Research and Optimization of 3D Printing Process Parameters for Supportless 3D Printing with Powder Bed Fusion Selective Laser Melting

Pagac Marek[1,*], Jiri Hajnys[2], Jan Krejčí[3], Josef Hlavsa[4], Jiri Kratochvil[5]

Abstract: *The Laser Powder Bed Fusion Selective Laser Melting technology has a wide range of applications. This technology requires 3D printing of the support material, which has advantages and disadvantages. Considering the current trends that are led by the elimination of 3D printing of support material, this manuscript deals with the optimization of process parameters with the elimination of 3D printing of support material. In the introduction of the manuscript, research is described that summarizes the findings of this issue in foreign countries. In the experimental part, 3D printing of samples with different printing parameters was carried out and their effect on the quality of production was observed. The results of the experiment are a source of information for follow-up experiments, which will be the measurement and evaluation of mechanical properties. The results of the experiment have application potential.*

Keywords: *Powder Bed Fusion, SLM, Selective Laser Melting, 3D Print*

1 INTRODUCTION

The Powder Bed Fusion (PBF) Selective Laser Method (SLM) is experiencing increasing attention in industrial manufacturing. It is a very promising manufacturing method for the 3D printing of complex and precise metal parts. An important component in printing with this technology is the added support structures that provide heat dissipation and stabilization of the manufactured part during the manufacturing process. The supports are mostly used for printing overhanging surfaces. The main purpose is to avoid deformations caused by internal stresses, heat, or gravity. The formation of support structures entails many pitfalls. Powder metal for some parts does not fulfill the support function sufficiently. These structures are usually generated automatically. Commercial software may not be able to adapt to complex geometries, so the resulting support structures are often oversized. Their design plays a huge role. Since the supports are not functional parts of the print, they must be removed after production. Their removal can be very complex, laborious, and time-consuming, whether they are removed manually or using chemicals. In addition, the quality of the final surface at the point of support removal may also be affected by the removal. [1, 2]

It is commonly recommended to produce parts with overhanging surfaces with an inclination angle greater than 45° for suitable resistless printing quality. In this manuscript, the modification of printing parameters for components with an overhanging surface angle of less than 45° without the use of support structures was investigated. The main printing parameters affecting supportless printing are scanning speed, laser power, layer height, and the selection of an appropriate scanning strategy. Inappropriate selection of parameters can lead to rough surfaces, geometric inaccuracies, or even part breakage, etc. [3, 4]

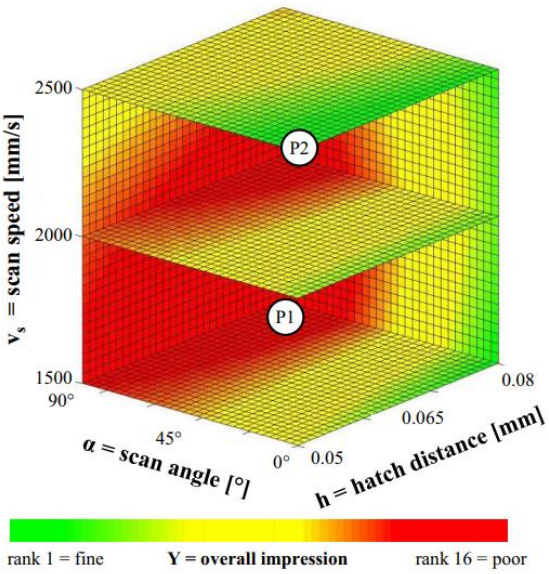
In their research, Cloots and colleagues [5] investigated the possibilities for minimizing overhanging angles in parts produced by the SLM method. The idea of this work is to segment the test specimen into core and shell parts. The main purpose of this segmentation was to build critical areas with specifically adjusted process parameters to realize the best possible quality of the specimens. This work aimed to define the process parameters and scanning strategies for the shell-core structures to achieve the minimum overhang angle without any supporting structures. The testing was divided into two parts. Two types of SS316L austenitic powder with different particle sizes were used for testing. Powder 1 had a mean particle size of 13 µm. The mean particle size of powder No.2 was about 24 µm.

The first part of the testing was the parameters for the minimum overhang angle αmin. The effect of hatching distance, angle, and scanning speed was investigated for the production of the shell part. The scan angle will vary as the laser exposure is either parallel to the edge of the part (scan angle $\phi = 0°$), perpendicular to the overhanging contour ($\phi = 90°$), or a combination of these ($\phi = 45°$). The laser power of 200 W and the layer thickness of 30 µm are constant parameters here. For all combinations of parameters, the layer exposure always starts inside the sample and ends at the edge of the overhang, due to avoid the entry of excessive energy at the edge of the sample, where it is difficult to dissipate heat. The test series starts with an overhang angle of 35°. Each repetition involves a 5° reduction in the angle. There were 16 test points for each overhang angle α tested. A qualitative assessment of the samples was performed by pairwise comparison. The results of this comparison were used to determine the significance of the process parameters and scanning strategy used.

Up to an overhang angle of $\alpha = 30°$, all 16 samples were successfully formed. For the samples with an overhang angle of $\alpha = 25°$, not all process combinations were performed with suitable quality. Four of these samples were so poor that surface quality measurements on the overhanging side were not feasible. Because the quality difference of these test samples was huge, the samples were suitable for determining the effect of the process parameters of hatch distance, scan angle, and scan speed. With the results shown in Figure 1, it can be concluded that the scan angle has the greatest effect on the quality of the sample. The best results were obtained at a scan angle of 0°. Here the heat of the melt spreads up to the previously formed layer. In the case of a 90° scan angle, the heat spreads almost exclusively downwards, so there is a much greater risk of thermal accumulation. Concerning the scanning speed v, it can be concluded that the quality of the minimum overhang can be improved by increasing the scanning speed. The achieved surface quality at a scan angle of 0° corresponds to a range of Ra = 13-21 μm. Using this scanning angle is also the only way to realize overhang angles of 20°. The realization of the overhanging surface strongly depends on the length of the scanning track. The accumulation of two adjacent scan tracks is significantly affected by the length of the scan track.

process parameters				*results*				
	h	α	v_s					*Y*
sample	*hatch distance*	*scan angle*	*scan speed*	*surface quality Ra 30°*	*25°*	*20°*	*density*	*over. impr. 25°*
[No.]	***[mm]***	***[°]***	***[mm/s]***	***[μm]***	***[μm]***	***[μm]***	***[%]***	***[rank]***
1	0.08	90	1'500	23	--	--	89.2	16
2	0.05	0	2'500	17	17	18	94.2	2
3	0.065	45	2'500	23	22	--	90.1	12
4	0.05	90	1'500	22	--	--	97.2	14
5	0.05	45	2'000	25	23	--	95.6	7
6	0.065	45	1'500	24	21	--	97.2	5
7	0.08	45	2'000	21	--	--	92.6	13
8	0.065	45	2'000	22	20	--	95.1	11
9	0.065	0	2'000	14	17	19	95.1	3
10	0.065	90	2'000	20	16	--	95.1	15
11	0.065	45	2'000	22	16	--	95.1	10
12	0.08	0	2'500	13	18	20	86.9	1
13	0.08	90	2'500	18	--	--	86.9	8
14	0.05	0	1'500	16	21	--	97.2	9
15	0.05	90	2'500	20	16	--	94.2	6
16	0.08	0	1'500	14	16	19	89.2	4

visualised model (2nd order) based on 25°



$a_0 = 12.5$; $a_1 = -0.9$; $a_2 = -7.7$; $a_3 = 3.3$; $a_{12} = -2.375$; $a_{13} = -1.875$; $a_{23} = 1.375$ $a_{123} = 1.125$; $a_{11} = 0$; $a_{22} = 1$; $a_{33} = 3$
R = 0.89

Fig. 1. Results of the first test part. [5]

The second test aimed to derive the minimum required cladding thickness t_s min. The core of the segmented sample was created with standard parameters. The shell thickness was varied until the formed sample was defect-free and suitable for production. Testing was carried out on a Concept Laser M2 machine in combination with powder 1. The experiment was repeated with powder 2. Finally, the same testing was carried out on a Renishaw 250 machine.

Preliminary studies show that scanning strategies in which the laser exposure is parallel to the overhanging contour are most appropriate. The specimen shell is realized by scanning the contour numerous times and the core is processed with standard parameters. The exposure of the mantle was performed immediately after the core exposure. The samples with an overhang angle α = 35° had no deformation or overheating effects only when the minimum thickness t_s min = 1.625 mm was observed, corresponding to 25 contour scans. With decreasing overhang angles, the value of the minimum thickness ts min increases. The overhang angle α = 30° is realizable with a minimum thickness t_s min = 2.275 mm, which corresponds to 35 contour scans.

In general, the qualities produced in the first test cannot be repeated on the segmented samples of the second test series. Regardless of the printing machine used, better results were always obtained when using powder number 2. The results show that SLM technology can realize overhanging surfaces without support due to the appropriate choice of scanning strategy and process parameters. Particularly good results are achieved whenever the exposure direction is parallel to the sample contour. The realization of overhanging angles of less than 35° is only possible with high sheath thicknesses in the millimeter range. This strategy cannot be applied to components where high mechanical strength is required.

In their research, Zhonghua Li and colleagues [6] describe a procedure for designing lightweight structures without the need for support structures, which they call the L&S Design Method. Instead of support structures, the part design is optimized to satisfy all the constraint conditions for SLM printing. Topology optimization (TO) is an effective method for reducing the weight of structures. First, an analysis of the original part is performed. The finite element method (FEM) is used to analyze the original model. It can be used with commercial software. To achieve low weight, the model must be optimized. In practice, FEM consists of three steps. The first step is pre-processing, where the original models have meshed and loads are applied to the nodes. The second step is an analysis and the third is post-processing.

Topological optimization (TO) is crucial for the construction of lightweight designs. It is a mathematical solution that optimizes the material distribution for a given load and boundary conditions. The SIMP method is chosen here for the implementation of TO due to its advantages over other methods. This method has been extensively studied and can be used to solve complex problems.

In their research, Hongyu Chen and colleagues [7] investigate the fabrication of overhanging surfaces by SLM without support structures so that all quality requirements are met. The major problems in the formation of overhanging surfaces include the staircase effect, deformation due to thermal stress, and slag formation.

A numerical simulation using FLUENT software has been carried out to predict the melt pool behavior and the response of the overhanging structure. The obtained temperature field from the simulation process is shown in Figure 2. According to previous studies, optimized SLM printing parameters were selected. The operating parameters were as follows: laser power (P) = 300 W, hatch space = 50 µm, and powder layer thickness (h) = 50 µm. Laser scanning speed (v) = 1000 mm/s, 1500 mm/s, 2000 mm/s and 2500 mm/s were chosen as the variable parameter. Therefore, the bulk energy density (Ev) = 120 J/mm^3, 80 J/mm^3, 60 J/mm^3, and 48 J/mm^3 was also varied.

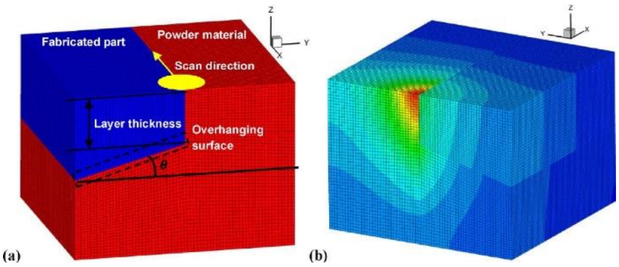


Fig. 2. Temperature field obtained by the simulation process. he fabricated part (a) and the temperature distribution obtained in the simulation process (b) [7]

In the experimental procedure, powder of AlSi10Mg material with a purity of 99.7% was processed. The mean particle size was 30 µm. The process was carried out on an SLM apparatus using a Ytterbium laser YLR-500 with a maximum output power of 500 W and a spot size of 70 µm. The protective atmosphere consisted of argon gas. The examination of the surface morphology and microstructure of the overhanging parts was performed using a PMG3 optical microscope.

The collective Wang [3] dealt with the problem of printing overhanging surfaces. First, the appropriate length of the overhanging surface was calculated. Several surfaces with different inclination angles were investigated. The fixed printing parameters were laser power, scanning area, layer thickness, and the number of printed layers. The variable was the scanning speed. An interlayer scanning strategy was chosen here, alternating with raster scanning. The tilt angle was gradually reduced as the experiment was conducted. It was found that at a scanning speed of 200 mm/s, even an overhanging surface with an inclination angle of α = 45° could not be produced without visible deformations. It was confirmed that the tilt angle and scanning speed have a great influence on the production of overhanging surfaces. The experiments were consistent with the theoretically calculated results. Thus, the minimum inclination angle that can be produced, subject to quality requirements, can be calculated. For a small inclination angle, the scanning speed needs to be increased. According to the tested results, the printing parameters can be optimized to print a qualitatively ideal overhanging surface.

2 MATERIALS AND METHODS

2.1 Manufacturing samples

For the experimental verification, a component with an overhanging surface was chosen. The shape and dimensions of the printed component are shown in Figure 3. All the dimensions of the printed samples were fixed, only the inclination angle was variable. The printed samples, without support structures, were printed at 35°, 30°, and 25° angles. A component designed in this way is ideal for observing the printing process without support structures.

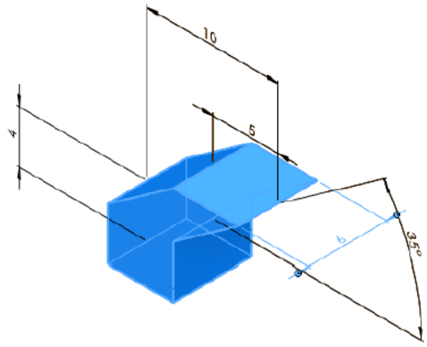


Fig. 3. Dimensions 3D printing samples.

2.2 Material Aluminum alloy AlSi10Mg

The experimental part was carried out on a TruPrint 1000 machine and the printing material was AlSi10Mg aluminum alloy. Preparing a print job and slicing was done in Materialise Magics software. A preview of the print job is shown in Figure 4.

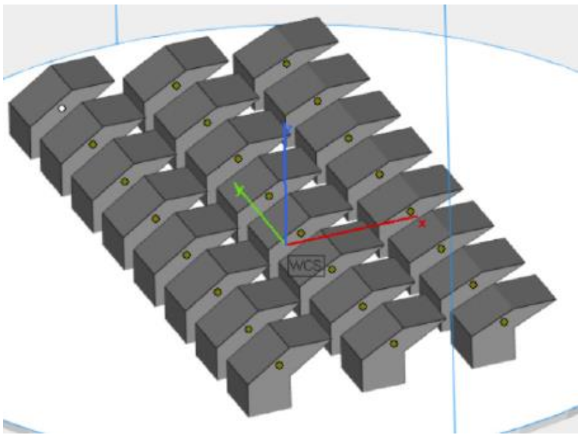


Fig. 4. printing preview of the samples.

2.3 3D Printing parameters

The choice of the printing parameters was based on the conducted research. It is necessary to distinguish the choice of printing parameters if the printing is of the contour of the overhanging surface (Down-skin) or the printing of the fill (In-skin).

However, for both printing variants (Down-skin and In-skin) constant parameters were chosen: laser power P = 175 W, laser beam diameter at the fusion point D1 = 0.055 mm, hatch offset h_o = 0.08 mm. For the printing of the in-skin spaces, the scan angle was varied for all samples in the range α = 0-90°. For printing down-skin spaces, the variable parameters were: hatch spacing in the range h_d = 0.05-0.08 mm and scanning speed vs in the range 1500-2500 mm/s. The specific values for each sample and other printing parameters for in-skin are described in Figure 5 and for down-skin in Figure 6.

		Printing Parameters											
		In-skin											
		Path Generation								Scanning			
			Borders			Hatching					Borders		
Sample	Name of Prinitng Parameters	Layer Thickness	Number of Borders	Border Distance	Scan Order	Hatch Offset	Hatch Distance	Pattern Style	Hatch Style	Scan Angle	Laser Spot Diameter	Scan speed	Power
		t	Bn	B	So	ho	hd	Ps	hs	α	D_l	v_s	P
No.	[-]	[µm]	[-]	[mm]	[-]	[mm]	[mm]	[-]	[-]	[°]	[mm]	[mm·s^{-1}]	[W]
1	No-1-90-8-2500	20	1	0,8	In to Out	0,08	0,12	No Pattern	Zig-Zag (unc)	90	0,055	1400	175
2	No-2-90-5-2500									90			
3	No-3-90-65-2000									90			
4	No-4-90-8-1500									90			
5	No-5-45-65-1500									45			
6	No-6-0-5-2500									0			
7	No-7-45-5-2000									45			
8	No-8-0-8-2500									0			

Fig. 5. 3D printing parameters for In-skin.

		Printing Parameters										
		Down-skin										
		Path Generation							Scanning			
		Instances										
		-	Borders			Hatching				Borders		
Sample	Name of Prinitng Parameters	Surface Threshold Angle	Number of Borders	Border Distance	Scan Order	Hatch Offset	Hatch Distance	Pattern Style	Scan Order	Laser Spot Diameter	Scan speed	Power
		/	Bn	B	So	ho	hd	Ps	So	D_l	v_s	P
No.	[-]	[°]	[-]	[mm]	[-]	[mm]	[mm]	[-]	[-]	[mm]	[mm·s^{-1}]	[W]
1	No-1-90-8-2500	45°	1	0,8	In to Out	0,08	0,08	Offset Filling	In to Out	0,055	2500	175
2	No-2-90-5-2500						0,05				2500	
3	No-3-90-65-2000						0,065				2000	
4	No-4-90-8-1500						0,08				1500	
5	No-5-45-65-1500						0,065				1500	
6	No-6-0-5-2500						0,05				2500	
7	No-7-45-5-2000						0,05				2000	
8	No-8-0-8-2500						0,08				2500	

Fig. 6. 3D printing parameters for Down-skin

3 EVALUATION

In this processed phase, the printing of the prepared samples follows. A total of 24 samples of AlSi10Mg material were printed. Each time 8 samples had the same inclination angle but different printing parameters. The final stage of the printed parts is shown in Figures 7 and 8.

It was found that by setting the parameters in this way, all parts with inclination angles of 35°, 30°, and 25° could be printed without support structures. None of the printed parts had visible deformations.

Further research will include evaluating the roughness of the overhanging surfaces created, the density of the printed material, and other strength or quality testing.

Fig. 7. Top view of the samples

Fig. 8. View of the bottom side of the samples

4 CONCLUSION

This work aimed to test the printing parameters for printing samples, without support structures, using the SLM method. This is also related to production efficiency, saving production time and money.

The experimental part was carried out based on a search, which was for foreign papers. A total of 24 samples were printed. Eight samples were always printed with the same overhang angle but with different printing parameters. The total printing time was 53 minutes.

As a result, all components were printed, without supporting structures, with the good surface quality of the overhanging surface. There was no visible deformation of the overhang on any of the components and no indication of slag formation.

Thanks to experimental testing, it is now possible to print similar components with an overhanging surface at a minimum inclination angle of 25°.

Following this experimental work, further investigations will include testing the roughness of the overhanging surface, the density of the printed material, and other strength or quality analyses.

The optimized parameters for SLM printing without support structures result in a more efficient production as complex support removal is not required. In some cases, the removal of supports may be difficult or impractical. Therefore, this research has resulted in savings in production time and costs associated with further processing. Printing parameters can also influence the resulting surface quality of the overhanging surface.

REFERENCES

[1] Yadroitsev I, Thivillon L, Bertrand P, Smurov I (2007) Strategy of manufacturing components with designed internal structure by selective laser melting of metallic powder. Appl Surf Sci 254 (4):980–983

[2] Alberto Boschetto, Luana Bottini, Francesco Veniali, Roughness modeling of AlSi10Mg parts fabricated by selective laser melting, Journal of Materials Processing Technology, Volume 241, 2017, Pages 154-163, ISSN 0924-0136, https://doi.org/10.1016/j.jmatprotec.2016.11.013.

[3] WANG D., YANG Y., YI Z., SU X. (2012), „Research on the fabricating quality optimization of the overhanging surface in SLM process“.

[4] LI, Z., ZHANG, D., DONG, P., KUCUKKOC, I. (2016), „A lightweight and support-free design method for selective laser melting“.

[5] CLOOTS, M., ZUMOFEN, L., SPIERINGS, A., KIRCHHEIM, A., WEGENER, K. (2017)," Approaches to minimize overhang angles of SLM parts ", Rapid Prototyping Journal, Vol. 23 Iss 2 pp.

[6] ZHANG, X., WANG, J., KANG, J., RONG Y., DUAN, G., WU, P., ZHENG, L. (2020), „ The dynamic arch bending mechanism of flat bridge structure of AlSi10Mg during SLM process“. Materials and Design.

[7] CHEN H., GU D., XIONG J., XIA M. (2016), „Improving additive manufacturing processability of hard-to-process overhanging structure by selective laser melting“.

Authors addresses

[1] *Marek Pagac, VSB-TU Ostrava, 17.listopadu 15, +420 597 321 285, marek.pagac@vsb.cz*
[2] *Jiri Hajnys, VSB-TU Ostrava, 17.listopadu 15, +420 596 999 064, jiri.hajnys@vsb.cz*
[3] *Jan Krejčí, VSB-TU Ostrava, 17.listopadu 15, +420 597 321 285*
[3] *Joseh Hlavsa, VSB-TU Ostrava, 17.listopadu 15, +420 597 321 285, josef.hlavsa@vsb.cz*
[4] *Jiri Kratochvil, VSB-TU Ostrava, 17.listopadu 15, +420 596 994 476, jiri.kratochvil@vsb.cz*

Contact person

* *Marek Pagac, VSB-TU Ostrava, 17.listopadu 15, +420 597 321 285, marek.pagac@vsb.cz*