THE INFLUENCE OF THE LASER POWER ON THE UTILITY PROPERTIES OF THE SURFACE ROUGHNESS PARAMETER OF THE OVERHANGS DURING THE SLM PROCES

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Abstract

The subject of the paper is finding optimal setting of the laser power for the utility properties of the surface roughness parameter in the Additive technology by SLM method for differently large overhangs. The overhangs created on the sides, which are not supported by a supporting structure and are not designed in any way for printing by Additive technology. The samples were printed from stainless steel 316L (1.4404) under constant building parameters with change only of laser power. In total three laser power sizes were tested on differently large overhangs. The surface roughness parameters were measured and evaluated on the lower side of the overhang. The quality of the surface roughness parameter shows the suitability of overhangs in cases where it is not possible to add supporting construction. In conclusion, the most appropriate laser power was determined in relation to the size of the overhang and its surface roughness parameter.

Keywords: Laser power, SLM, overhang, angles, stainless steel

1. INTRODUCTION

Selective laser melting is a additive manufacturing process based on a layer-by-layer principle, that allows you to create relatively complex three-dimensional shapes from powder metal without the use of any tools. Due to the high energy density of the laser, materials such as nickel alloys, aluminum alloys, titanium, steel and cobalt-chromium alloys can be successfully printed. According to the Wohlers research [1], SLM technology, thanks to flexible input material, has a great potential for producing advanced cellular lattice structures, lightweight components and cooling channels. These products are widely used in the aviation, automotive and healthcare industries where they represent the future. Current conventional modeling methods will no longer restrict designers and thus opens up the possibility to freely think about component design. With the right choice of printing parameters, selective laser melting can be achieved components with the same or even better mechanical properties than conventional parts [2].

Selecting print parameters does not only affect the internal structure of the part but also its surface. One of the disadvantages of the SLM process lies in the need to create supporting structures that are necessary in creating overhangs larger than 45° and bridges. These constructions have the task of supporting the structure and thus preventing warping or collapse of the structure, which is often the case in the construction of internal channels. The second function is to conduct the heat produced by melting the laser into the substrate. Creating supports is negatively reflected in the production time and application of post-processing, as Calignano [3] states, minimizing the amount of support improves the efficiency of the process. In some cases, the volume of support material may be greater than the volume of the component itself. One way to eliminate the amount of support is to effectively orient the part in the building chamber in such a way that the overhang angle during the construction is in the horizontal position. Another option is to use the algorithm proposed by Allen and Dutta [4], where a candidate list is first created, which contains certain criteria according to which the optimal orientation on the substrate is chosen.

2. OVERHANGING

The Vandenbroucke and Kruth study [5] shows that the overhang is characterized by a surface roughness several times higher than that of other surfaces created in the SLM process. Yadroitsev et al. [6] defined three major problems that arise when creating an overhang. This is a Stairway Effect, Warp and Dross Formation.

2.1. Fabrication defects

The Stairway Effect is a known issue of 3D printing from the very beginning when additive methods based on layer-by-layer were born. This effect is formed from the individual laying of layers on top of each other, always with a certain length over the previous layer, that is, when forming overhangs. Determining the length of the portion that will be larger for the previous layer is the task of the slicer software, but this relation can be defined and calculated according to the formula determined by Hongyu et al. [7]

$$L_0 = \frac{h}{\tan(\gamma)} \qquad (1)$$

Where:

L_0 - length of overhang (µm)

h - layer height (µm)

γ - angle of overhang (°)

As can be seen from the formula (1), it is the dependence of the height of the layer height on the angle of magnitude between the horizontal plane and the tangent line to the given surface. It can be seen from the formula that by reducing the size of the layer *h*, the size of the overhanging portion L_o is reduced, however, the smaller the layer value, the longer the production time, it is also apparent that the same reduction effect also has the effect of increasing the slope angle *γ*. Unfortunately, the staircase effect cannot be completely eliminated, it can only be reduced. The graphical diagram of the parameters that determine the stairway effect is shown in **Figure 1**.

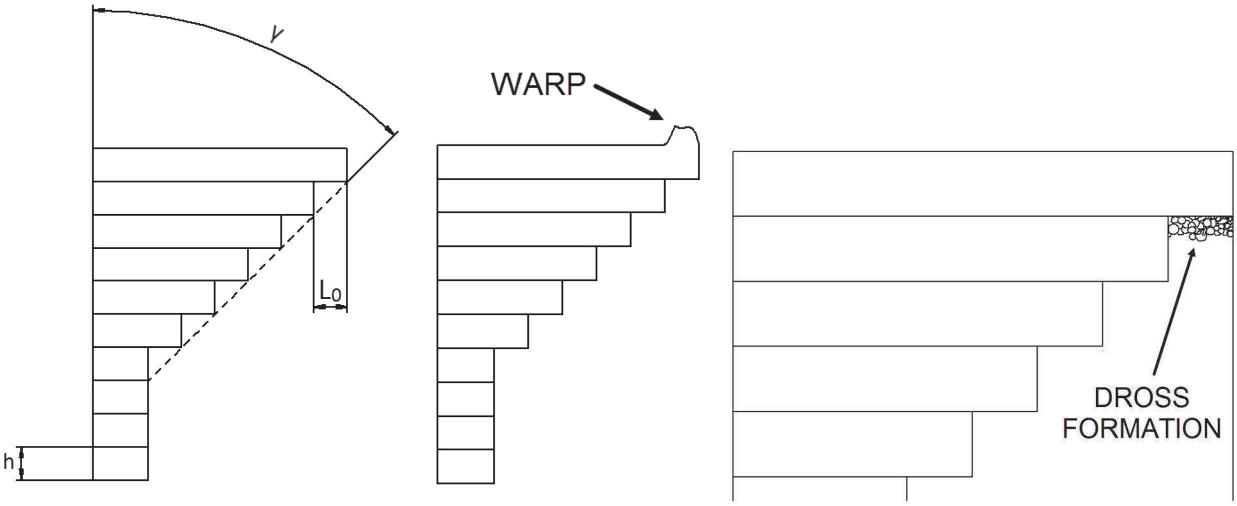


Figure 1 Staircase Effect, Warp, Dross Formation

Warping is a defect that has not yet been eliminated in the SLM process. The emergence of warp (**Figure 1**, middle) can be caused in two ways. The first reason for the occurrence is irreparable warp occurs at thermal stress due to rapid metal solidification, where the thermal stress exceeds the strength of the material and plastic deformation occurs. This phenomenon occurs on the upper layer, which lies below the powder metal and according to Zhao et al. [8], a bending angle towards the laser beam is produced, Zhao finds that thermal residual stress is centered on both edges of the scan path, and low scanning speeds can lead to high cooling rates, resulting in greater thermal residual stress. Zhang et al. [9] recommends that the substrate preheat temperature be adjusted and remelted to reduce it. Another option is to change the laser scanning strategy. The second reason for the emergence of warping when a part of the curl begins to overhang is the lack of support that does not support the previous layers.

Dross formation is considered the worst and most unpredictable defect that can occur in the SLM process. This defect results in increased of surface roughness and change in overhang geometry. Clijsters et al. [10] developed an in-situ quality control method for the laser and powder process interaction, which can monitor in real time the high-speed camera to create dross formation directly in the pool melt. However, it is difficult to understand the underlying mechanism of creating a dross defect in the overhang. Kovalev and Gurin [11] not only developed a threedimensional multivortex model for simulating two-phase thermohydrodynamic flow in a laser induced melt of a metal substrate but also found that melt fluid flow plays a significant role in the mechanisms of heat and mass redistribution. Dross formation occurs when the laser scans the already formed layer and the thermal conduction speed is too high, unlike when the laser scans the powder layer and the thermal conduction speed is much lower than the fixed layer. This often happens when an overhang is formed when the absorbed energy is higher and it results in the melt pool being enlarged and due to the action of gravitational and capillary forces it falls deeper into the powder see **Figure 1** on the right.

3. EXPERIMENTAL SETUP

For experimental testing, samples with overhangs with different angle angles were created. The purpose of the experiment was to determine and measure the surface roughness of these overhangs that were printed with different laser power usage. The printing was done on the Renishaw AM400, which has an additive SLM. The research was conducted on stainless steel 316L (1.4404) under constant construction parameters. All samples were produced in one building. The shape and location of the samples is shown in **Figure 2**. The powdered metal used has already been sieve several times, so it is necessary to take into account that the resulting roughness of the surface can also be affected by this fact. For the most accurate results, it would be necessary to use virgin powder, given the financial difficulty this is not possible and would not have a great benefit for the practice. Only down-face surface was measured. Altogether 25°, 35° and 45° angles were selected for testing assuming that the last angle of inclination will have the best roughness parameter values.

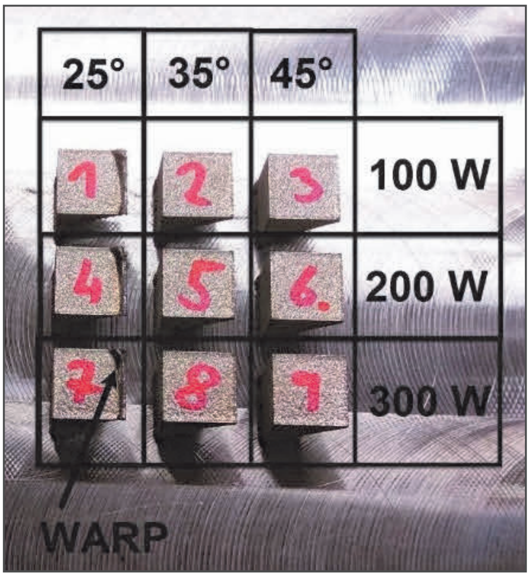
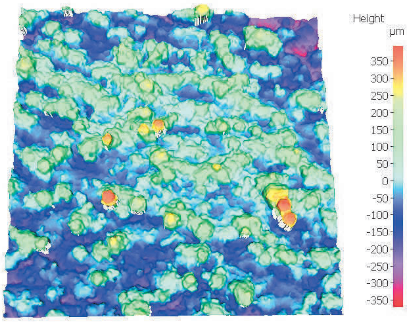
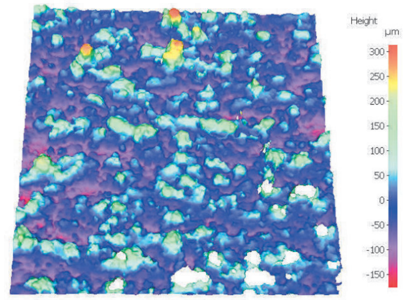
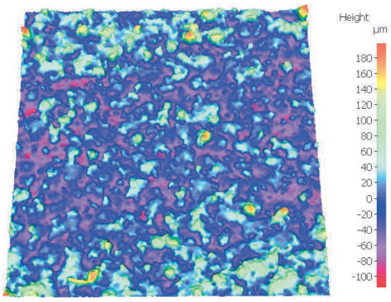
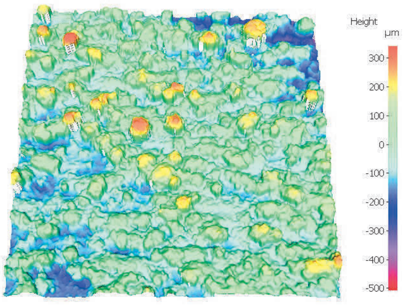
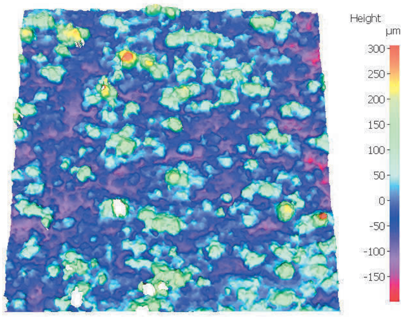
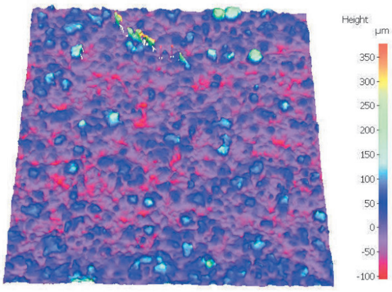
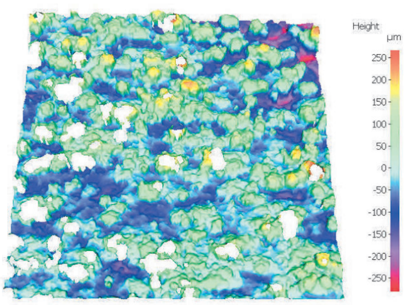
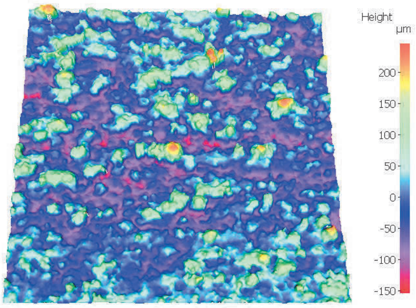
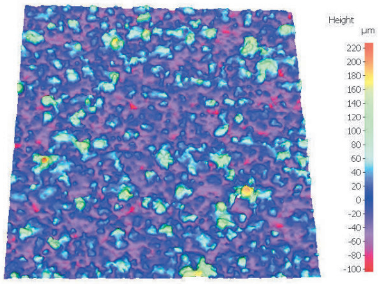


Figure 2 Layout of samples on the print plate

Table 1 Measured values

	γ = 25°					γ = 35°					γ = 45°				
P = 100 W															
	No.	R_a [µm]	R_z [µm]	S_a [µm]	S_v [µm]	No.	R_a [µm]	R_z [µm]	S_a [µm]	S_v [µm]	No.	R_a [µm]	R_z [µm]	S_a [µm]	S_v [µm]
	1	73	338	55	217	2	45	250	40	188	3	26	149	27	106
P = 200 W															
	No.	R_a [µm]	R_z [µm]	S_a [µm]	S_v [µm]	No.	R_a [µm]	R_z [µm]	S_a [µm]	S_v [µm]	No.	R_a [µm]	R_z [µm]	S_a [µm]	S_v [µm]
	4	65	314	55	193	5	47	258	39	146	6	31	193	28	97
P = 300 W															
	No.	R_a [µm]	R_z [µm]	S_a [µm]	S_v [µm]	No.	R_a [µm]	R_z [µm]	S_a [µm]	S_v [µm]	No.	R_a [µm]	R_z [µm]	S_a [µm]	S_v [µm]
	7	56	299	47	196	8	47	256	37	148	9	28	175	28	108

4. RESULTS

Table 1 summarizes all results. Visual inspection revealed the negative effect of warp on the upper surface of samples 1, 4 and 7, ie samples with the smallest angle of inclination and the largest length of the overhanging surface. For other samples, warp did not appear. The stairway effect, due to the low layer thickness (*h = 50 µm*), was not visually observed. Dross formation, on the other hand, according to theory, manifested itself in all samples and influenced surface roughness. Roughness measurements were carried out on the Alicona device and the 2D parameters were measured: R_a - mean arithmetic profile deviation, R_z - largest profile height and 3D parameters: S_a - mean arithmetic height, S_v - maximum depth of recess. The 3D surface parameters are defined by the standard ČSN EN ISO 25178-2 and allow quantitative assessment of the surface in all technically important directions, not only in the selected direction of the imaginary section through the surface, as is the case with the profile evaluation. Thanks to the profile rating, you can also specify the amount, layout and height of the individual points of contact between the two surfaces. Thus, the general texture and overall shape of the surface can be determined in the area evaluation. The basic advantage of 3D parameters is to reduce the number of basic parameter sets that have analogy in profile parameters. Instead of three sets of parameters for the unfiltered profile, roughness profile and waviness, the area is evaluated by one parameter for a given scale-scaled surface. E.g. three parameters (R_a, P_a, W_a) are used in the profile evaluation for the mean arithmetic deviation, while only the S_a parameter is used in the peer evaluation. The S-filter (Gauss filter, which removes very short spatial wavelength elements from the surface) was applied to the samples, and the so-called primary surface was measured.

Measurements brought interesting results. When observing a 25 ° angle of inclination, the roughness of the surface, as predicted, shows the worst of both the profile measurement and the area measurement. The performance of the laser has been positively influenced by the rule, the higher the performance, the better the surface, most likely due to the amount of energy needed to create a surface where the powder can better melt and create a smoother surface despite dross formation. Observing a 35° angle of inclination showed that the influence of laser power does not play a major role, and both profile and area parameters are still constant at different outputs. The most recent 45° angle projection has shown that for laser overlaying it is appropriate to set the laser output to 100 W where the best results and the worst roughness parameters have been achieved at 200 W laser power.

5. CONCLUSION

At present, it is a burning problem of additive metal production of overhanging, when the surface roughness is noticeably higher at an angle of less than 45°, and the geometric accuracy beyond tolerance. If the overhang has to be inevitably created, it is possible to construct the supporting structure under the overhang, but it means longer time for removal, and in post-processing it is another used powder, which can be reflected in the total cost of the component. The aim of the experiment was to determine the effect of laser performance on the utility properties of the surface roughness parameter of the overhangs without the use of a supporting structure, and this was done. Printing took place under standard conditions to build a SLM process only with a change in laser performance. In total, 9 samples were designed for measurement.

The following conclusions can be drawn from the tests performed on the Renishaw AM400:

1) Visual inspection of the upper surface of components showed that for samples with a 25° angle of inclination, warp is formed irrespective of the laser power used
2) Viewed all the sloping surfaces created look similar and the differences showed up when viewed under a microscope
3) Generally, assuming a 45° angle of inclination, it has the best values of both area and profiled roughness irrespective of the laser power used
4) The 200 W laser power has negatively influenced all angle inclinations, so it is not recommended to use the skew to create overhangs where it is important to have the smallest roughness parameter

The results obtained can help in designing the process parameters of the components where the overhangs have an angle of inclination of less than 45°. Some partial conclusions have been drawn from which instruction follows. For further investigation, it is proposed to extend the range of angular inclinations tested and perform multiple repetitions.

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