# Influences of Scan Strategy and Exposure Parameters on Diameter and Surface Quality of Struts in Lattice Structures

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*Abstract*

*A modified point-exposure strategy is presented which enables the use of point-exposure on industry-standard laser beam melting systems without modifying its software configuration. Therefore exposure points are replaced by short scan vectors of defined power and scan speed. The influence of the length of the exposure vectors as well as of the laser power and the scan speed on the strut diameter and the surface quality are investigated. It is shown that with this method manufacture of lattice structures which exhibit strut diameters of 150 µm or less and smooth surfaces compared to contour hatch-exposure is possible. Additionally a qualitative comparison of the micro structures of contour hatch-exposed and point-exposed specimens out of Ti6Al4V is carried out. Specimens of both exposure strategies show a similar micro structure.*

## 1 Introduction and State of the Art

The requirement-oriented dimensioning of lattice structures and their production in a high quality by means of laser beam melting (LBM) is still an insufficiently solved challenge. The dependency of the component's quality and thus of its mechanical characteristic values on the influence of the LBM process is of particular importance.

According to VDI 3405 [1] important criteria for the quality of components manufactured by LBM are the material density and the surface roughness. These quality criteria are predominantly influenced in a nonlinear manner by numerous process parameters stated Rehme et al. [2]. The exposure strategy, the laser power $P$, the laser scan speed $v$ and the laser focus diameter have a particular influence on the quality of the component. These parameters significantly determine the input of energy and the cooling rate and thus the resulting micro structure in the component according to Merkt [3].

Lattice structures differ from conventional components out of bulk material in that they exhibit many individual areas with a low area-to-perimeter ratio in the cross-sectional plane perpendicular to the build direction as reported by Abele et al. [4]. As a result, the surface quality of lattice structures has a greater effect on the mechanical properties than in objects made of bulk material conforming to Kordass et al. [5].

The contour hatch-exposure strategy (CH-exposure) is primarily used for objects made of bulk material: Suitable parameter sets are known for many common LBM materials. They lead to components with relatively smooth surfaces and a high material density within the bulk material. For lattice structures, however, two different types of exposure strategies can be considered: the CH-exposure and the point-exposure (P-exposure) [3, 6].

In CH-exposure, the strut diameter is determined by the position of the contour vectors and the size of the area within the contours. An advantage of the CH-exposure is that the files required for the production can be generated with commercially available slicers. However, it is disadvantageous that considerable deviations between the specification of the geometry and the finished strut diameter are to be expected, especially in the case of small strut diameters. Kordass et al. [5] indicate that a geometry specification of 0.2 mm strut diameter leads to a resulting diameter of at least 0.4 mm, depending on the exposure parameters. Variations within the slicer used, undefined geometry specifications can result, as shown in Figure 1, which then lead to inconsistent strut diameters or even defective struts.

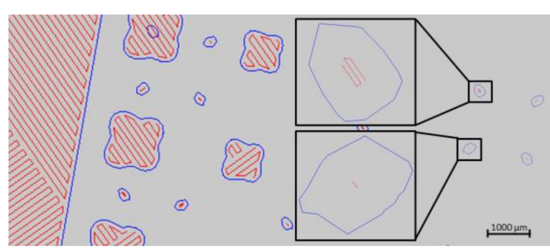



*Figure 1: Large variation of the hatch geometry in the cross sections of tiny lattice structures.*

In P-exposure, the intersections of the strut's central axes with the layer to be produced are determined and successively targeted by the laser focus point. It remains on each of the points for a defined period of time. The strut diameter is defined by the size of the melt pool, which in turn depends on the exposure parameters. A major advantage of the P-exposure is the great potential to increase the manufacturing speed by reducing the paths that the laser focus needs to cover during exposure. A further advantage is that finer strut diameters can be achieved compared to the CH-exposure stated Merkt [3]. The disadvantage, however, is that conventional file formats for commercially available LBM systems do not support the use of the P-exposure. Also commercial slicers usually do not provide the possibility to create the necessary exposure data for the P-exposure. Merkt [3, 7] also points out for SS316L that various mechanical characteristic values of P-exposed lattice structures fall significantly short of CH-exposed lattices using the common implementation of the P-exposure.

In the course of this work an exposure strategy is presented, which is a modification of the P-exposure using the means of the CH-exposure. Thus, a requirement-oriented point-exposure can also be implemented on commercially available LBM systems without modifications in the machine control software.

## 2 Modelling

Commercially available slicers do mainly just export the slices of the CAD-model. The hatching is normally performed on the machine which is a "hidden" process with a very limited opportunity for the operator to vary the scanning strategy. Thus, commercially available slicers currently do not provide direct support for P-exposure. Therefore, a slicer with combined hatching, specifically for P-exposure of lattice structures was developed, exporting the data needed for exposure in the CLI format. Due to file size limitations it is optionally possible to split the batch of layers into several CLI files.

In contrast to other works presented in the literature [3, 6, 7], the point-exposure is not implemented by the static targeting of a point and subsequent application of the laser for a predetermined period of time. Instead, points are represented by short scan vectors, which the laser focus travels at a given speed. Therefore, the energy input is defined by the length and speed of the scan vector instead of the resting time of the laser. Their length and orientation as well as their order of exposure are flexibly defined by the slicer as shown in Figure 2.

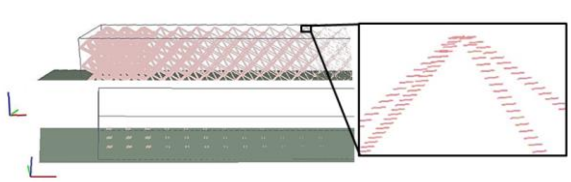


*Figure 2: Scan vectors for the exposure of a lattice structure created by the here-developed slicer.*

This approach results in some advantages compared to the CH-exposure as well as the common realisation of the point-exposure:

- There is a high degree of freedom in defining the desired point representation and thus the cross section geometry of the struts
- By the specification of the exposure order and the orientation of the scan vectors there is a high optimization potential considering the manufacturing time compared to CH-exposure
- P-exposed and conventionally CH-exposed sections in the same file are possible
- More flexibility in the choice of the data format to be used for manufacturing compared to many commercially available slicers

## 3 Experimental Setup

For the qualification of suitable parameter sets to achieve a target strut diameter and for verifying the suitability of the P-exposure strategy presented here for the production of lattice structures, the correlations

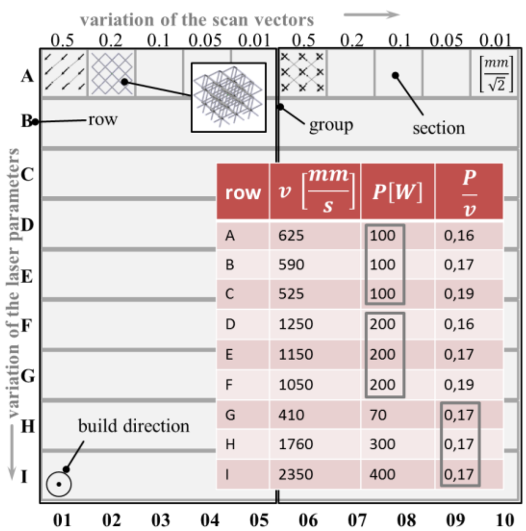
- between geometry specifications and resulting strut diameter are determined quantitatively,
- between exposure parameters and resulting strut diameter are assessed quantitatively as well
- and between exposure and surface quality are determined qualitatively.

The findings of Merkt [7], which point out that P-exposed lattice structures have inferior mechanical characteristic values than CH-exposed lattice structures, are further taken into account. Qualitative microscopic investigations of the micro structure of selected specimens and a comparison to CH-exposed specimens of lattice structures are carried out.

### 3.1 Specimen Geometry and Experimental Design

All lattice structures considered in this article are made of Ti-6Al-4V and have unit cells of the bcc type with an identical edge length of 3 mm in all principal directions. As shown in Figure 3 a single specimen section consists of a lattice of 3 x 3 cells in the build plane. Each specimen section has a height of two cells in the build direction, as well as a processing allowance of 0.5 cells. Ten specimen sections are combined to a row. Within the row, the specimen sections form two groups. In the first five specimen elements of a row, the exposure of the struts is carried out by a single exposure vector, and in the last five specimen elements by two orthogonally crossed exposure vectors. Within the five elements of a group the length of the exposure vectors is varied.

Nine rows are combined in the vertical direction to form a matrix of the exposure parameters: The laser power and the scan speed are varied around confirmed parameters for bulk material. The single specimen sections can be identified by the letter for their row and the number for their column. For example the upper-left specimen is labelled “A01” and has a scan speed of 625 $mm \cdot s^{-1}$ and a laser power of 100 W. Additionally, two specimens (Z2_1 and Z2_3) are manufactured using CH-scan strategy with a similar parameter set as the specimens in row A for microstructure comparison (cf. Table 1). The specimens are separated from the build plate by wire EDM before characterization.




| row | $v\ \left[\frac{mm}{s}\right]$ | $P[W]$ | $\frac{P}{v}$ |
|---|---|---|---|
| A | 625 | 100 | 0,16 |
| B | 590 | 100 | 0,17 |
| C | 525 | 100 | 0,19 |
| D | 1250 | 200 | 0,16 |
| E | 1150 | 200 | 0,17 |
| F | 1050 | 200 | 0,19 |
| G | 410 | 70 | 0,17 |
| H | 1760 | 300 | 0,17 |
| I | 2350 | 400 | 0,17 |

*Figure 3: Scheme of specimen matrix and laser parameters used. The geometry is varied within the rows and the laser parameters are varied within the columns.*

All specimens presented in this paper were manufactured on a M2 cusing machine (manufacturer: Concept Laser GmbH) using a layer thickness of 25 µm. This LBM machine is equipped with a 400 W CW-diode-pumped fiber laser (wavelength 1,070 nm, M² < 1.2, focus-Ø = 100 µm).

### 3.2 Strut Diameter and Surface Quality

For the analysis of the strut diameter and the surface quality, microscope images of the individual specimen sections were made. For each specimen section in the matrix, the strut diameters of four struts were measured. Two of the measured struts are located on the diagonal inVecDia alongside the exposure vector and two are positioned on the diagonal vertVecDia orthogonally to the exposure vector, which are marked in Figure 4.

The diameters are determined manually using the software tool of the microscope. Considering the large number of struts to be measured, this procedure represents a practical compromise between effort and accuracy of the measurement results.

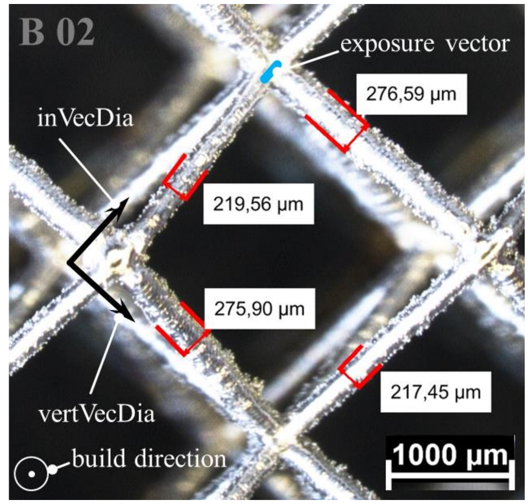



*Figure 4: Measured struts for determination of strut diameters. Struts can be oriented on two different diagonals compared to the exposure vector.*

The struts are very thin and highly tilted within the lattice structure, so a quantification of the surface roughness with measuring equipment like laser scanning microscope is not possible. Instead, a classifying assessment of the specimen sections’ surface quality is carried out. Four quality classes are defined (cf. Figure 5) and specimens are classified by manual comparison.

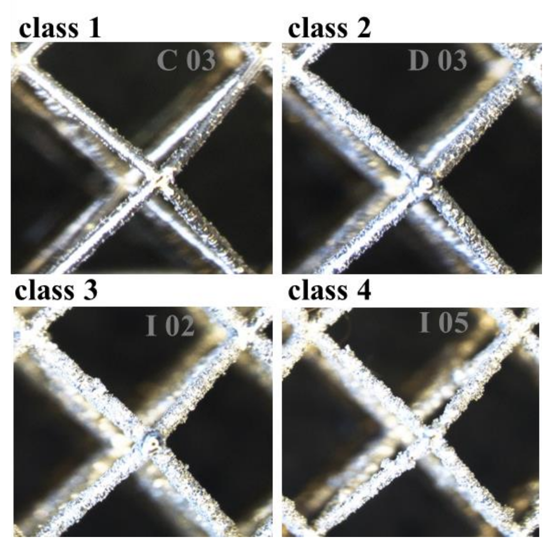



*Figure 5: Exemplary surface qualities of the four different quality classes. Class 1 has a smooth surface and nearly no adhered particles. Class 2 has a smooth surface but occasionally adhered powder particles. Class 3 has significant amounts of adhered powder and occasional agglutinations. Class 4 has significant amounts of adhered powder and significant agglutinations and therefore notable variations in the strut diameter.*

### 3.3 Micro Structure

To get a first impression as a pre-screening for mechanical tests, a separate study of the micro structure is carried out on selected specimen sections as shown in Table 1.

*Table 1: Specimen sections with varying exposure parameters and scan strategies, whose micro structure was analysed.*

| label | exposure strategy | parameter set |
|---|---|---|
| A03 | P | 100W, 625 mm/s |
| A08 | P, crossed scanvectors | |
| Z2_1 | CH, only contour | |
| Z2_3 | CH, contour and hatches | |

All specimens used for analysis of micro structure do show up a same parameter set of their exposure parameters, but they differ in geometry specification of their scan vectors. Specimens A03 and A08 are produced using the P-exposure strategy with similar scan vector lengths. A03 is exposed with a single exposure vector and A08 with crossed scan vectors. Z2_1 and Z2_3 use contour-hatch scan strategy omitting the hatches in Z2_1.

The micro structure was analysed in a micro section. To ensure a representative result, the analysis was carried out at four different locations on two to three struts in each cross section. The specimen's preparation was done by cold mounting, grinding and four-minute etching with a hydrogen peroxide - sodium hydroxide-solution. It is investigated whether a manual observation shows up, significant qualitative differences in the micro structure between the two exposure strategies. These could indicate significant differences in the mechanical characteristics of the lattice structures considered.

Since the analysis of the micro structure is carried out using a destructive test, the rows containing specimen sections to be examined are manufactured again using identical parameter sets. The results of Kordass et al. [5] indicate that lattice structures produced under identical conditions also have comparable mechanical characteristics. In addition, the strut diameters of the newly manufactured rows are gauged and compared with those of the initial trial matrix. Since the deviations of the measured rod strengths are within the tolerances of the measuring method, a sufficient reproducibility of the results is assumed.

## 4 Results

A visual inspection shows that connected lattice structures are formed for all manufactured specimen sections under use of the selected parameter sets. The predominant amount of the specimen sections produced also has a smooth surface appearance. Nevertheless, there are clear differences in the strut diameter between the different specimen sections within a row as well as between different rows.

### 4.1 Strut Diameter

The lattice with the finest struts is formed at a parameter set of $P = 70\,W$ and $v = 410\,mm \cdot s^{-1}$ and has a diameter of $130\ \mu m$. A z-shift of the laser focus can be neglected because of the short exposure time when manufacturing lattice structures.

By substituting the points to be exposed with short scan vectors, different strut diameters can occur longitudinally and orthogonally to the exposure vector specified. This influence is unwanted and leads to anisotropies in the mechanical behaviour of the lattice structure.

Figure 6 shows the ratio of the average measured strut diameter in the direction of the vertVecDia-diagonal relative to the inVecDia-diagonal, depending on the length of the given exposure vector and the laser power. A ratio of 1:1 means that the measured strut has the same diameter in the directions of both diagonals. If deviations of 10% between the strut diameters in both diagonal directions are tolerated, the influence of given exposure vectors with a length lower than 140 µm on the strut's shape can be assumed as irrelevant, using standard delay times for bulk material.

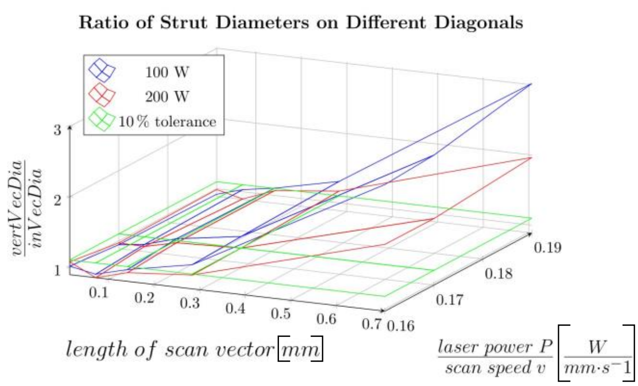



*Figure 6: Ratio of strut diameters on verVecDia per strut diameter on inVecDia dependent on the length of the scan vector and the laser power to scan speed-ratio.*

The influence of the laser power as well as the beam guiding speed is shown in Figure 7. It can be seen that the strut diameter seems to be linearly dependent on the laser power for a power ranging at least from 70 W to 200 W. However, only few laser powers could be considered.

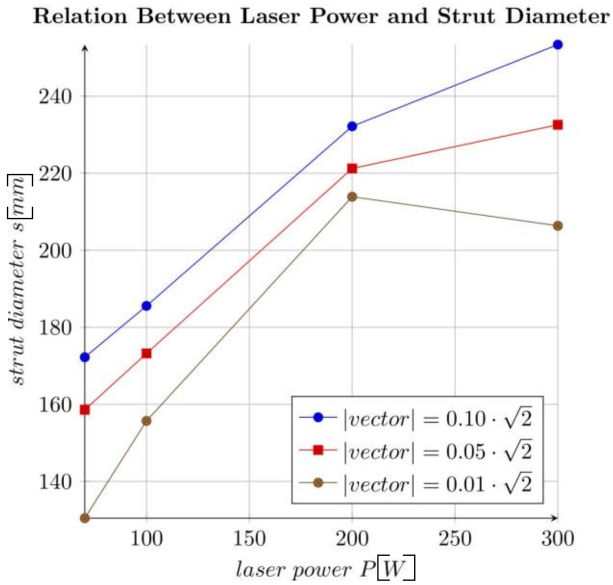



*Figure 7: Relation between laser power and strut diameter for different lengths of the exposure vector. The ratio of laser power to scan speed is kept constant.*

### 4.2 Surface Quality

Direct comparison points out a clear qualitative difference in the surface roughness between the CH-exposed specimens and the P-exposed specimens using the same laser parameters. Figure 8 shows these relations.

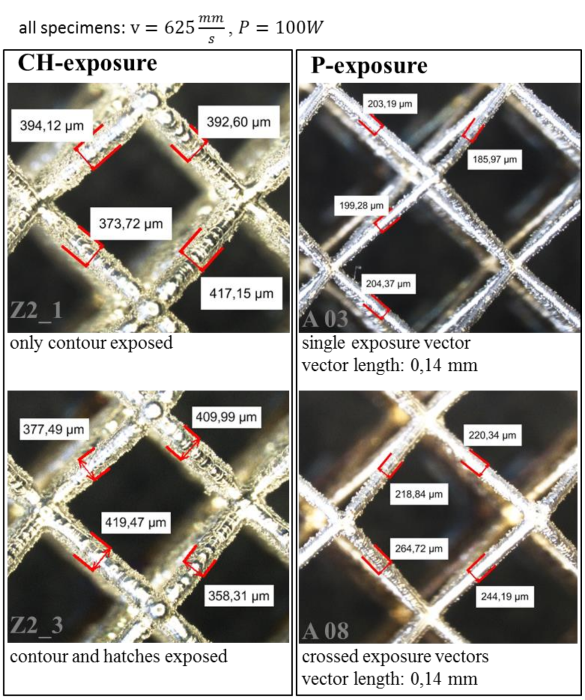



*Figure 8: Specimens exposed with identical laser parameters, but two by CH-exposure and two by the P-exposure shown here*

The results of the classification of the surface roughness are shown in Figure 9. The labelling of the axis represents the labelling of the specimens as already shown in Figure 3. The laser Power is depicted on the right side for further clarification. It is found that struts manufactured with a laser power in the range of 100 W tend to have smoothest surfaces.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 3 | P = 100 W |
| B | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 3 | P = 100 W |
| C | 3 | 2 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 1 | P = 100 W |
| D | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | P = 200 W |
| E | 3 | 2 | 3 | 3 | 3 | 1 | 1 | 2 | 2 | 2 | P = 200 W |
| F | 3 | 3 | 3 | 3 | 2 | 2 | 1 | 2 | 2 | 2 | P = 200 W |
| G | 4 | 3 | 2 | 2 | 3 | 2 | 2 | 1 | 1 | 2 | P = 70 W |
| H | 3 | 3 | 4 | 4 | 4 | 1 | 3 | 3 | 3 | 4 | P = 300 W |
| I | 3 | 3 | 3 | 4 | 4 | 2 | 3 | 3 | 4 | 4 | P = 400 W |

1 class 1 2 class 2 3 class 3 4 class 4

*Figure 9: Specimen sections classified into four classes by their surface quality.*

It can also be seen that the exposure with crossed vectors seems to reach better results at a laser power of 200 W than the single vector exposure. High laser powers like 300 W or 400 W result in a better surface quality for longer exposure vectors than for short ones. But altogether a laser power above 200 W tends to result in poorer surface qualities with more adhesions. On the other hand 70 W seems to be suitable for thin struts, but to be inappropriate for relatively long exposure vectors of 0.7 mm length.

### 4.3 Micro Structure

The anisotropic formation of the grains in the build direction described by Merkt in [3, 7] for the material SS316L can't be identified in the specimens out of Ti-6Al-4V exposed with the P-exposure strategy presented here. Figure 10 shows, that there is no preferred orientation of the microstructure in both, the CH-exposed and the P-exposed specimens.

The microstructure of specimen Z2_1 as well as the microstructure of A03 are characterised by α‘-martensite. This indicates a fast cooling, qualitatively related to that of oil quenched or water quenched Ti-6Al-4V as shown by Schumann [8].

The particular layers of the manufacturing process can't be identified in the cross section anymore.

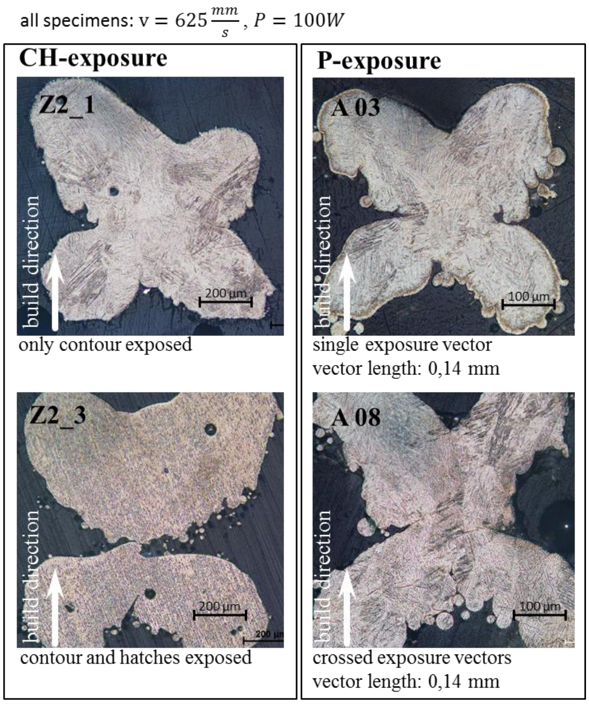



*Figure 10: microstructure of specimens exposed with CH-exposure and P-exposure*

There is no significant qualitative difference between the microstructure of the CH-exposed specimen Z2_1 and P-exposed specimens A03 or A08.

It should also be noted that the cross-vector exposed specimen A08 exhibits significantly more cracks and more adhesions than the specimen A03

## 5 Discussion

With the exposure strategy presented here, it is reliably possible to manufacture fine lattice structures with strut diameters of less than 140 µm with simultaneously smooth surfaces in Ti-6Al-4V. It has been shown that, if an exposure vector of appropriate length is selected, no more differences in the strut diameter alongside and orthogonally to the exposure vector can be observed. The aimed strut diameter can be reproducibly adjusted by the specification of an appropriate length of the exposure vector and the parameter set containing the laser power and the scan speed.

The CH-exposed specimens Z2_1 and Z2_3 were produced with identical parameters for laser power and scan speed as the P-exposed specimens A03 and A08. However, surface quality and strut diameter of specimens Z2_1 and Z2_3 are similar to those of the specimens D07 and H07, which are P-exposed with significantly higher energy input. It is to be assumed that this difference is caused by the higher length of the exposure vectors used by CH-exposure and therefore the higher total energy input into the lattice structure.

There are no significant differences in the micro structure between the here shown P-exposed and the conventionally CH-exposed specimens. Therefore it can be assumed that resulting mechanical properties are in a comparable range. The here presented Implementation of P-exposure seems to be suitable especially for thin struts.

## 6 Summary and Outlook

A modified P-exposure strategy was presented that enables the use of P-exposure on industry-standard LBM systems without modifying its software configuration. The influence of the length of the exposure vectors on the strut diameter and the surface quality as well as of the laser power and the scan speed, while keeping the laser focus diameter and the delay times constant, were investigated. A qualitative comparison of the micro structures of CH- and P-exposed specimens out of Ti-6Al-4V showed that there is no build direction dependent anisotropy in the micro structure. In addition, a direct comparison of the micro structures of P- and CH-exposed specimens shows no appreciable difference in the micro structure.

Although the manual measurement of the struts by means of microscopy is suitable for an estimation of the relations between exposure parameters and resulting struts, its suitability for a precise determination of the struts diameters has to be re-evaluated with regard to its measurement accuracy. As a subsequent step, it is possible to establish a database to assign resulting strut diameters to parameter sets. This enables the reliable realisation of a specific lattice geometry.

The analysis of the micro structure permits conclusions on the mechanical behaviour of the specimen only in very limited approaches. Therefore, mechanical tests of specimens produced with different parameter sets should be carried out. The approach presented here should also be extended to other materials. The long-term goal could be to select and assign suitable parameter sets for each desired target geometry and specification of the mechanical behaviour by means of appropriate slicer software. This would make the use of lattice structures also more reliable in load-bearing constructions and simplify their design.

## Acknowledgements

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