generally based on the production of an array of samples where the laser power and scan speed are varied. A large number of samples needs to be analysed for selecting a suitable combination of parameters. This makes parameter optimisation for L-PBF complicated and time consuming. In this work, an efficient procedure is proposed for optimising the key parameters of the laser scan pattern. Build files for samples are generated, which cover a predefined parameter range. Scripts are used for automated evaluation of optical microscope images of cross-sections. This procedure allows variation of parameters within a sample and thereby strongly reduces the required number of samples and time for parameter optimisation.

Contents

Abbreviations

ACRONYM	DESCRIPTION
AM	Additive Manufacturing
L-PBF	Laser Powder Bed Fusion
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1 Introduction

Laser Based Powder Bed Fusion (L-PBF) is an Additive Manufacturing (AM) process that offers great opportunities such as weight reduction and improved performance for metallic components [1]. The L-PBF process applies one or multiple laser sources to selectively melt thin metal powder layers. The capability to produce complex thin-walled internal structures makes the process extremely suitable to produce components for thermal control modules such as high-performance heat exchangers. Thermal constraints, weight and dimensions of these parts can be drastically reduced by using L-PBF. Leak tightness is essential for heat exchangers which requires a homogeneous material without defects.

Important L-PBF material properties like porosity, microstructure and surface roughness are largely determined by the applied layer thickness, laser power, scan velocity and distance between laser scan vectors. Especially the combination of laser power, scan speed and distance between scan lines influences the process stability and the chance of formation of defects [2]. A right combination of process parameters must be applied to enable the production of homogeneous parts with high quality. An infinite number of parameter combinations is possible, which makes it a difficult task to select an optimum. This is why there is a great need for a fast, efficient and straightforward method to find an optimal L-PBF process window for a specific alloy.

Numerous studies have investigated L-PBF parameter optimisation approaches. These studies are generally based on the definition of a test matrix that covers an array of samples with different combinations of parameters [3]–[5]. These methods require the production and analysis of a large number of samples, which makes it a time consuming and expensive exercise.

The present paper describes the work done on the development of a methodology for selecting L-PBF parameters. This approach is based on the analysis of a large number of parameter combinations with a minimum number of samples. Parameters are optimised for processing AlSi10Mg alloy, which is selected because of its suitability for application in thermal control applications. Selected parameters are required for the production of helium leak-tight heat exchangers out of AlSi10Mg within the IMPACTA European project. Therefore, in this work, the methodology for optimising the contour, hatch (also named as core or bulk) and interface parameters was investigated. For optimising the contour, thin walls with varying laser power and scan speed were built. For the hatch area, blocks with varying hatch distance along the sample length were built. Lastly, for selecting the optimum interface settings, the hatch area was rotated relative to the sample contour in order to induce a variable offset between the contours and the hatch. The selection of the parameters was carried out based on the analysis of sample cross-sections. The selection methodology is described for each optimised setting.

2 Overview of study

In this work, an AlSi10Mg powder supplied by Carpenter Additive was used as feedstock. The powder composition is shown in Table 1. The powder particles were not fully spherical with particles between 20 and 63 µm and an average particle size of 43.8 µm, measured by laser size diffraction according to ASTM B822. The samples were produced on an SLM® 280[HL] machine. In this work, three types of geometries were generated: thin walls, blocks with varying hatch distance and blocks with rotated hatch. The latter two are shown in Figure 1 (a) and (b). A scan pattern is created for a single layer which is repeated *x* number of times in order to create 3D components.

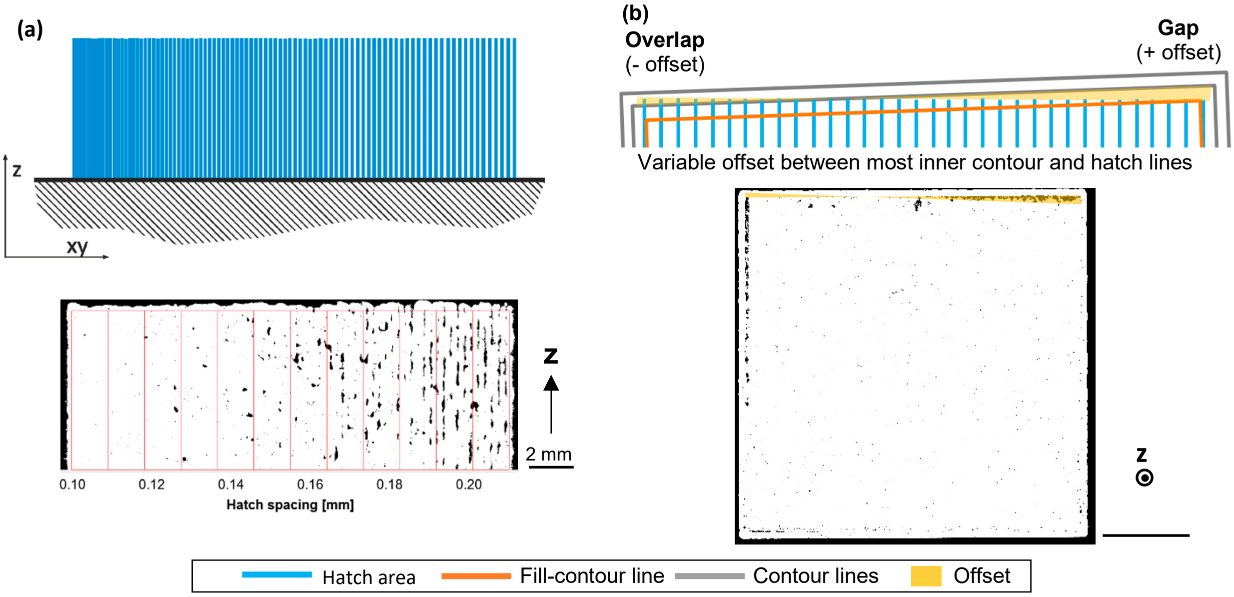

Figure 1 (a) Example of a block with variable hatch distance across the length, where the 12 analysed fields are depicted with red colour rectangles. (b) Schematic representation of the blocks built with a rotated hatch for creating a variable offset along the edge.

Thin wall samples were built by stacking single vector scans in multiple layers. Each wall was built with specific laser power and scan speed combination. The laser power (P) was varied from 70 to 300 W, and the scan speed (v) from 300 to 667 mm/s, building a total of 120 single track walls. Variable hatch block samples (10x20x7 mm) were made in which the applied hatch line distance (track distance/space) is increased in small steps from 0.1 to 0.21 mm. Each block was built with specific laser power and scan speed combination. 24 blocks were printed with a P of 350 W or 380 W, and a v between 875 and 1900 mm/s. An example of the variable hatch spacing within the block is shown in Figure 1(a), where on the left side a hatch distance of 0.1 mm is applied and it increases up to 0.21 mm on the right side. Lastly, two blocks (20x20x7 mm) with a rotation of the hatch area were built, using the selected hatch and contour parameters from the thin walls and blocks. This rotation is made in order to create a variable offset between -0.1 and 0.2 mm between the contour and the hatch area (core), as shown in Figure 1(b). For simplicity, sometimes the linear energy density (E_L) term is used for determining a P and v combination. It is calculated as follows: $E_L = P \cdot v$ [J/mm].

Table 1 Composition of AlSi10Mg powder in weight percent.

Al	Si	Mg	Fe	O	Ni	Zn	Ti	Pb	Mn	Cu	Other
Bal.	10.10	0.36	0.22	0.06	<0.01	<0.1	<0.01	<0.01	<0.01	<0.05	<0.05

After less than two hours production, the thin walls and blocks were removed from the baseplate and cross-sections were made for microscopy analysis. The samples were ground and polished, using a diamond-based polishing solution. A Zeiss Axioplan 2 microscope was used for optical imaging.

The quality of the samples was evaluated by analysing the optical microscopy images of the cross-sections using a MATLAB script. For the thin walls, the porosity, thickness and roughness were evaluated. The blocks with variable hatch and rotated hatch were analysed based only on the porosity. For that, the region to analyse was sub-divided into 12 equally shaped rectangular fields (Figure 1(a)). This way, the porosity could be analysed along the cross-section as a function of the varied parameters. The porosity was calculated by counting the black pixels divided by the total number of pixels for each field.

3 Results and discussion

In this work, the contour, hatch and contour-hatch interface parameters were investigated. First, thin walls were built in order to optimise the contour parameters. Second, blocks were printed with varying hatch spacing in order to select the hatch parameters. Last, blocks were built with a rotated hatch for selecting the correct offset.

3.1 Optimisation of contour parameters

For selecting the contour parameters, 120 thin walls were built with varying laser power and scan speed settings. The cross-sections of the walls were analysed based on the thickness, roughness and porosity, as shown in Figure 2. The latter two are the most important for the selection. From the graphs, it is observed that a low roughness is obtained at high *v* and E_v, and low porosity for low E_v. Therefore, medium E_v and high *v* should be selected for a compromise between low porosity and low roughness. This selection is highlighted in Figure 2(b-d): 667 mm/s, 190 W and 0.28 J/mm. After selection, the thickness was considered for setting the beam compensation and the distance between neighbouring contours. The former is taken as half of the track width and for the latter, 30% overlap is recommended. In this case, the wall thickness is 0.296 mm, hence the beam compensation is 0.15 mm and the distance between contours 0.21 mm.

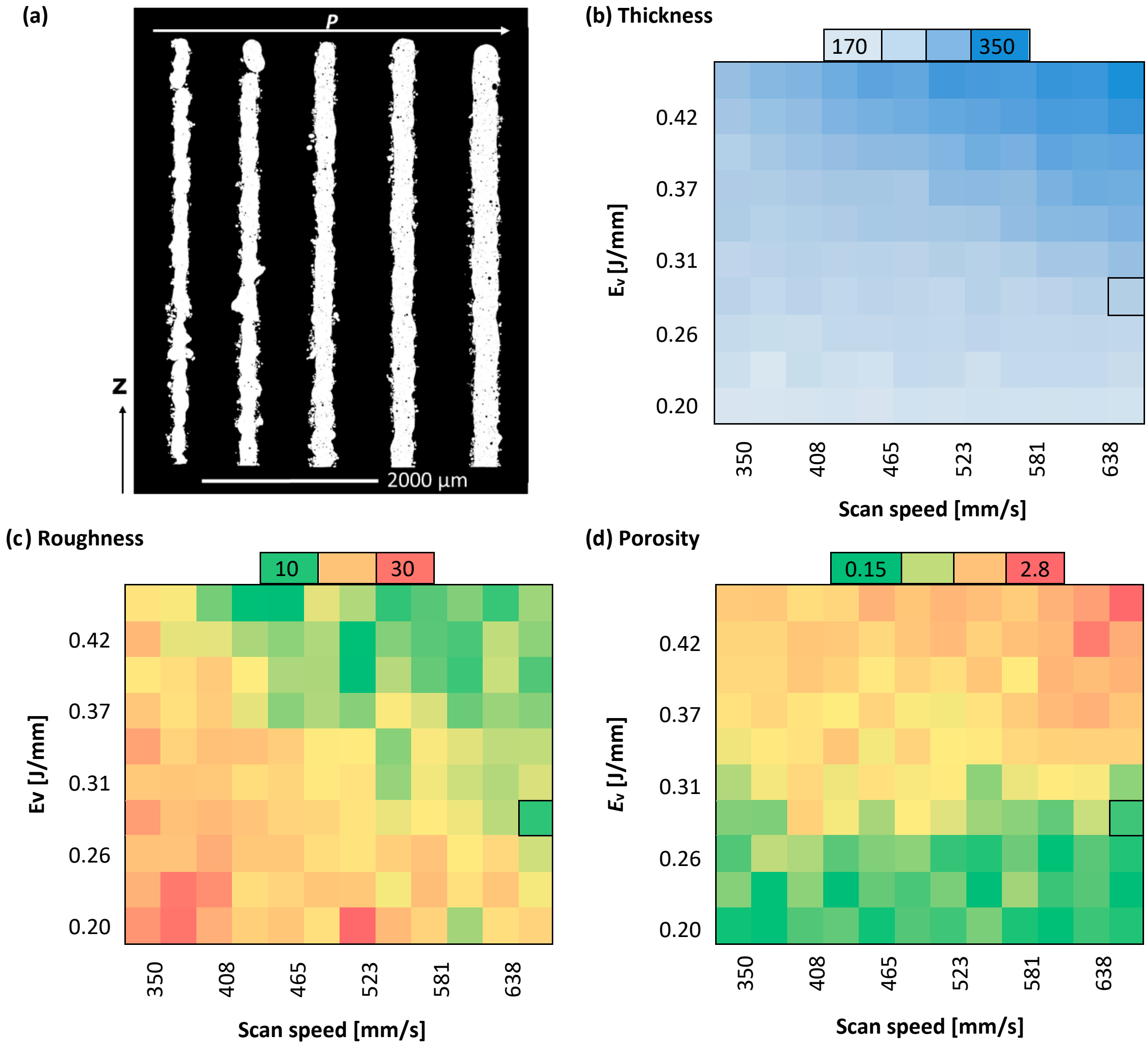

Figure 2 Evaluation of the thin walls based on the (a) cross-sections. In (a), several walls are shown built with 494 mm/s and increasing laser power from left to right. (b) Thickness, (c) porosity and (d) roughness of the walls as a function of the scan speed and linear energy density (E_v).

3.2 Optimisation of hatch parameters

After selecting the contour parameters based on the thin walls, the parameters for the hatch or core are selected. Blocks with varying hatch distance are built, each block with a specific laser power and scan speed combination. In the case of aluminium, it was observed from previous internal studies that high laser power is required for building parts with low porosity. Therefore, only two laser powers were selected in this work; 350 and 380 W. When analysing other materials or novel materials, a wider range of laser powers is selected. Table 2 gives an overview of the analysis of the variable hatch blocks. From each block, the porosity in the 12 fields is determined. The minimum value of these porosities is shown in column 5. The field number in which this minimum porosity is measured is shown in column 6. In addition, the average porosity over a larger area of four fields is evaluated in column 7 in order to rule out the effect of clustered porosities. The latter represents how stable the parameters are over a larger area. Lastly, the average of the values in column 7 is calculated for each laser power, shown in column 8.

Table 2 Overview of the analysis of the blocks with variable hatch. The column number is shown in between brackets.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
						Average porosity [%]	
Sample number	*P* [W]	*P/v* [J/mm]	*v* [mm/s]	Minimum porosity [%]	Min. Porosity per field	min. in 1/3 of the block	of rolling average 4 fields with same P
1	350	0.200	1750	0.41	1	1.09	0.57
2	350	0.218	1606	0.11	1	0.46	
3	350	0.236	1483	0.27	5	0.39	
4	350	0.254	1378	0.16	4	0.27	
5	350	0.273	1282	0.05	1	0.07	
6	350	0.291	1203	0.05	4	0.12	
7	350	0.309	1133	0.05	1	0.14	
8	350	0.327	1070	0.21	6	0.31	
9	350	0.345	1015	0.27	10	0.36	
10	350	0.363	964	0.15	5	0.72	
11	350	0.382	916	0.75	2	1.09	
12	350	0.400	875	1.36	7	1.81	
13	380	0.200	1900	0.40	1	1.58	0.48
14	380	0.218	1743	0.08	1	0.37	
15	380	0.236	1610	0.07	1	0.20	
16	380	0.254	1496	0.09	3	0.14	
17	**380**	**0.273**	**1392**	0.04	1	0.06	
18	380	0.291	1306	0.10	4	0.13	
19	380	0.309	1230	0.09	4	0.14	
20	380	0.327	1162	0.06	2	0.24	
21	380	0.345	1101	0.17	6	0.28	
22	380	0.363	1047	0.20	7	0.37	
23	380	0.382	995	0.50	10	0.61	
24	380	0.400	950	1.41	4	1.62	

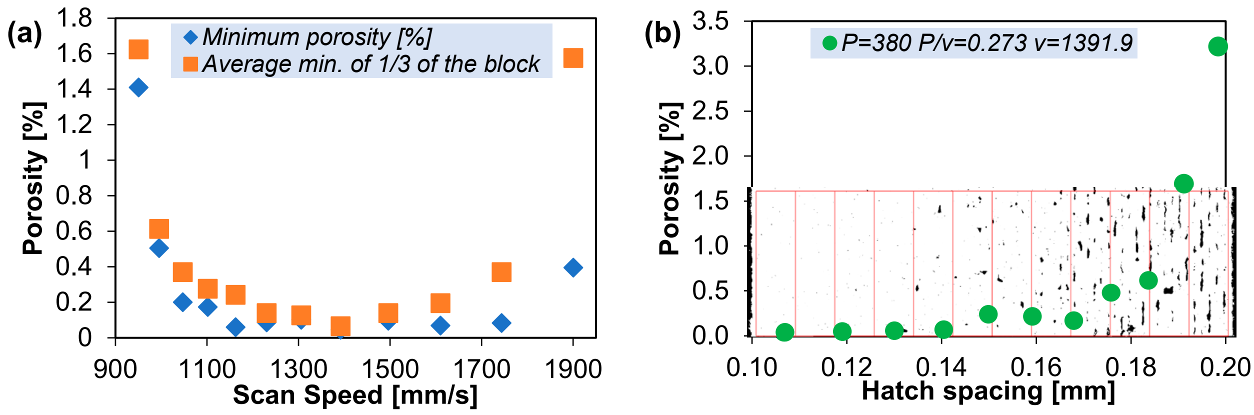

Figure 3 (a) Minimum porosity in one field and in four fields as function of the scan speed, for samples built with 380 W. (b) Porosity percentage of the chosen block for the hatch spacing (380 W and 1392 mm/s).

From Table 2, it can be observed that using a laser power of 380 W results in lower porosity. In addition, by looking at the rolling average (column 7), a low porosity is found in a wider scan speed range. After selecting the laser power, the scan speed is selected. For this, columns 5 and 7 are considered and are shown in Figure 3(a). It can be concluded that the sample built with 1392 mm/s shows the lowest porosity values. After selecting the P and v combination, the chosen block is analysed by looking at the porosity level for the hatch spacing (Figure 3(b)). From the graph, it can be observed that below 0.14 mm hatch spacing, low porosity values are obtained, below 0.09%. A hatch distance of 0.11 mm results in 0.04% porosity.

3.3 Optimisation contour-hatch overlap

After selecting the contour and the hatch parameters, the interface between the two needs to be optimised. Porosity in this region must be minimised when the parts are subjected to fatigue loading since it is known that surface and sub-surface defects are detrimental [6], [7]. Therefore, in this work, the hatch area is rotated in order to create a variable offset between the hatch and the contour as shown in Figure 1(b). On top of that, the effect of using a fill-contour, an extra contour scanned between the contour and the hatch, was evaluated.
The measured porosity in the hatch-contour region as a function of the hatch-contour offset is shown in Figure 4.
In Figure 4(a) it is shown that the fill-contour strongly reduces the porosity between the hatch and contours. When scanning without fill-contour, the porosity increases when increasing the offset to higher positive values. This is shown in Figure 4(b), where more irregular-shaped pores are present on the right-hand side of the cross-section. It can be observed that above 0.00 mm, big lack-of-fusion pores are present. In order to select the right offset value, a negative offset should be applied. In this case, an offset of -0.03 mm was selected. On top of that, it is recommended to use a fill-contour to ensure good overlap. It should be noted that these blocks were built without skywriting methods, which are known to decrease the key-hole pores at the start of the tracks [8]. Therefore, it is recommended to also repeat this methodology on blocks built using skywriting mode.

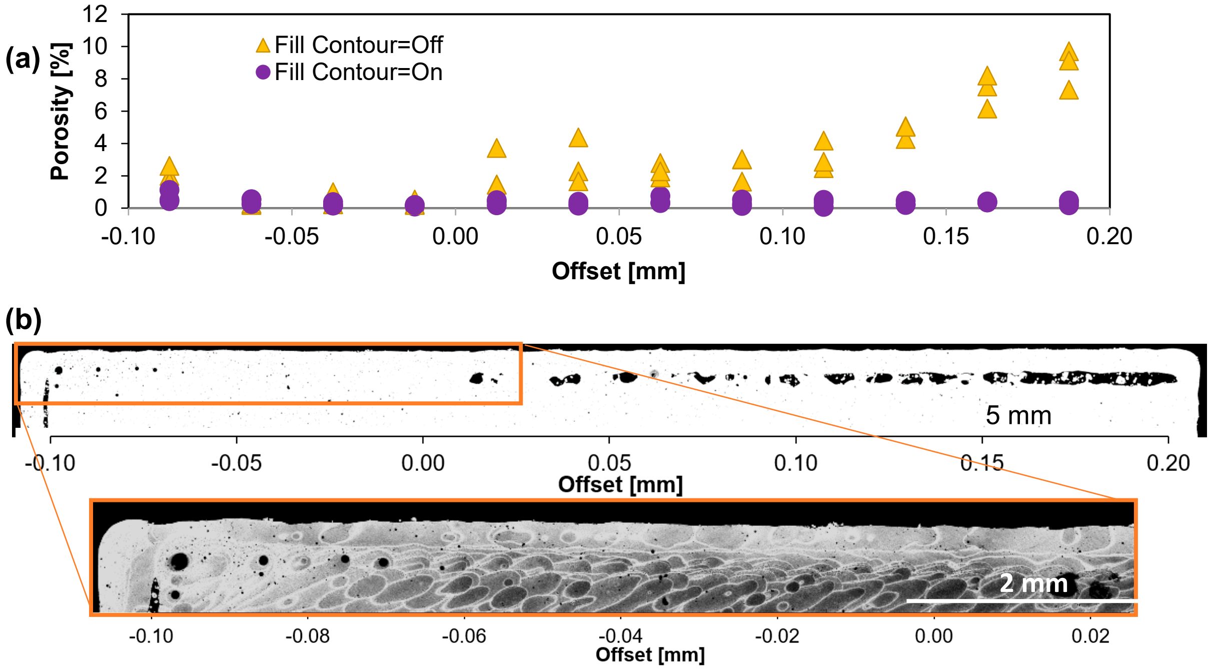

Figure 4 Evaluation of the contour hatch interface with a variable offset along the length. (a) Porosity percentage as a function of the offset for the blocks built without fill-contour and with fill-contour. (b) Block without fill-contour showing a good overlap for offsets <0.00 mm.

This methodology enables efficient optimisation of the key L-PBF process parameters by building fewer blocks than with established methods. As mentioned before, with the rotated hatch the effect of different dynamic modes could be also investigated together with the offset and the influence of fill-contour. The proposed method requires the possibility to generate custom laser scan profiles with a variation of parameters. This option is not available as standard for all L-PBF machines. More freedom and flexibility in the generation of build files with a variation of parameters would greatly stimulate the further development of parameter optimisation methods for L-PBF. Besides the analysed parameters, efficient optimisation of other parameters such as the up-skin and down-skin (also named as up-facing or down-facing) should be further investigated.

4 Conclusions

The proposed methodology allows an efficient optimisation method for contour, hatch and interface parameters. The contours can be optimised by building thin walls with varying laser power and scan speed. For parameter selection, the porosity, as well as the roughness and wall thickness are considered. The hatch parameters were selected based on blocks built with a variable hatch spacing. This method reduces drastically the number of samples that need to be built for selecting the optimum hatch parameters. Lastly, a rotated hatch allows optimising the offset between the contour and the hatch in just one block. This method also allows the evaluation of the use of fill-contours and different laser dynamic modes.

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