“Assessing new support minimizing strategies for the additive manufacturing technology SLM”

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Abstract

To successfully produce metal parts by SLM, additional support structures are needed to support overhanging surfaces in order to dissipate process heat and to minimize geometrical distortions induced by internal stresses. These structures are often massive and require additional post-processing time for their removal. A minimization of the extent to which support structures are needed would therefore significantly reduce manufacturing and finishing efforts and costs. A specific component segmentation strategy is developed. It allows the segmentation of critical areas of the component by applying a specific scanning strategy with appropriate energy input and optimized supporting strategies. The results indicate that the supporting effort can generally be reduced, e.g. overhang geometries with an angle to the horizontal of less than 35° can be manufactured without any support. The successful realization of the segmentation strategy in combination with optimized support structures allows the implementation of a stacking strategy, thereby using the available work space more efficiently.

Introduction

Selective Laser Melting (SLM) belongs to the additive manufacturing process, which is characterized by the layerwise production of the component. The high degree of geometric freedom, which is a unique feature of the additive processes, is often limited by process-specific effects. In the SLM process, high temperature gradients, and consequently high internal stresses are the cause for the limitation in the degree of complexity (Pohl H., 2001).

In SLM research there are the numerous attempts dealing with the fundamental development of strategies to avoid of tension and deformation in the component. Kruth points out that the exposure strategy has a significant influence on the stress development within the component (Kruth et al., 2004). From this, recommendations for a stress-optimized powder exposure are formulated. Mumtaz shows a completely new approach in the use of eutectic alloys (Mumtaz, 2011). In comparison to conventional metallic alloys, eutectic alloys have a low melting point. Therefore, due to lower required process temperatures, the thermo-mechanical effects decreases. Another way to counteract component thermomechanically induced defects is demonstrated by Ott and Buchbinder (Zaeh & Ott, 2011) (Buchbinder, Schilling, Meiners, Pirch, & Wissenbach, 2011). By heating up the base plate, a decrease in the temperature gradients can be achieved. It is proven that defects in the microstructure and strains in the part can be significantly reduced. The successful conversion and use of the described strategies leads automatically to a diminished utilization of support structures.

A segmentation strategy is introduced in this work as another instrument to avoid massive support structures. With the segmentation strategy, the component is segmented according to its position in the construction field in critical and uncritical regions. Uncritical are those regions of

the workpiece which are surrounded with sufficient solid material underneath able to act as a sufficient heat sink dissipating the process heat. Regions of the workpiece are critical when sufficient heat dissipating is unavailable.
Overhanging structures and surfaces are typically classified as critical, because of their limited possibilities to conduct process heat in lower regions of the workpiece.

In this work, two objectives are pursued:

1) Supported overhang

Process parameters are to be determined for a maximum overhang of 0 °, which should be designed with a minimal support structure.

2) Unsupported overhang

Through the use of appropriate process parameters and exposure strategies, the smallest possible critical overhang angle is presented, in which the support is omitted.

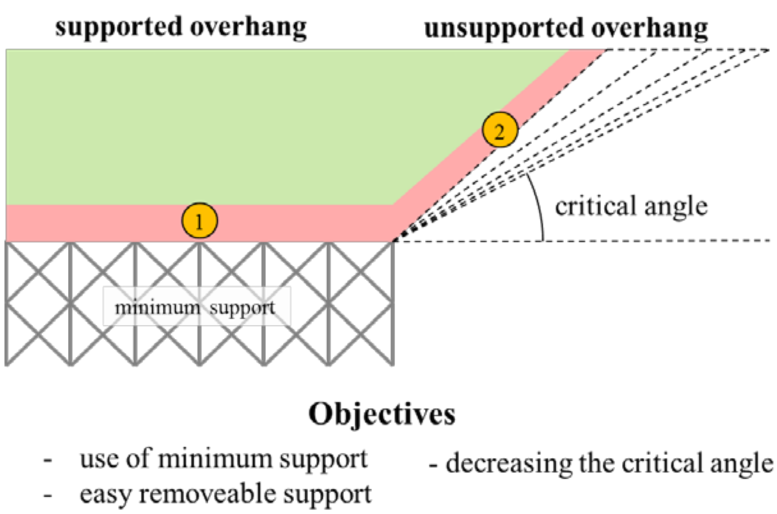


Figure 1: Example of a segmented sample used to describe the objectives of this work

A further benefit of these two goals is to make apparent the possibilities of using stacking strategies. The stacking strategy helps to make the SLM process more economical, due to using the available space in the SLM-machine more efficiently.

Experimental setup and methodology

SLM-Machine

The investigations are performed on an industrially prepared system: Concept Laser M2. It includes a 200 W Nd:YAG fiber laser at a wavelength of 1070 nm The beam has a M^2 of 1.3 and a measured diameter of 90 microns (D4σ) in the focal plane. The focused beam is measured using a Spiricon SP620U beam analysis camera.

Powder used

A series of experiments are carried out with 316L stainless steel powder. The powder fraction has a particle size distribution of D_{10}= 7.12 µm to D_{90} = 24.17 µm.

Surface quality
The surface quality is measured tactilely using a perthometer by Mahr.

Density measurement
The Archimedes method is used to determine the sample density (Spierings A.B., 2011).

Minimum Support
For the studies, a special support structure is developed. The support structure used here has the following properties.

1) The connection to the part is realized only via fixation points. The fixation points have the task to connect the part and dissipate the process heat. The purely selective connection of the component on the support intends to simplify and to ease the separation of the support structure from the component.
2) Due to the lattice structure, there are no walled structures, which imbeds powder. So the waste of powder can be avoided.
3) The grid structure is used for support rigidity so that horizontal and vertical forces can be absorbed by the crossbars.

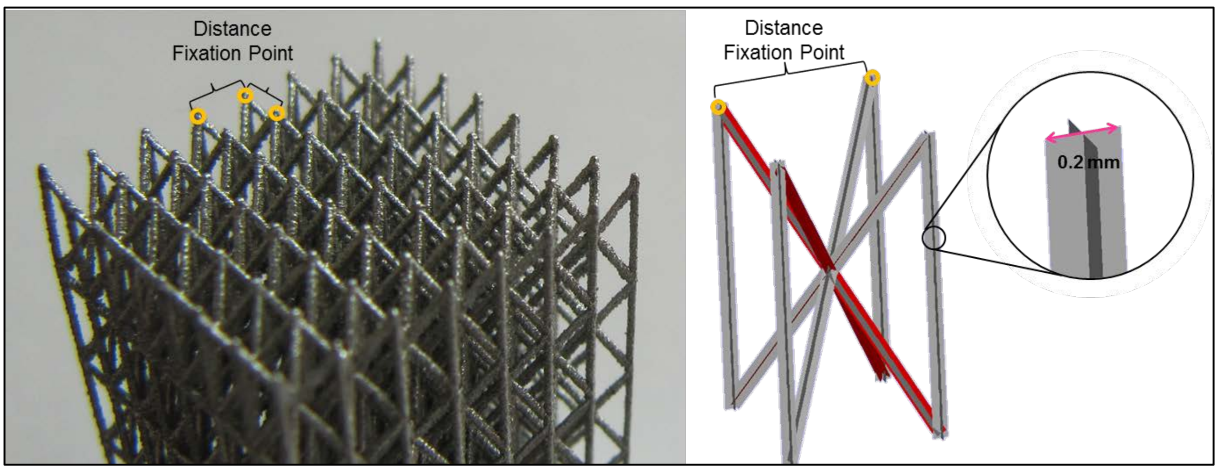


Figure 2: Realized (left) and schematic (right) of support elements

Methodology
The results are analyzed using Design of Experiments (DoE). The answer **Y** (the measured value) will be expressed according to the process parameters to the following relation (factors: see Table 1) to the following relation (development of Taylor):

$Y = a_0$	constant
$+a_1X_1 + a_2X_2 + a_3X_3$	1st order
$+a_{12}X_1X_2 + a_{13}X_1X_3 + a_{23}X_2X_3 + a_{123}X_1X_2X_3$	interactions
$+a_{11}X_1^2 + a_{22}X_2^2 + a_{33}X_3^2$	2nd order

Where $\mathbf{X_1}$, $\mathbf{X_2}$ and $\mathbf{X_3}$ are the used influence factors and $\mathbf{a_i}$ the coefficients of the model. The determination of the various coefficients $\mathbf{a_i}$ of the models is carried out by the least square method.

sample	*normalized process parameter*		
[no.]	*X1*	*X2*	*X3*
1	1	1	-1
2	-1	-1	1
3	0	0	1
4	-1	1	-1
5	-1	0	0
6	0	0	-1
7	1	0	0
8	0	0	0
9	0	-1	0
10	0	1	0
11	0	0	0
12	1	-1	1
13	1	1	1
14	-1	-1	-1
15	-1	1	1
16	1	-1	-1

Table 1: Central Composite Design (CCD) plan

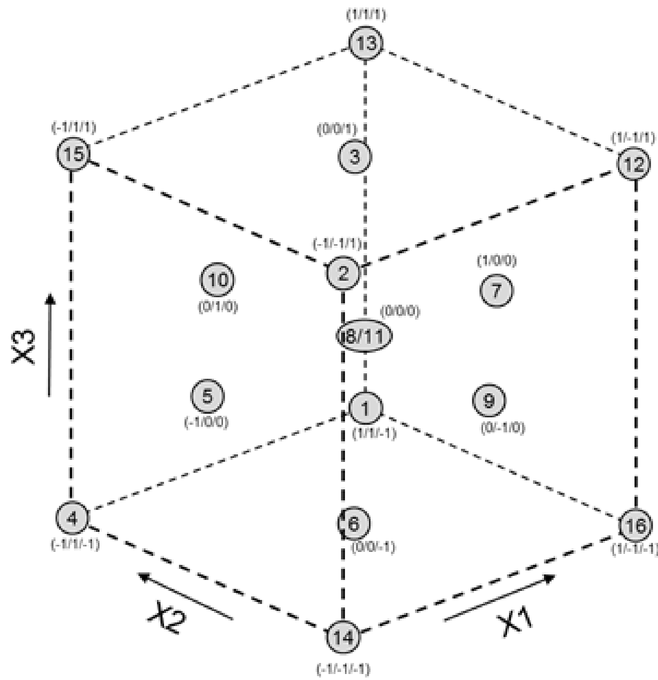


Figure 3: Graphical representation of CCD plan

Pairwise comparison

Pairwise comparison is a tool to rank a set of decision-making criteria and rate the criteria on a relative scale of quality. In this work the quality is ranked from 1 (=fine) to 16 (=poor).

<u>Experiments, Part 1: Supported Overhang</u>

Process parameters and support density for critical layers

While applying the DOE to a selected overhang geometry needing support structures, an optimization has to be found for the following three goals: high dimensional stability, surface quality and material density.

The support used here is characterized only by selective attachment sites at the critical layers. Consequently, a moderate energy input in the production of critical layers has to be chosen. Due to the low heat dissipation of such support structures (Figure 2), a high energy input would result in unintended agglomerations of powder particles.

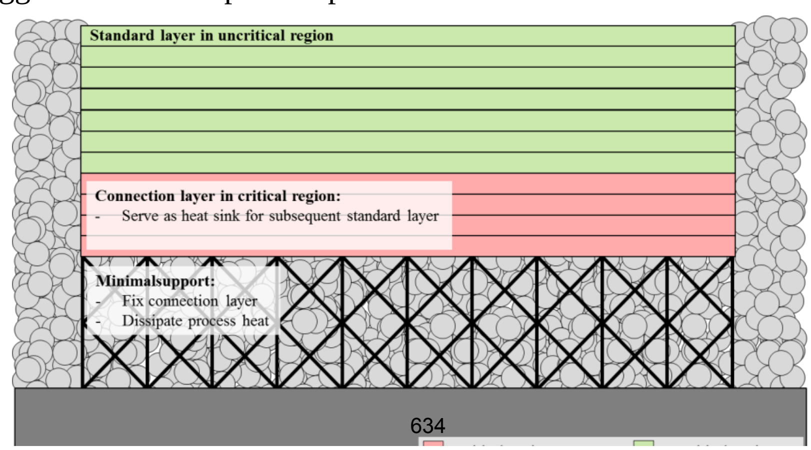


Figure 4: principle of connection layers and support structures

Therefore, it is necessary to develop process parameters, which guarantee a minimum of support and a good connection to the densest possible material for the critical layers above the support. After finishing the so-called connection layers, these serve as a heat sink for the subsequent standard layers. To ensure the production of the part using –"standard layers" (Figure 4) on the connection layers, it is important to investigate which process parameters generate defect-free connection layers.
In parallel, it has to be investigated how large the maximum possible distance between the fixation points of the minimum support should be in order to build the connection layers successfully. In Table 2, the DOE factors used are listed.

Process parameter	**type**	**unit**	
Laser power	constant	[W]	200
Layer thickness		[µm]	30
Exposure strategy		[-]	unidirectional
X1 = hatch distance	variable	[mm]	0.08/ 0.095 / 0.11
X2 = distance fixation point		[mm]	2 / 4 / 6
X3 = scan speed		[mm/s]	1,000 / 1,500 / 2,000

Table 2: Process parameters for supported overhang experiments

The combination of the connection layers and the minimum support substitutes the use of solid support structures to a wide degree and contributes to a more efficient post-processing.
To determine the optimal SLM process parameters (scan speed and hatch distance) for the connection layers in the critical area, 24 x 24 mm² samples consisting of 5 connection layers, which are based on different densely populated minimum supports (distance fixation point), are produced. 5 connection layers are sufficient to evaluate the influence of the process parameters. Within the study 16 samples are created such that experiments are designed using a Central Composite Design experiment plan.

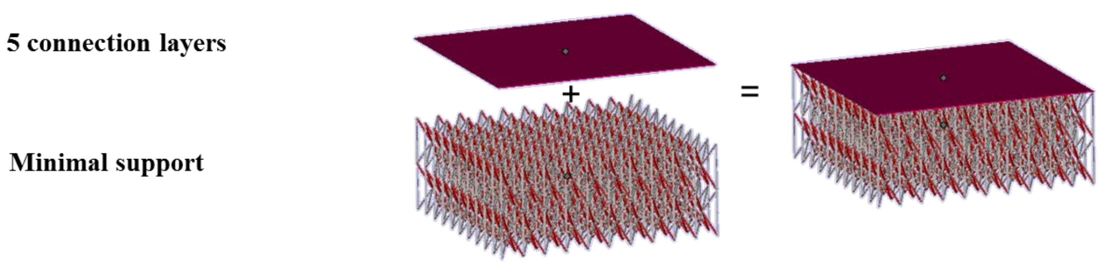


Figure 5: Sample Composition

The production of the 5 connection layers are realized with a unidirectional hatch strategy, thereby minimizing heat concentration effects at the end of the single scan lines.
Preliminary investigations show that the more economical bidirectional hatch strategy does not produce satisfactory surface structures at the connection layers. The reason is the inhomogeneous energy input of the bidirectional hatch strategy.
When evaluating the samples to determine the best process parameters set for the production of connection layers, their surfaces are qualitatively analyzed with regard to a closed defect-free surface (figure 8, sample 12 and 14) which could influence the ongoing process.

Quantitative measurements of the surface have been omitted. Nevertheless, to represent a gradation in the results obtained, a pairwise comparison is chosen for evaluating the surfaces and defining the surface quality via a rank position (1 = fine; 16 = poor).

Number of necessary layers in the critical region

In a further step, it is examined how many connection layers are actually needed to provide sufficient thermal and mechanical support for the subsequent layers under normal production conditions. These samples are generated, which consist of minimal support, connection layers and, if necessary, standard layers.

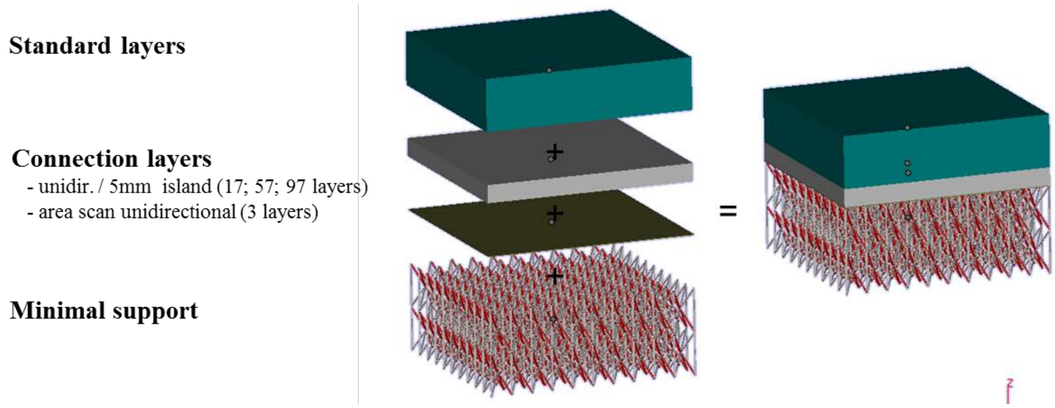


Figure 6: Sample composition for optimal number of connection layers

The first three connection layers are always generated with a unidirectional area scan strategy. The remaining layers are produced with island scanning (Spierings, 2009), using a unidirectional scanning, to minimize the induced stresses and strains.

process parameter	**type**	**unit**	
# connection layers	variable	[-]	20 / 60 / 100

Table 3: Number of connection layers within the experiments

<u>Experiments, Part 2: Unsupported Overhang</u>

Conventionally, the construction of overhanging structures with an angle to the horizontal below a certain value is only possible through the use of support structures. The primary objective of support structures is to dissipate process heat and shrinkage. Since there is powder underneath the outer contour of the overhang, the process heat can only be dissipated laterally, as metallic powder material has a comparably low thermal conductivity (Sih & Barlow, 2004).

At decreasing overhang angles, the difficulties in heat dissipation arise. Overhang angles smaller than 45 ° can negatively affect the surface quality due to heat accumulation (Wang, Yang, Yi, & Su, 2013) and consequently adhering metallic powder particles.

By combining certain exposure strategies with low heat input process parameters giving a lower heat input, it is possible to reduce the overhang angle without any losses to surface quality and work piece geometry. Thereby, the influence of the hatch distance, scan speed and scan angle are investigated.

The scanning strategy will be varied in that way that the laser exposure runs parallel to the contour / edge of the component (scan angle 0 °), runs perpendicular to the edge of the component (scan angle 90 °) or a combination of both (scan angle 45 °) (Table 4).
For all parameter combinations, the exposure of a layer always starts inside the sample and ends at the edge. The exposure begins therefore always inside the sample, to prevent excessive energy input at the edge of the sample where heat dissipation is difficult.
Parameter combinations of particularly good results are also tested on smaller overhang angles.

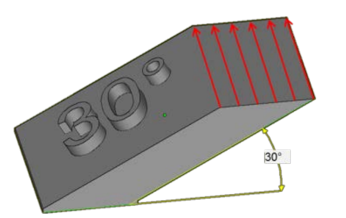
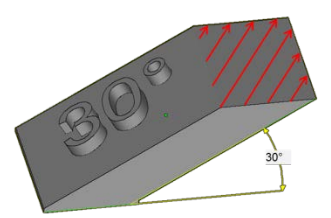
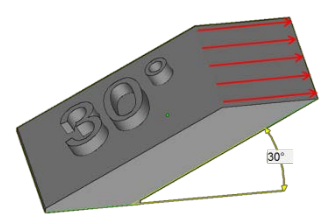
<table>
<tr><th>Process parameter</th><th colspan="2">type</th><th>unit</th><th></th></tr>
<tr><td>Laser power</td><td colspan="2" rowspan="3">constant</td><td>[W]</td><td>200</td></tr>
<tr><td>Layer thickness</td><td>[µm]</td><td>30</td></tr>
<tr><td>Exposure strategy</td><td>[-]</td><td>Unidirectional</td></tr>
<tr><td>Angle of overhang</td><td colspan="2" rowspan="4">variable</td><td>[°]</td><td>30° / 25° / 20°</td></tr>
<tr><td>X1 = hatch distance</td><td>[mm]</td><td>0.05 / 0.065 / 0.08</td></tr>
<tr><td>X2 = scan angle</td><td>[°]</td><td>0° / 45° / 90°</td></tr>
<tr><td>X3 = scan speed</td><td>[mm/s]</td><td>1,500 / 2,000 / 2,500</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">scan angle 0°</td><td colspan="2">scan angle 45°</td><td>scan angle 90°</td></tr>
</table>

Table 4: Constant and variable process parameter

To evaluate the overall impression of the sample, the qualitative evaluation method of pairwise comparison is used. The visual impression of the surface quality and the quality achieved at the edges contribute to the overall impression of the sample.
Since the overhang areas represent a final, and thus visible surface in contrast to the connection layers, the surface quality of the overhanging faces are also measured quantitatively for the evaluation of the parameters. In addition, the generated component density is also determined.

Results, Part 1: Supported Overhang

The distance between the fixation points has the greatest influence on the results. As expected, the best results are achieved when the minimum distance (2 mm) is used. The remaining parameters scan speed and hatch distance have less influence on the final results. This is particularly evident with samples 12 and 14.(sample # = parameter set #)

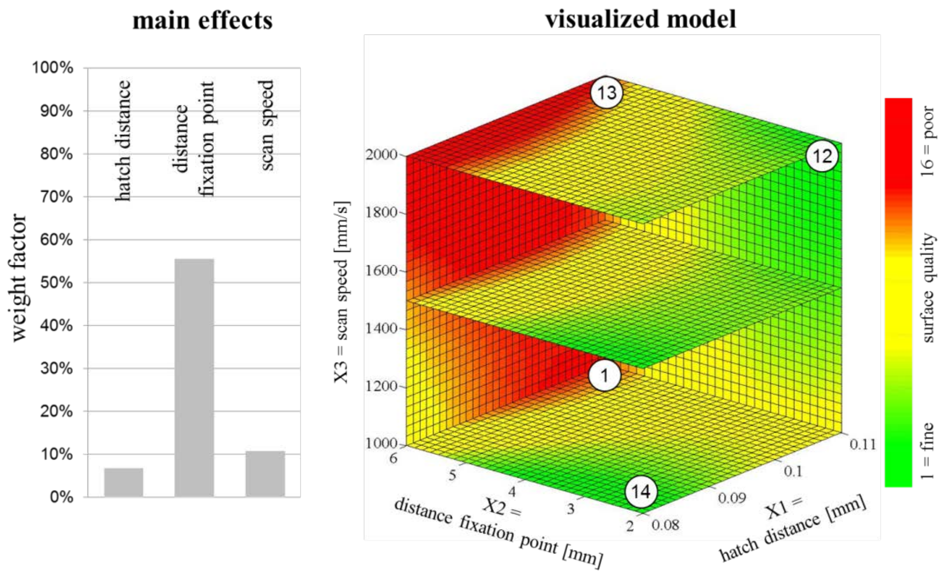


Figure 7: Main effects on surface quality (left); visualized model (right)

sample	energy density	rank surface	sample density
[No.]	[J/mm²]	[-]	[-]
1	1.71	15	98.6%
2	1.18	4	92.0%
3	0.99	13	88.1%
4	2.35	10	98.4%
5	1.57	9	96.6%
6	1.98	7	98.9%
7	1.14	6	91.1%
8	1.32	3	93.4%
9	1.32	11	93.4%
10	1.32	12	93.4%
11	1.32	5	93.4%
12	0.85	2	89.4%
13	0.85	14	89.4%
14	2.35	1	98.4%
15	1.18	16	92.0%
16	1.71	8	98.6%

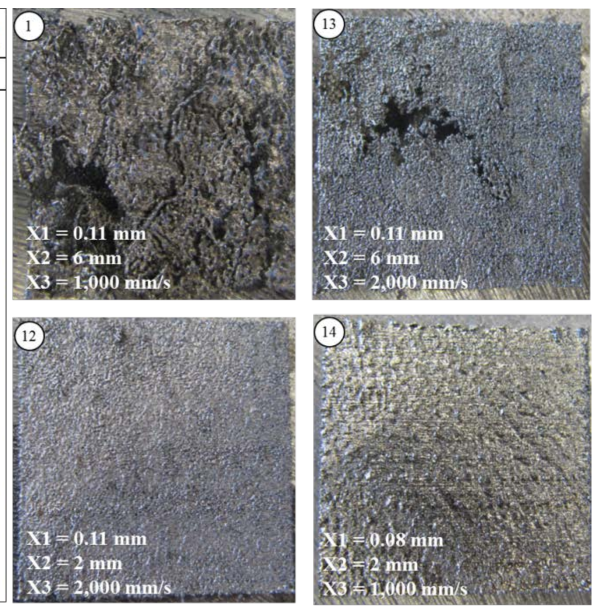


Figure 8: Resulting track energy; surface quality and density; surface examples of fine and poor results

Both samples show excellent results, with regards to surface quality. However, the energy input for sample 14 is almost 3 higher times as the energy input of sample 12. Both parameters will be used as a benchmark for further investigations.

Necessary number of connection layers

When determining the optimal number of connection layers, parameter set of sample 12 and 14 are used. With both parameters, it is, compared to other combinations, possible to realize good surface qualities, thereby generating optimal conditions for building up subsequent layers.

The influence of the volume energy becomes apparent when studying the optimal number of connection layers. The lattice structure of the support cannot avoid the resulting shrinkage of the connection layers. This is particularly evident in the samples, which are produced with parameter set 14. Thereby, the samples created by using parameter set 12 show a much lower shrinkage, compared to the samples prepared with parameter 14.

Furthermore, the investigations show that one can already continue the build process using standard parameters after only 20 connection layers.

Up to here it is possible to say that the connection to the minimal structure, in principle, is possible. With decreasing layer density, the dimensional stability of the connection layers increases.

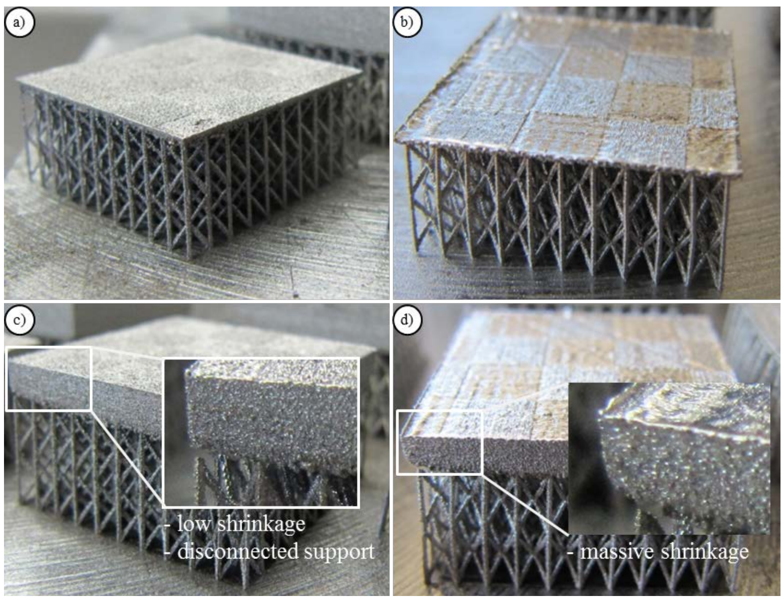


Figure 9: a) 20 connection layers (parameter set 12); b) 20 connection layers (parameter set 14) c) 60 connection layers (parameter set 12); b) 60 connection layers (parameter set 14)

Measurements and micrographs to derive the component density show that the component densities using parameter set 12 is only 90%. However, parameter set 14 reaches a density of 98.4%.

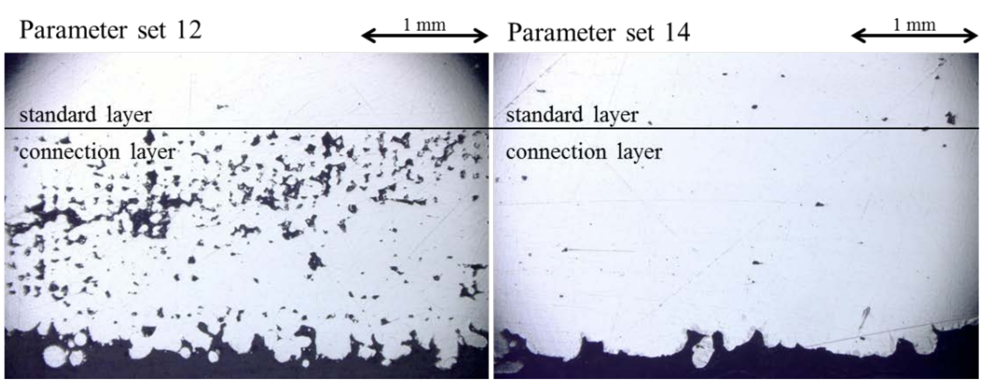


Figure 10: Polished cross section of samples 12 and 14

Due to the lower energy input with parameter set 12, the connection of the support structure to the component is not as strong as when using the parameter set 14. This is particularly noticeable in the separation of the component from the support. Samples, which were produced with parameter set 12, can be separated from the support without mechanical assistance. There are no support rests on the sample. Samples, which were produced with parameter set 14, can be separated only mechanically (e.g. sawing) from the support.

Results, Part 2: Unsupported Overhang

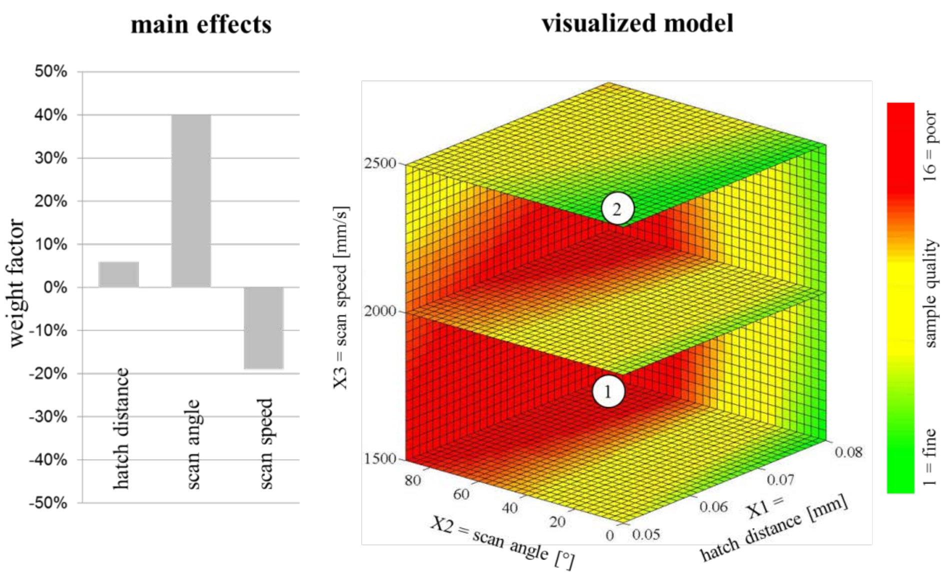


Figure 11: Main effects on surface quality (left); visualized model (right)

With all 16 parameter combinations, the samples are built successfully up to an overhang angle of 30 °. In the test series with an overhang angle of 25 ° not all process combinations perform to high qualitative sample. Four samples of the test series are of such a weak quality that a measurement of the sample surface on the overhanging side is not possible (Figure 13, sample 1). Since the quality of the results varies strongly within the 25 ° test series, the samples of this test series are ideally suited to determine the influence of process parameters.

Figure 11 (left) shows the results of the qualitative assessment, which are transferred into the Taylor series model previously mentioned. Thus, the scan angle has the greatest influence on the sample quality such that scan angles of 0° lead to the best results.

Regarding the scanning speed, it can be said that with high scanning speeds better results are typically achieved. The measurement results of the tactile surface measurements underline once again the result of the qualitative evaluation samples. For scan angles of 0°, the best surface results are achieved across all overhang angles (Figure 12). The achieved surface qualities, Ra, lie between 13 and 20 µm. Not only the best results are obtained with the scan angle of 0 °, the smallest investigated overhang angle of 20° is only possible with a scan angle of 0° (Figure 13). The achievable sample densities are between 86.9% and 97.2%.

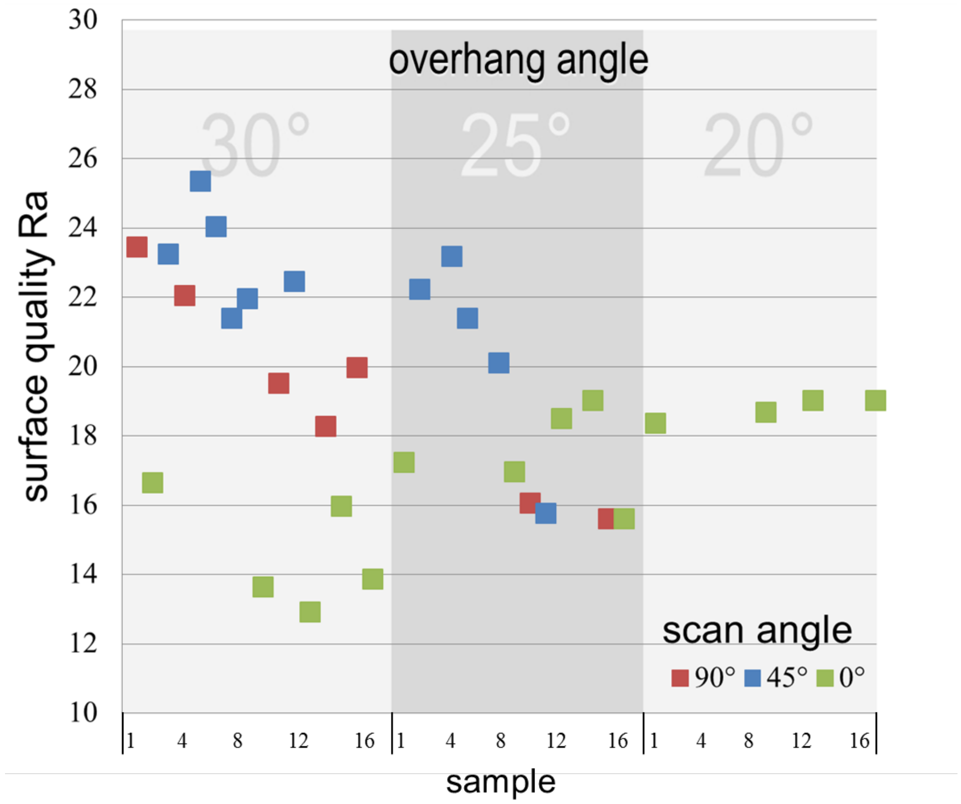


Figure 12: surface qualities (scan angle; overhang angle)

sample	energy density	surface quality Ra			rank sample quality 25°	sample density
[No.]	[-]	30°	25°	20°	[-]	[-]
1	1.57	23			16	89.2%
2	1.50	17	17	18	1	94.2%
3	1.16	23	22		12	90.1%
4	2.51	22			14	97.2%
5	1.88	25	23		7	95.6%
6	1.93	24	21		5	97.2%
7	1.18	21			13	92.6%
8	1.45	22	20		11	95.1%
9	1.45	14	17	19	3	95.1%
10	1.45	20	16		15	95.1%
11	1.45	22	16		9	95.1%
12	0.94	13	18	20	2	86.9%
13	0.94	18			8	86.9%
14	2.51	16	24		9	97.2%
15	1.50	20	16		6	94.2%
16	1.57	14	16	19	4	89.2%

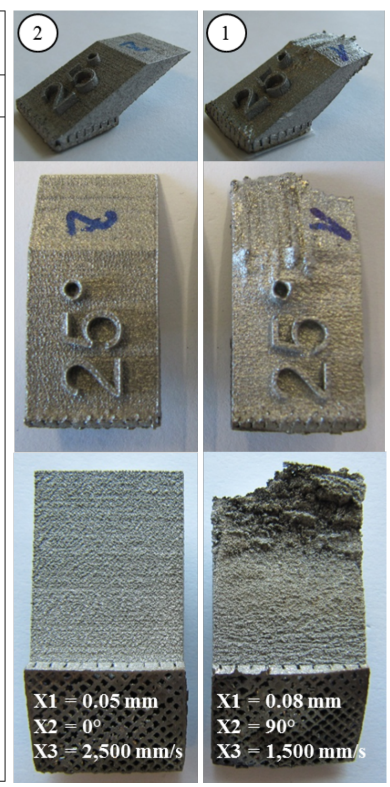


Figure 13: track energy; surface quality and density; sample 2 (fine) and sample 1 (poor)

Results, Part 3: Stacking Strategy

The application and refinement of the chosen process parameters for supported and unsupported overhang situations can make the SLM process even more effecient. Until now, the number of parts placed on a base plate is limited by the lateral dimensions of the plate. With the stacking strategy, a new dimension is realized and allows increasing the number of manufacturable parts and improved machine utilization.

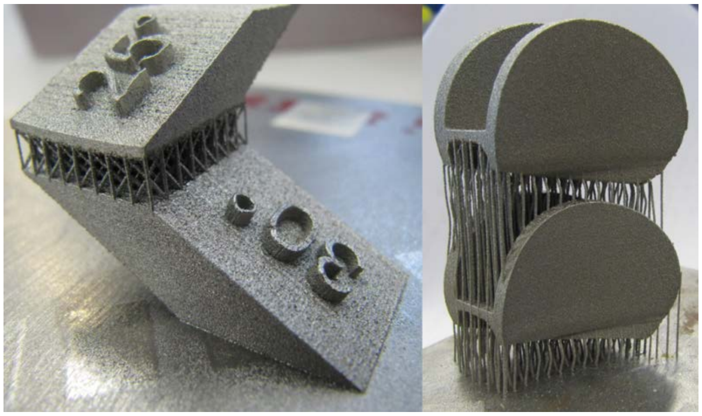


Figure 14: Demonstrator samples

The examples in figure 14 show that this strategy is feasible in principle.

Conclusion

The segmentation strategy is derived from the fact that the heat dissipating conditions during manufacturing are inhomogeneous. For this reason, components are segmented into critical and non-critical areas, which are manufactured with specific process parameters and exposure strategies.
In this work, therefore, two particularly challenging component situations were investigated.
At the maximum possible overhang of 0 ° (supported situation), it was shown that good results are possible with the use of minimal support given that the fixation points are at a distance of 2 mm**,** and can be separated with little effort from the support structure. Already after 20 connection layers**,** subsequent standard layers can be produced. Depending on the energy input and accuracy**,** a part density between 89.4% and 98.4% can be reached.
The results of the overhang tests (unsupported situation) show that an overhang angle of 20° is realizable. The best results in surface quality and part density are obtained by using a scan angle of 0°. The maximum possible part density at the smallest possible overhang of 20° is 95.1%. The surface qualities R_a are in a range of 13 to 20 µm.
In addition, it was shown on demonstrator parts that with the use of a minimal support in combination with the segmentation strategy that the stacking strategy can be implemented.

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