Joint Special Interest Group meeting between euspen and ASPE
Advancing Precision in Additive Manufacturing
Inspire AG, St. Gallen, Switzerland 2021
www.euspen.eu

A two step modelling approach to limit the exploitable AM parameter space and optimized parameter selection for finest lattice structures using LPBF

H. Korn[1], P. Koch[2], S. Holtzhausen[2], J. Thielsch[1], A. Seidler[2], B. Müller[1], W.-G. Drossel[1]

[1]*Fraunhofer Institute for Machine Tools and Forming Technology IWU, Germany*
[2]*Technische Universität Dresden, Institute of Machine Elements and Machine Design, Germany*

hannes.korn@iwu.fraunhofer.de

Abstract
Lattice structures manufactured by Laser Powder Bed Fusion (LPBF) show a high potential for a wide range of applications. But the lack of experience in the reliability regarding defects and precision currently impedes their use. Technological limits are the complex shape of the exploitable Additive Manufacturing (AM) parameter space, the dependency of quality criterions on multiple input parameters and the question which precision can reliably be achieved for lattice structures within a certain optimized parameter window. To handle the first two issues, a model based, two step approach is developed and evaluated on different LPBF machines and with different metal alloys. The achievable precision and repeatability of the manufacturing process under constant conditions is analysed by determining the geometrical precision of about 600 strut-like specimens out of titanium alloy Ti6Al4V. In particular, the manufactured strut thickness can be mapped very well by two process parameters with the model-based approach for all the materials and machines analysed. A generalisable system emerges in terms of correlation between lattice strut diameters and LPBF build parameters. The geometric scatter on the specimens appears to be constant for the case investigated and hardly differs between individual build jobs.

LPBF, Accuracy, Precision, Predictive Modelling, Lattice Structures, Scan Strategies

1. Introduction

Lattice structures manufactured by Laser Powder Bed Fusion (LPBF) show a high potential in numerous applications. However, their use is currently limited, as their mechanical behaviour is difficult to predict or simulate. The finer the manufactured structures are, the more sensitively the resulting diameters of lattice struts depend on the process parameters used. Therefore, defects and scatter introduced by the manufacturing process have a stronger effect on the struts [1, 2]. Previous work predominantly uses the “contour-hatch” scan strategy. The strut thickness of lattice structures is adjusted by drawing the contour line closer around the strut axis. Finer lattice structures can be achieved using point exposure as scan strategy [3]. In this work, a different approach is taken based on point exposure: The precision is achieved by an adapted scan strategy of short scan vectors, which ensures a more homogeneous energy input [2, 4 - 6]. The accuracy of the strut thickness is achieved here by parameterising the LPBF process using a regression model approach. Influences of the manufacturing parameters on the geometry of the lattice structures can thus be compensated for in a targeted manner. There is previous scientific work dealing with modelling using regression models in the context of Additive Manufacturing (AM) [7, - 12]. For example, [12] has used it to investigate the interrelation of process parameters. However, this methodology has not been established in AM yet.

In this work, the usable parameter space is narrowed down by means of regression models on the basis of a few manufactured lattice specimens. As a second step, the strut diameters of these lattice structures are measured and a second regression model is developed to predict the resulting strut diameter in dependence of the laser power and scan speed. Additionally the achievable precision and repeatability of the LPBF manufacturing process under constant conditions is analysed by determining the geometrical precision of about 600 strut like features on bridge shaped specimens out of titanium alloy Ti6Al4V.

2. Methodology and Experimental Setup

Altogether manufacturing experiments in five different build jobs have been carried out (see Table 1). In order to narrow down the exploitable parameter space and to determine the influence of the process parameters on the strut thickness of lattice structures using different LPBF machines and materials, a total of three build jobs have been produced by using the procedure described in section 2.1. Two further build jobs with bridge-like specimens have been produced in order to determine the achievable precision and repeatability under constant process conditions. These test series are described in section 2.2.

Table 1 overview of build jobs manufactured and analysed in this work.

build job	machine	material	aim
LT_AlSi10Mg	DMG Mori Lasertec 12	AlSi10Mg	strut diameter
M2_316L	Concept Laser M2	316L	strut diameter
TP_316L	Trumpf TruPrint 1000	316L	strut diameter
M2_B1	Concept Laser M2	Ti6Al4V	precision
M2_B2	Concept Laser M2	Ti6Al4V	precision

2.1. Determination of the influence of the process parameters

In order to investigate the influence of the process parameters on the quality and strut diameter of lattice structures, production experiments have been carried out on three different LPBF systems (see Table 1: LT_AlSi10Mg, M2_316L, TP_316L). Here, two different materials have been used. Twenty-seven individual specimens have been produced per build job. Each of these specimens consists of a solid cuboid, a thin walled structure and a lattice structure (see Figure 1).

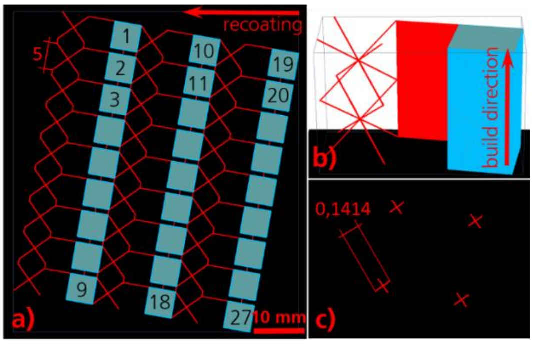

Figure 1. Specimens to determine the influence of process parameters. a) Arrangement of specimens within the build job. b) Geometry of the specimens used. c) In each layer, two crossed scan vectors form each cross-section of a strut.

The unit cells of the lattice structures are bcc cells, the struts are inclined by approx. 35° with reference to the build plate. The lattice structures are not represented by a contour-hatch scan pattern in the production data but by two short crossed scan vectors with a length of 0.1414 mm each. These are arranged around the centre of the strut axis (cp. [2, 4]).

The production data are created using a software tool developed by TU Dresden and Fraunhofer IWU. This ensures that the scan vectors used by the various machines to produce the specimens have been identical for all test series and machines.

The layer thickness has been 25 µm for all build jobs. Line energy, scanning speed and focus diameter have been varied with identical settings and within a wide range for the LT_AlSi10Mg and M2_316L tests (laser power: 70 W - 200 W, scanning speed: 100 mm/s - 1400 mm/s, focus diameter: 55 µm - 200 µm). With TP_316L, the same parameter variants have also been used for most specimens. However, this LPBF system has a fixed focus diameter (55 µm), so that samples whose focus diameter deviates from this have been replaced here. In the case of LT_AlSi10Mg, it has also been necessary to deviate from the initial test plan for some parameter combinations, as the back reflection triggers a protective device in the AM system in the particular case of high energy inputs. The other system parameters (e.g. protective gas flow, recoater speed) have been selected according to the standard settings of the respective machine for the respective material.

After manufacturing, the specimens have been separated from the build plate by wire EDM and the lattice structures have been manually separated. Microscope images of the lattice structures have been taken using a Zeiss Smartzoom 5 (depth of field by z-stack, 34x zoom, if necessary stitching of individual images).

Based on the microscope images, the three quality characteristics "qInterruptions", "qDownNose" and "qDownRough" on the individual specimens have been classified manually by assigning into classes between 1 (best quality class) and 5 (worst quality class). Examples for the best and worst quality classes for each of the three quality characteristics are shown in Figure 2.

Furthermore, using the open-source multidimensional image processing software ImageJ, the strut thicknesses of the lattice structures have been measured in the top view and the side view on two struts of each sample at five locations on the strut. These data form the basis of the model for the strut thickness.

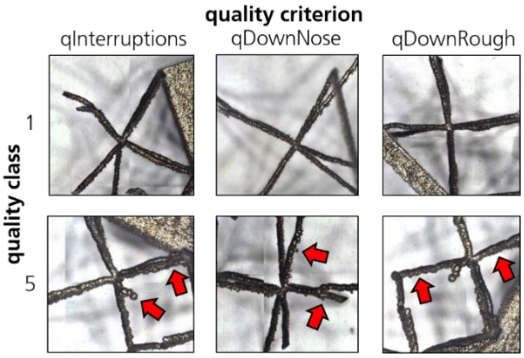

Figure 2. Examples of the "best" (1, top row) and the "worst" (5, bottom row) quality classes for the three quality features qInterruptions, qDownNose and qDownRough for lattice structures. Arrows highlight significant characteristics.

2.2. Determination of precision and repeatability

Based on the build jobs M2_B1 and M2_B2 the achievable precision and repeatability under identical process conditions has been determined. In both build jobs, approx. 150 individual bridge-like specimens have been distributed in a grid across the entire build plate (cp. Figure 3 a). Each of them consist of two strut-like geometry features (altogether approx. 600) that are analysed here. These strut-like specimens are 10 mm in height. The cross-section of each specimen has been exposed by exactly three individual scan vectors with a length of 2 mm and a distance of 100 µm to each neighbouring vector (cp. Figure 3 b). The order of this exposure has been constant across all layers and has been the same for all specimens. Laser parameters laser power P = 100 W, scan speed v_s = 625 mm/s, focus diameter d_f = 100 µm have been kept constant for all specimens.

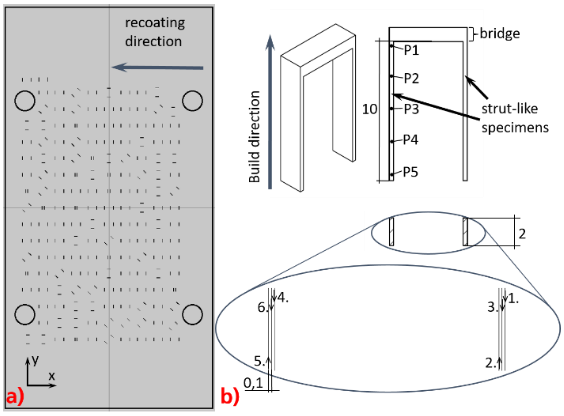

Figure 3. a) Arrangement of the specimens on the two build jobs, b) Geometry of the strut-like specimens and position of the individual scan vectors in one exemplary layer for LPBF manufacturing.

After fabrication, the bridge-like specimens have been detached from the build plate using wire EDM. Depth-focus microscope images of the specimens have then been taken using a Zeiss SmartZoom 5. Afterwards ImageJ software has been used to measure the width of each struts' cross-section at five locations (P1 - P5) per strut as shown in Figure 3 b). These data form the basis for an investigation of the scatter of the width of the specimen cross-section and for a determination of whether this scatter is location-dependent.

3. Evaluation and modelling

The evaluation of the manufacturing experiments has primarily been carried out using statistical methods and by the formation of regression models. The Cornerstone 7.1.2.1 software (camLine GmbH, Germany) has been used for this purpose.

3.1. Limitation of the exploitable parameter space

The exploitable parameter space has been narrowed down separately for each machine and material. The quality characteristics evaluated in classes have also been considered separately from each other. If lattice structures could not be produced with a certain parameter combination, it has been assessed with quality class 5.

For each quality characteristic, an attempt has been made to find a regression model with up to quadratic terms that maps the class values of the quality characteristics particularly well. Subsequently, these models have been used to predict the quality characteristics for the entire parameter space. In a next step, the exploitable parameter space has been determined from these predictions: all parameter combinations that lead to quality characteristics of class 1 or class 2 in the model have been regarded as exploitable parameter space.

3.2. Modelling of the strut diameter

For a better comparability of the different systems and materials, only the specimens manufactured with 55 µm laser focus diameter have been used for the modelling of the strut diameter. For each of the three manufacturing experiments LT_AlSi10Mg, M2_316L, TP_316L, a linear regression model with quadratic terms has been calculated. Input variables are laser power and scanning speed, output variable is the strut diameter. There has no distinction been made whether the strut diameter is measured from the top or the side. That is because previous investigations showed only minor differences between these measurement directions. Each model has been optimised using the automatic model optimisation tool in Cornerstone. The quadratic term (laser power)² has improved the models only marginally. Therefore it has been manually removed for simplification.

3.3. Investigation of precision and repeatability

In order to characterise the achievable precision and repeatability of the process, a linear regression model with cubic terms has been formed exclusively from the input variables “x position” and “y position” of the respective strut-shaped sample. The output variable has been the measured strut thickness. The "Adj. R Square" of this model has been determined and its magnitude has been evaluated. A very small Adj. R Square indicates that the occurring scatter cannot be explained by the x and y coordinates of the specimens. In this case, there would be no spatial dependence of this quality characteristic.

4. Results

4.1. Limitation of the exploitable parameter space

Manual assessment of quality characteristics is a very simple measure of narrowing down the usable parameter space that can be carried out with reasonable effort. However, it is also imprecise and subjective. In some cases, there is a risk that the assessments in quality classes are ambiguous – parameter combinations that are very close to each other are frequently assigned to different parameter classes. The models for the screening phase therefore only have a low "Adj. R Square" and a suitable model cannot be found for all machine and material combinations.

Nevertheless, the model formed from the manual evaluations represents the experimental space relatively well in over 50% of the cases examined (cp. Figure 4 a).

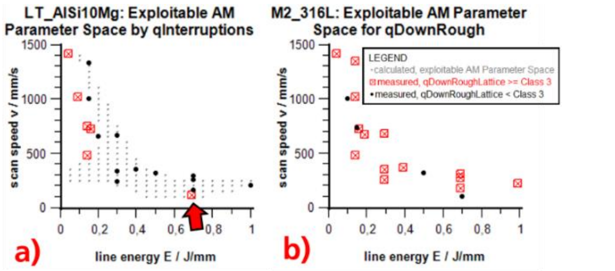

Figure 4. The exploitable parameter space identified by modelling. In a), the exploitable parameter space is well defined. In b), data points representing "good" and "bad" parameter combinations are mixed in such a way that no model for sharp delineation could be found with this approach.

In particular, many of the parameter combinations, for which specimens could not be fabricated successfully, have been avoided. However, it cannot be guaranteed that all unsuitable parameter combinations reside outside the identified parameter space. In particular, if "good" and "bad" samples are very close to each other in the parameter space or are intermixed, no valid parameter space can be determined by this methodology without adjustment of the selection parameters in some cases.

4.2. Modelling of strut diameter

In contrast to the limitation of the usable parameter space, the measured strut thicknesses can be represented very well for all investigated material and machine combinations by regression models with quadratic terms from the input variables laser power and scanning speed. The characteristic values for the models are summarised in Table 2.

Table 2 Characteristic values of the models for description of the strut diameter.

Model name	“Adj R Square”	“Pure Error” / mm	“Residual df”
LT_AlSi10Mg	0,89	0,025	155
M2_316L	0,79	0,027	290
TP_316L	0,86	0,025	455

The prediction models examined are shown pictorially in Figure 5. They do match qualitatively. The degressive dependence of the strut diameter on the scanning speed is well represented by a quadratic term, the correlation with the laser power has an almost linear character.

Particularly in the range of low scanning speeds (v_s < 500 mm/s), there is still a high dependence of the strut diameter on the scanning speed for all the systems and materials investigated. In this range, the correlation is almost linear. Here it is particularly striking that the gradient between laser power and scanning speed and thus their common effect is almost identical for all the systems and materials considered. However, they differ in terms of absolute values for the various strut diameters. The models for the material 316L show similar sensitivities of the strut diameter to laser power and scanning speed for low scanning speeds on both systems. They differ from each other primarily by an offset on the strut thickness. In the case of material AlSi10Mg on the Lasertec 12 system, a larger dependence of the strut diameter on both the laser power and the scanning speed can be observed. On the basis of the available data, it is not yet possible to figure out whether this higher sensitivity is mainly caused by the system or the material.

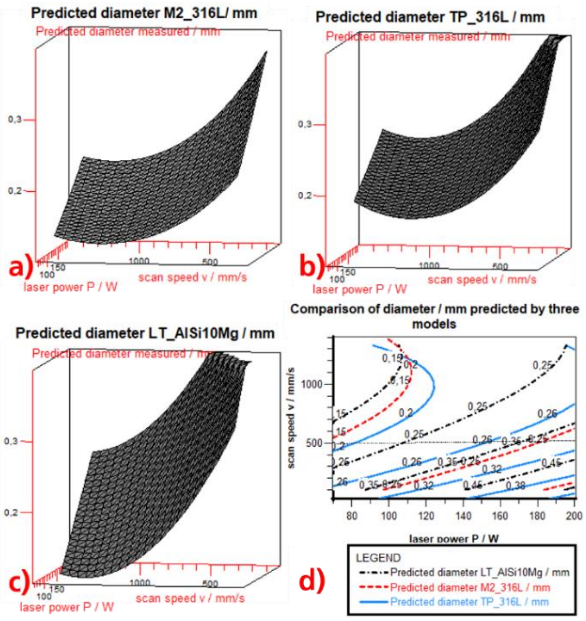

Figure 5. a) - c): Individual diagrams of the strut diameter models and d) comparison of the models in a combined diagram.

4.3. Investigation of precision and repeatability

The model for the effort to explain the strut diameter from x and y position has an Adj. R Square of 0.028. Thus, the occurring scatter can barely be explained by the x or y position of the specimen. It can therefore be assumed that the systematic deviation in the strut diameter caused by location dependence is very small, compared to the typical scatter in the process, and can therefore be disregarded. The scatter of the measured values is shown in Figure 6, listed according to measuring position (P1 - P5) and build job (M2_B1, M2_B2).

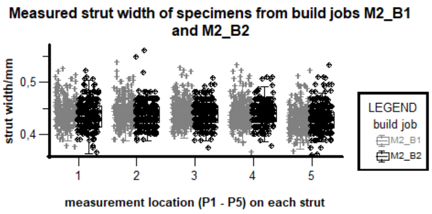

Figure 6. Distribution of the measured strut diameters broken down by measurement location and build job.

5. Summary, conclusions and outlook

Overall, the use of regression models has proven to be very suitable for the generalised analysis and description of the LPBF process: Although the suitable parameter space can be delimited by a regression model from manual assessment of quality characteristics, the result is very much dependent on the quality and validity of the assessment. Without an individual adjustment of the model parameters, a valid model cannot be found in any case. It appears feasible that a subjective assessment of the quality features in five quality classes does not have sufficient discriminatory power. A relative evaluation of the components against one another, instead of a rigid class allocation, has potential for improvement. Furthermore, quality features could be weighted, depending on their importance for manufacturability.

However, the regression approach has shown its strengths in the systematic description of the dependence of the strut diameter on the process parameters laser power and scanning speed. The qualitative curves of the strut diameter are only shifted and slightly deformed in the series of tests, investigated here for the material 316L. This clearly has the potential to significantly reduce the qualification effort for new materials or systems, as only a few support points have to be determined by manufacturing experiments. However, further experiments have to be undertaken to prove general validity of this system. In the future, the parameterisation of the manufacturing process could be carried out automatically on this basis to achieve an improved accuracy.

Furthermore, it could be shown that, for the investigated specimens, there is no significant spatial dependence of the resulting strut diameters. The expected magnitude of the process scatter is constantly approx. +/- 35 µm for the present case as investigated. This rather large basic scatter limits the achievable precision in LPBF manufacturing under the given conditions. On the other hand, this means that measuring methods with limited precision can be used for measurements of filigree struts, as long as their imprecision is small in relation to the LPBF process scatter.

Acknowledgements

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 289647464. The authors also thank their research assistants Merle Bergmann and Louise Elstner for supporting this work by recording microscopic images and manually measuring thousands of struts in diameter as valuable data base for these investigations.

References

[1] Abele E; Stoffregen H; Klimkeit K; Hoche H; Oechsner M 2015 Optimisation of process parameters for lattice structures *Rapid Prototyping Journal* **21 (1)**, 117–127

[2] Korn H; Koch P; Kordaß R; Schöne C; Müller B; Holtzhausen S; Stelzer R 2018 Influences of Scan Strategy and Exposure Parameters on Diameter and Surface Quality of Struts in Lattice Structures. *DDMC - Conference 2018*

[3] Rehme O. 2009 Cellular design for laser freeform fabrication. *Hamburg-Harburg, Techn. Univ., Inst. für Laser- und Anlagensystemtechnik*

[4] Korn, H.; Koch, P.; Kordaß, R.; Holtzhausen, S.; Schöne, C.; Müller, B.; Stelzer, R. 2018 Adapted Scan Strategy and Slicing Tool for Improvement of Strut Precision in Lattice Structures *Proceedings of ASPE and euspen Summer Topical Meeting, Berkeley*

[5] Koch, P; Korn, H; Kordaß, R; Schöne, C; Müller, B; Stelzer, R: 2018 A CAD-based Workflow and Mechanical Characterization for Additive Manufacturing of Tailored Lattice Structures *Proceedings of the 29th SFF Symposium*, 782 – 790.

[6] Gustmann, T; Gutmann, F; Wenz, F; Koch, P; Stelzer, R; Drossel, W-G; Korn, H 2020 Properties of a superelastic NiTi shape memory alloy using laser powder bed fusion and adaptive scanning strategies *Progress in additive manufacturing,* **Vol.5 (2020), No.1**, 11 – 18. DOI: 10.1007/s40964-020-00118-6

[7] Calignano, F., 2014 Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting. *Materials & Design* **64**, 203–213.

[8] Charles, A; Elkaseer, A; Thijs, L; Hagenmeyer, V; Scholz, S, 2019 Effect of Process Parameters on the Generated Surface Roughness of Down-Facing Surfaces in Selective Laser Melting. *Applied Sciences* **9 (6)**, 1256.

[9] Cloots, M; Zumofen, L; Spierings, A B; Kirchheim, A; Wegener, K, 2017 Approaches to minimize overhang angles of SLM parts *Rapid Prototyping Journal* **23 (2)**, 362–369.

[10] Piscopo, G; Salmi, A; Atzeni, E, 2019 On the quality of unsupported overhangs produced by laser powder bed fusion. *International Journal of Manufacturing Research* **14 (2)**, 198.

[11] Sun, J; Yang, Y; Di W, 2013 Parametric optimization of selective laser melting for forming Ti6Al4V samples by Taguchi method. *Optics & Laser Technology* **49**, 118-124.

[12] Huxol, A; Villmer, F-J, 2019. DoE Methods for Parameter Evaluation in Selective Laser Melting *IFAC-PapersOnLine* **52 (10)**, 270–275.