INFLUENCE OF BASIC PROCESS PARAMETERS ON MECHANICAL AND INTERNAL PROPERTIES OF 316L STEEL IN SLM PROCESS FOR RENISHAW AM400

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The paper deals with the study and experimental evaluation of the influence of process parameters determining the resulting mechanical properties of the components after additive production using the 1.4404 (316L) stainless steel SLM method. The determining process parameters that have been investigated are laser power, scanning speed and layer creation strategy. These parameters fundamentally affect the microstructure and macrostructure of components created by the SLM method, therefore, they have been subjected to closer examination. The results then determined the ideal set of parameters according to the assessment criteria - tensile test, porosity and roughness of the surface. Experiments were performed on the Renishaw AM400 and therefore the results and recommendations are directly related to this particular machine.

KEYWORDS

Process parameters, mechanical properties, SLM, additive manufacturing, porosity

1 INTRODUCTION

Unstoppable technical progress has created new production technologies. One of these production technologies is called additive manufacturing. The technology uses the layer-by-layer principle has been experiencing a huge boom in recent years and is increasingly finding its way into other industry sectors where it is looking for its place. A great promise for the future is the use of additive technology to create bionic structures that can replace or create completely new structures while adhering to specified mechanical properties, but with the advantage of less consumed material. For these reasons, it is necessary to fully understand the technology and to find out its weaknesses and strengths during the printing process itself. Observing all the parameters influencing the manufacturing process is impossible in a single article. Yadroitsev states in his book that there are over 100 parameters, but among the most important ones may be laser power, scanning speed, layer thickness, hatching distance, scan strategy, temperature of bed, morphology of powder and used atmosphere in chamber [Yadroitsev 2009].

The objective of the article is to investigate the influence of the basic procedural parameters that determine the resulting mechanical properties. The authors have set out to investigate a certain range of process parameters (laser scanning speed, laser power and layer creation strategy) for 1.4404 (316L) stainless steel material on the Renishaw AM400 using the SLM method (Selective Laser Melting). The research of this type of steel in the 3D printing process has already been dealt with by some scientists. The team around Kamath [Kamath 2014] examined the density of samples at different laser outputs and scanning speeds, but did not deal with scanning strategy. Another author, Yasa, deals with the change in laser power (85-105 W) and the layer thickness change (20-60 µm) at constant scanning speed (300 mm/s), reaching a relative density of 99.2% [Yasa 2009]. A similar contribution by A. Spierings examines the relative density with scanning speed change (300-800 mm/s) at a constant laser power (104 W), its results showing a relative density of 99.5% [Spierings 2009]. The same results were obtained by Kruth with a 105 watts laser power setting, a scanning speed of 380 mm/s and with a layer thickness variation (20-40 µm) [Kruth 2010]. A similar experiment was performed by Liu [Liu 2011]. All of these authors, however, did not include scanning strategy in their DOE and applied lower laser power and scanning speeds.

It is known from Li´s study that increasing laser power or reducing scanning speeds leads to a higher energy density and thus to the complete melting and joining of individual particles. Increasing energy density means a larger melt pool and lower porosity [Li 2009]. However, there is a limit where excessive increase in energy density leads to evaporation of the metallic powder and changes to plasma, resulting in the formation of voids which are the cause of porosity. This phenomenon is also known as keyhole, for a better idea it can be imagined that the laser "burns" through multiple layers and leaves a hole in which a crack may occur [Rai 2007]. Keyholes are well known and described in the welding process. Conversely, low energy density results in dust particles not being sintered and can result in the production of an incomplete component. It follows that it is necessary to move within such an energy density range so that the particles are sufficiently sintered, but no keyhole are created.

When manufacturing more complicated structures in the SLM process, it is necessary to consider some fabrication defects that may occur. The most well-known defect is the staircase effect that arises when laying individual layers on each other, always with a certain length over the previous layer, that is, when creating overhangs. For this overhang, the characteristic surface roughness is several times higher than for other surfaces [Vandenbroucke 2007]. It can be partially eliminated by inserting a supporting structure. Staircase effect is directly associated with the dross formation defect, which is considered the worst and most unpredictable defect, its resulting effect is increased surface roughness and change of the overhang geometry [Kovalev 2014]. The last defect which can often be encountered is warping, it is due to thermal stress caused by fast metal curing, where the thermal stress exceeds the strength of the material and a plastic deformation occurs. This phenomenon occurs on the upper layer, which lies below the powder metal and according to Zhao et al., a bending angle towards the laser beam is formed, Zhao found that the thermal residual stress concentrates on both edges of the scan path, and low scanning speed can lead to high cooling rates, thus causing greater thermal residual stress [Zhao 2009].

2 EXPERIMENTAL METHODOLOGY

To determine the mechanical properties and the porosity of the 316L material, higher laser outputs and scanning speeds were varied, and layer formation strategies (see Tab. 1) were included. The experiment followed the Taguchi (fractional factorial design) [Atkinson 2007], Orthogonal Array Design L16 (4 ** 2 2 ** 1) with 3 factors – Power, Speed and Pattern, 4 Levels and 3 responses – Strength, Strain and Porosity. Altogether, 16 combinations were selected to create samples that were tested. The other process parameters hatch distance (0.11 mm), spot diameter (~70 µm), layer thickness (50 µm) were constant throughout the printing period. Substrate preheat was not applied. Since the Renishaw AM400 uses a pulsed laser, an expression time calculation based on Equation 1 was required to determine the effective scanning speed [Carter 2018].

$$v = \frac{60}{ET+12} \cdot 10^3 \qquad (1)$$

Where :
v – effective scanning speed [mm/s]
ET – exposure time [µs]

Renishaw recommends an ideal parameter combination of 200 W and 80 µs (650 mm/s), which corresponds to sample number 2. The assumption, therefore, is that this sample should achieve the best properties. Our experiment focused on the values above this ideal.

Sample Number	Set Power [W]*	Speed [mm/s]	Exposure Time [µs]	Scan Strategy
1	200	400	138	Meander
2	200	650	80	Meander
3	200	800	63	Chessboard
4	200	1200	38	Chessboard
5	250	400	138	Meander
6	250	650	80	Meander
7	250	800	63	Chessboard
8	250	1200	38	Chessboard
9	300	400	138	Chessboard
10	300	650	80	Chessboard
11	300	800	63	Meander
12	300	1200	38	Meander
13	350	400	138	Chessboard
14	350	650	80	Chessboard
15	350	800	63	Meander
16	350	1200	38	Meander

*according to [Rai 2007], the laser power setting is about 10 % less than the real power

Table 1. Process parameter combination

The chosen strategies Meander and Chessboard (see Fig. 1) have different uses and benefits. The most common strategy Meander works on the principle of scanning and gradual alternation of layers with mutual orientation and on rotating the new layer over the previous layer by an angle of 67°, thanks to which it reaches the same direction again after the 180th layer. This method reduces the occurrence of porosity and is recommended for components with smaller XY cross sections. It's fast and efficient. The disadvantage is that this strategy involves inconsistent heat distribution in each layer. The Chessboard strategy works on the principle of dividing individual fields (like a chessboard) into a size of ~5 mm^2, which are rotated on each other by 90°. To avoid porosity, field offset is used in this strategy to overlap the fields. The advantage of this strategy is that due to the division into individual fields the heat is not very high at one point, but the strategy is significantly slower than the others [Renishaw 2016]. For the tensile test were made samples in shape of classic tensile bars.

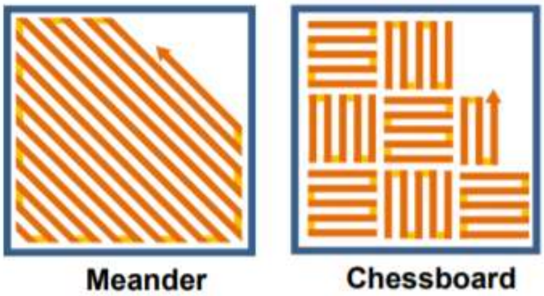


Figure 1. Used Scanning Strategies [Renishaw 2016]

3 RESULTS AND DISCUSSION

3.1 Meachanical properties

The tensile test, which is governed by the ČSN EN ISO 6892-1 standard, was chosen to evaluate the mechanical properties. Tests were carried out on the machine Hegewald & Peschke Inspekt 100 kN with capacity of the sensor 100 kN and using mechanical extensometer Hegewald & Peschke MFX 200 mm for evaluate strains. The authors' previous study [Pagac 2017] shows that there is no need to have several samples for static evaluation, but only one is sufficient, since the variance of values is around 5 % and the results can be considered as meaningful. The tensile tests showed that the best yield stress and strength values were achieved by sample number 2 as expected. On the other hand, the worst value was achieved by sample number 4 (see Tab. 2), where the combination of the highest speed and the smallest laser power is not convenient.

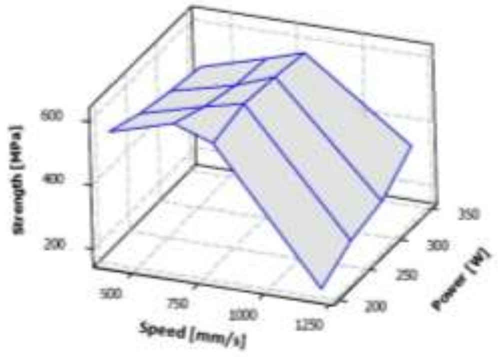
Sample Number	Yield Stress [MPa]	Strengh [MPa]	Stress [%]	Elasticity Modulus [GPa]
2	466	614	30.5	204
4	151	171	1	67

Table 2. The Best and the worst selected mechanical properties

From the Taguchi DOE results, a certain proportionality can be observed, where a higher scanning speed means worse mechanical properties (strength and elongation), this may be due to insufficient sintering of powder grains during rapid laser spot shift. This is illustrated in Tab. 3 Response Table for Strength Means according to Taguchi analysis, where DELTA is the difference between the highest and lowest average response values for each factor, and Rank indicates the relative effect of each factor on the response, where 1 has the largest effect. Tab. 3 shows that the greatest impact on strength has the scanning speed then the scanning strategy and the least impact the laser power. In Graph 1, the dependence of the scanning speed on the yield strength and the relative elongation in Graph 3 can be observed.

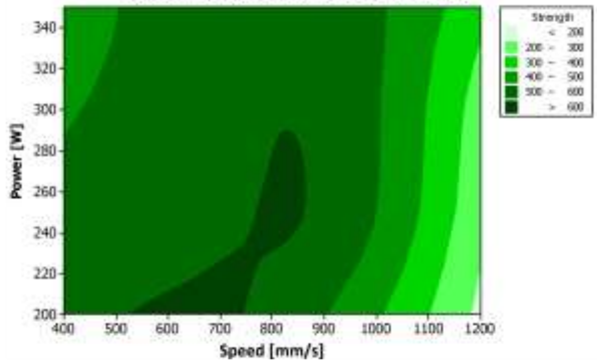
Level	Power [W]	Speed [mm/s]	Strategy
1	479.3	511.6	502.1
2	481.3	567.8	452.9
3	471.8	585.5	
4	477.5	245.0	
Delta	9.5	340.5	49.2
Rank	3	1	2

Table 3. Response Table for Strenght Means



Graph 1. Surface plot of influence of speed and power on strength

The following Graph 2 shows the prediction for the most suitable combination of parameters to achieve the best yield strength. For a more accurate prediction, it would be necessary to perform a fully factorial experiment where all possible combinations would be included. This would, however, contradict Mr. Taguchi's idea and the results would not have to be different at all, it would only be desirable to produce a lot more samples.

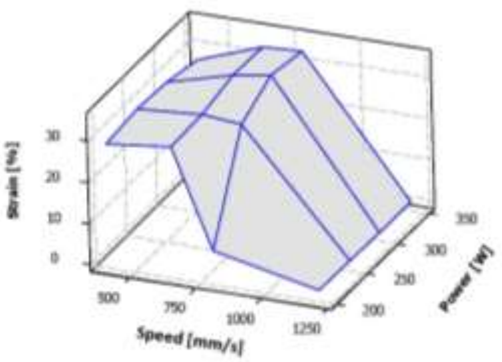


Graph 2. Contour plot of prediction of parameters for strength

The sequence of parameters influencing elongation is slightly different (see Tab. 4) than strength. The scanning strategy has the least impact.

Level	Power [W]	Speed [mm/s]	Strategy
1	16.635	28.4875	23.48
2	22.8425	31.7775	20.0063
3	24.2475	26.0450	
4	23.2475	0.6625	
Delta	7.6125	31.1150	3.4737
Rank	2	1	3

Table 4. Response Table for Strain Means



Graph 3. Surface plot of influence of speed and power on strain

3.2 Porosity evaluation

To evaluate the porosity, were made special samples (10 x 10 x 40 mm) which were cut parallel to the layering direction in the middle of sample then were put into resin and polished, that they could be further examined under the digital microscope (see Fig. 2). As with the tensile test, the scanning speed had the greatest impact on the overall porosity results (see Tab. 6). Tab. 5 shows the measured values of porosity for the best result and the worst result.

No. Sample	Porosity [%]	Density [%]
14	0.04	99.96
8	24.48	75.52

Table 5. Values of porosity and density

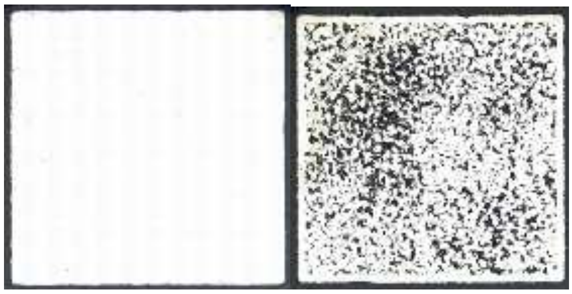
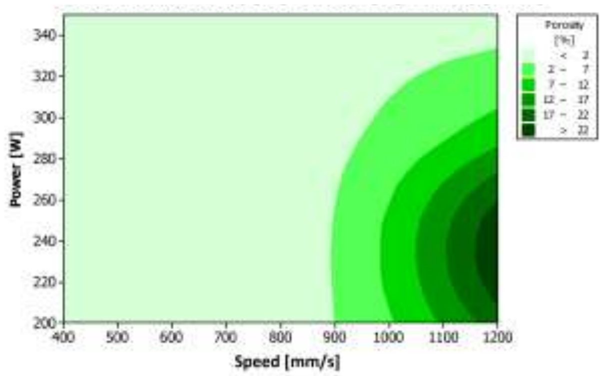


Figure 2. Porosity – left is sample 14 and right is sample 8

Level	Power [W]	Speed [mm/s]	Strategy
1	4.9892	0.2027	1.1135
2	6.1742	0.0457	5.6214
3	2.0377	0.1119	
4	0.2688	13.1095	
Delta	5.9053	13.0638	4.5079
Rank	2	1	3

Table 6. Response Table for Porosity Means

According to Taguchi's analysis, the largest influence on porosity has the scanning speed, the second biggest influencing factor is laser power, and the least influence on the occurrence of porosity has the scanning strategy. The following graph 4 shows the prediction based on Taguchi´s analysis



Graph 4. Contour plot of prediction of parameters for porosity

3.3 Evaluation of surface roughness parameter

The R_a parameter has been selected to evaluate the surface roughness because of the complex average roughness value that varies depending on the orientation of the print chamber. Measurement was performed with a contact profilometer, always at five locations on all sides of the sample. The measured sample had the dimensions of 10 x 10 x 40 mm and measurements were made only in the XZ axis. Tab. 7 shows the best and worst measured values of the roughness parameter R_a, the combined uncertainty was also calculated to ensure statistical correctness. It is important to keep in mind that the scanning strategy contains boundary vectors and the results may be slightly distorted due to them, however the core parameters have influenced it.

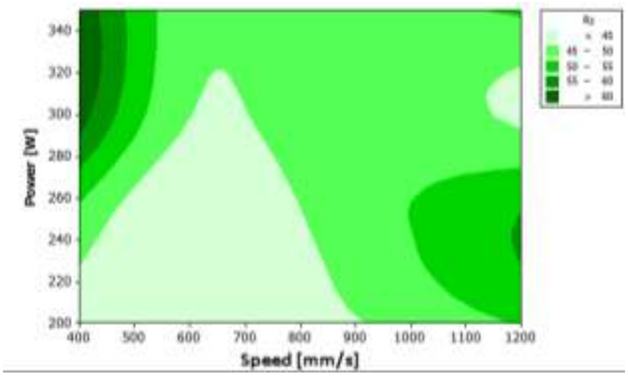
No. Sample	R_a [µm]	R_z [µm]
2	(7.69 ± 1.08)	(40.49 ± 10.15)
13	(12.02 ± 2.64)	(63.76 ± 12.89)

Table 7. The Best and the worst measured surface roughness

In addition, Taguchi´s analysis and predictions (see Graph 5) for ideal parameters were performed as in previous results. Tab. 8 shows the influencing factors where the scanning speed has the greatest and the scanning strategy the smallest impact.

Level	Power [W]	Speed [mm/s]	Strategy
1	8.219	10.163	8.356
2	8.868	7.979	9.520
3	9.000	8.246	
4	9.664	9.363	
Delta	1.446	2.184	1.164
Rank	2	1	3

Table 8. Response Table for Roughness Means



Graph 5. Contour plot of prediction of parameters for Roughness

4 CONCLUSION

Additive manufacturing allows the manufacture of complexly shaped components that would not be manufactured in a conventional manner or would require a lot of effort. The growing demand for more complex and refined components in the labor market is evidence that it is reasonable to further develop additive technology and come up with new ideas. The main potential of this technology, however, remains the production of bionic structures, lightweight components and the creation of lattice structures. The most widely used method of metal printing is SLM, which is based on the local melting of powdered metal particles by the laser and the individual layering of these parts on top of each other.

The article has focused on the research of the influence of basic process parameters that determine the resulting mechanical properties, the porosity and roughness of the surface of components. The SLM method was used for the experiment, and the material under study became AISI 316L stainless steel. Taguchi´s analysis was selected to evaluate the measured data. This analysis is based on certain algorithm which proposed 16 samples to determine the most important parameter of influence. The analysis also allows the prediction of ideal parameters. The individual results can be summarized as follows:

- The most important parameter determining the strength of the material is scanning speed, then scanning strategy and ultimately laser power. With regard to the relative elongation, the order of significance in elongation at break is: scanning speed, laser power, and scanning strategy.
- The results of porosity have shown a similar dependence, with the most important influence being scanning speed, laser power and ultimately scanning strategy.
- The last chosen assessment criterion was surface roughness. Once again, the scanning speed has played the biggest role here, then laser power, and the scanning strategy has the smallest impact.
- It was confirmed that the parameters recommended by the Renishaw machine manufacturer really have an ideal setting.

The results obtained, as mentioned above, are based on 16 samples. Further research will address combinations with a smaller range of selected parameters.

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