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Surface quality in selective laser melting of metal powders

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ABSTRACT

Purpose: The main objective of this study was performed to determine the effect of selective laser sintering parameters such as power output, laser distance between the point's sintered metal powder during additive manufacturing as well as the orientation of the model relative to the laser beam and substrate on the surface quality of the model.

Design/methodology/approach: In research the device for the selective laser sintering of metal powders Renishaw AM 125 machine was used. On the basis of an experiment plan, 24 models sample was made, which were tested to determine the surface roughness and thus describe an influence of process parameters on the model and the orientation of the surface quality. Research model was developed and manufactured with the Autofab software, and then imported into the machine, which, based on the plan of the experiment carry out models.

Findings: On the basis of studies it was found that the surface quality models using 316L stainless steel with the assumed parameters of the experiment depends on the process parameters used during the selective laser sintering method as well as the orientation of formed walls of the model relative to the substrate and thus the laser beam.

Research limitations/implications: Studies were carried out to determine the effects of only two parameters on the quality of surface. In the following, it is planned to perform metallographic studies to determine the effect of process parameters on the mechanical properties and the structure executed models. In the future planned are the investigations on the influence of laser parameters such as speed, focus offset, exposure time, diameter of laser beam and hatch parameters such as hatch type, distance and hatch distance on the quality of the elements structure and mechanical properties as well.

Practical implications: Making models of metallic powders by selective laser sintering allows quickly designing and building functional models and equipment, quick verification of the project without opportunity to incur significant costs to the complex and expensive tools.

Originality/value: While SLM can be used as a rapid prototyping process, it is extremely useful as a direct manufacturing process able to produce extremely complex parts with different surface quality which would be impossible to produce by other means. The ability to produce almost any 3D shape gives engineers complete design freedom.

Keywords: Powder metallurgy; Rapid prototyping; Additive manufacturing

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

The rapid prototyping method was first introduced to the market in 1987, after it was developed with the help of stereo lithography. Today this method, it is also known as solid freeform fabrication, 3-dimensional printing, freeform fabrication and additive fabrication. The manufacturing process of rapid prototyping can produce automatic construction of physical models with 3-dimensional printers, stereo-lithography machines and laser sintering and melting systems. Rapid prototyping is a computer program that constructs three-dimensional models of work derived from a Computer Aided design (CAD) drawing. It is used to quickly and easily turn product designs into physical samples [1-6].

Selective laser sintering SLM is a method of additive manufacturing production models, prototypes and tools, involving the merging of layers of powder using a laser beam. The whole process is controlled by software installed on a specialized computer workstation. In this method, a transition layer of the input material in powder form to a liquid state and return to the solid state. Starting the process consists of spreading a thin layer of powder on the table about the Z-axis adjustable position. This layer serves as the substrate for the created model [7-10].

The laser beam is carried out on the surface of the powder in accordance with the previously entered and properly configured information on the successive layers of the cross-sectional image of the spatial object. The choice of appropriate parameters of the laser beam allows the sintered in specific areas of the powder particles. Because the last layer is fused with the previously deposited layer, is obtained a uniform structure of the material. Powder surrounding the model takes the role of supporting the model performed in layers. Then the working platform of powder reduced by a predetermined height and another thin layer of powder is spread and particle bonding occurs again and the process is repeated until a whole model is created (Fig. 1). At the end of the sintering process and decreasing the temperature of the model, created part is removed from the chamber and carried out to appropriate treatment finishing.

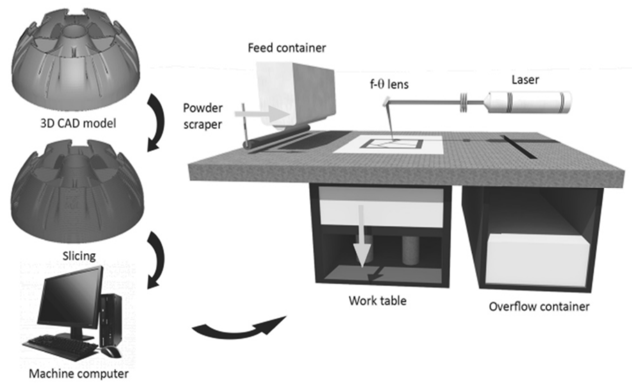


Fig. 1. A schematic of the SLS method

In this way the finished parts can be formed, and the entire assemblies of elements, including physically interconnected. An important aspect is the fact that using the SLS method produced can have a density almost equal to the density elements of solid material (99%), resulting in that the strength of these elements is almost the same as the parts made by conventional methods. The advantage of this technology is made possible further processing of the metal structure and the possibility of combining it with other materials, eg ceramics [11-14].

An example of the possibility to exercise models with this technique is shown in Figure 2. Figures presents spatial models of keyring bottle opener before removing from the working substrate and before finishing, completely made by SLS method. Implementation of such a model by traditional methods is very difficult or almost impossible.

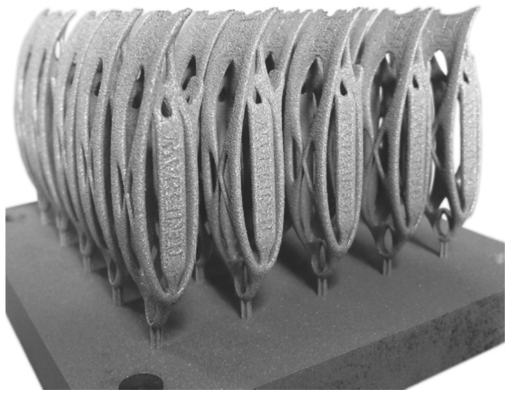


Fig. 2. Bottle opener keyring models on the substrate made by SLS method

Selective laser sintering is a thermo-physical complex process, which is dependent on the material parameters of the laser and the environment work (Table 1). Density of manufactured items, related to the laser power, scanning speed, the distance between consecutive paths sintering and the thickness of the layer is expressed by the relation:

$$E = \frac{P}{V \cdot S \cdot t} \tag{1}$$

where:
E - energy density, J/mm^3,
P - laser power, J/s,
V - scan speed, mm/s,
S - distance sintering paths, mm,
t - thickness of the layer, mm.

The number of the fabrication technology of the incremental layer-by-layer causes the SLM process is very complicated which requires a high engagement and in understanding the phenomena connected with the formation geometry. Presented in Table 1 SLS technology parameters affect the surface roughness, relative density, mechanical properties, or structure [1,6,8,9,13].

SLS technology gives the possibility of producing powder metal components with a wide range of grain size. Commercially used powders have a grain size from 0.005 (0.015) to 0.1 mm.

The quality of manufactured components is not comparable to other methods. In created model there are no defects such as cavity or gas inclusions because the whole process can be carried out at reduced pressure or in protective atmosphere that accompanies the elements produced by precision casting. The lack of these drawbacks is related to the fact that the SLS technique does not come into contact alloy powder material i.e. outer crucible casting or gypsum. Solidification of the alloy, the moment when there are defects in cavity takes place in such a small part of the sintered, that the shrinkage cavity does not occur in reality [15-19].

Table 1.
Process parameters of SLM, divided into material, laser, scan andenvironmental parameters

Material	Laser	Scan	Environment
composition	mode*	scan speed*	preheating*
powder density	wave length	hatching space*	pressure*
morphology	power*	layer thickness*	gas type*
diameter of grains	frequency*	scan strategy*	O_2 level*
distribution	pulse width*	scan sectors*	
thermal properties	offset*	pulse distance*	
flow properties	spot size	scaling factors*	

* - studied parameters to reach high precision (material parameters and some laser parameters are not varied due to machine dependency)

The quality of the manufactured parts is one of the challenges of additive manufacturing (AM). Requirements for process repeatability and manufacturing standards for AM have considerably increased in the recent years. Principal process parameters in SLS are laser power, wavelength, spot size diameter, scanning speed, hatch distance, powder layer thickness. Material-based input parameters are powder granulomorphometry, chemical composition, thermal, optical, metallurgical, mechanical and rheological characteristics. It is important to establish links between the principal SLM parameters and surface morphology. The purpose of this study is to analyse the influence of the power output of laser, point distance between the laser beam and orientation of the model on quality of the skin layer produced by SLM from metal powders.

2. Experimental procedure and materials

Experiments were carried out on SLS machine type AM 125 (Renishaw). The source of radiation was YFL continuous wave Ytterbium fibre laser with a wavelength of 1070 nm. The main characteristics of AM 125 machine are as follows: the maximum laser power is 200 W in continuous mode; the maximum laser scanning speed is up to 2000 mm/s; laser beam diameter 35 µm diameter at powder surface and layer thickness 20 - 100 µm. By means of a stepper motor the build platform can be moved with a resolution of 2 µm. The process chamber provides a closed environment filled by nitrogen as a protective gas.

In experiment was used a powder of stainless steel 316L supplied by Renishaw Company with the grain size in range 15-45 µm. This alloy is an austenitic nickel-chromium steels which are widely used in chemical, pharmaceutical, petrochemical, energy and pollution control industries. Chemical composition of the powder used in this study is presented in Table 2.

On the basis of an experimental plan, in which the variables were the output power of the laser and point distance (Table 3) 24 sample models was performed, which were then tested to determine the roughness of the influence of process parameters on the model and the orientation of the surface quality. Models as shown in Figure 3 consisted of two walls of which one of them is perpendicular to the substrate and the other one is directed at an angle of 60 degree relative to the substrate.

Table 2.
Chemical composition (wt. %) of 316L powder

C	Si	Mn	P	S	Cr	Ni	Mo	Fe
0.024	0.51	1.25	0.024	0.009	16.3	10.1	2.11	bal

The measurements of the roughness of the inner and outer surfaces samples were carried out on the profilographometer Sutronic 25 of Tylor-Hubson Company. It was assumed the measurements length was 1.25 mm and measurement accuracy was ±0.01 µm. The parameter R_a acc. the Standard PN-EN ISO 4287:1999 was assumed as the quantity describing the roughness. It was carried out 5 measurements on each of the investigated samples on each side and it was determined the average, standard deviation and confidence interval, assuming the confidence factor at $1-\alpha=0.95$.

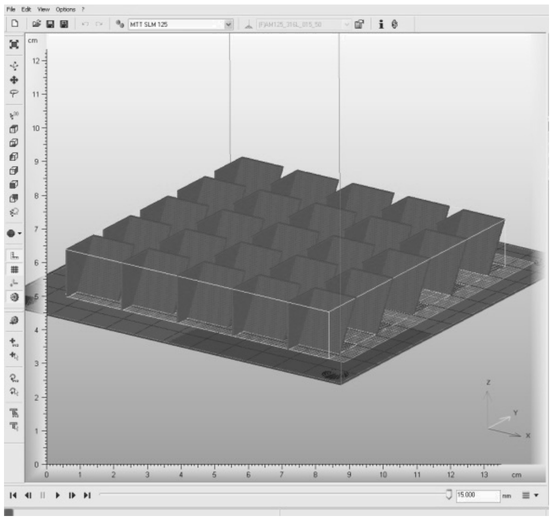


Fig. 3. Visualization in Autofab program of the working platform of the models placed to perform

The surface topography was observed on the scanning electron microscopy Supra 35 of Zeiss Company. To obtain the images of investigated samples, the detection of secondary electrons (SE) was applied, with the accelerating voltage 20 kV.

The qualitative and quantitative analysis of the chemical composition on the surface and microareas of the investigated samples was carried out using the X-ray energy dispersive spectroscopy (EDS) with the application of the spectrometer EDS LINK ISIS of the Oxford Company being a component of the electron microscope Zeiss Supra 35. The research was carried out with the accelerating voltage of 20kV.

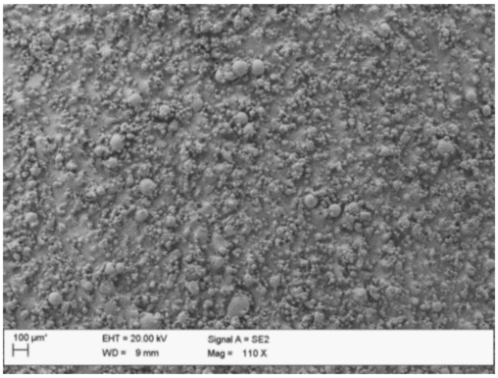
Table 3.
Matrix of experimental data (**bolded** is not included in the publication)

	Point distance 10-50 µm				
Power output 200-100 W	200/10	200/20	200/30	200/40	200/50
	175/10	175/20	175/30	175/40	175/50
	150/10	150/20	**150/30**	150/40	150/50
	125/10	125/20	125/30	125/40	125/50
	100/10	100/20	100/30	100/40	100/50

3. Results and discussion

In order to determine the relationship between the applied technological parameters and the model orientation relative to the incident beam and the quality of the surface structure of the test performed with the use of scanning electron microscopy and chemical composition using EDS method, the results of which are shown in Figs. 4 and 5.

a)



b)

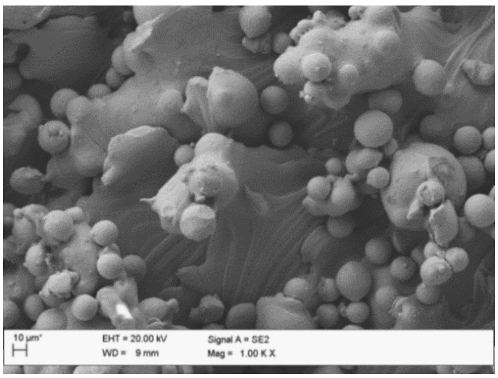


Fig. 4. Representative scanning electron microscope micrograph of the surface topography constructed models by AM125: a) mag. 110x, b) mag. 1000x

As a result of these studies it was found that all the analyzed surfaces models are characterized by a marked heterogeneity associated with the presence in the structure of the surface of the microparticles in the form of a number of drops of the powder particles as well as a batch of spherical shape, which does not completely sintered and only fixed to the substrate as a result of too short time between the implementation of the model walls and applying another thin layer of powder 316L stainless steel. Also was observed solidified spherically shaped particles as well as agglomerates formed from several combined microparticles (Fig 4). It was found some hollows formed probably when the sintered particles powder break off after the selective laser sintering process has been completed.

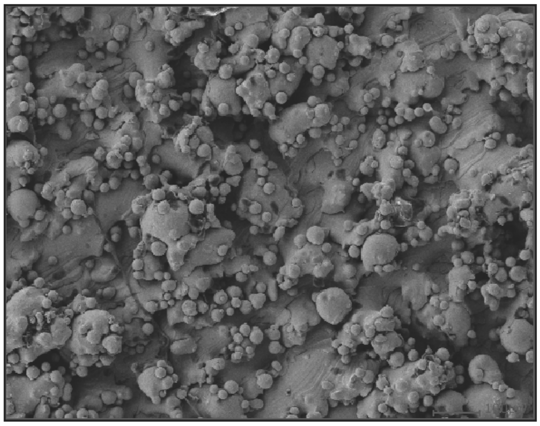


Fig. 5. Surface topography of representative model carried out by AM125 machine

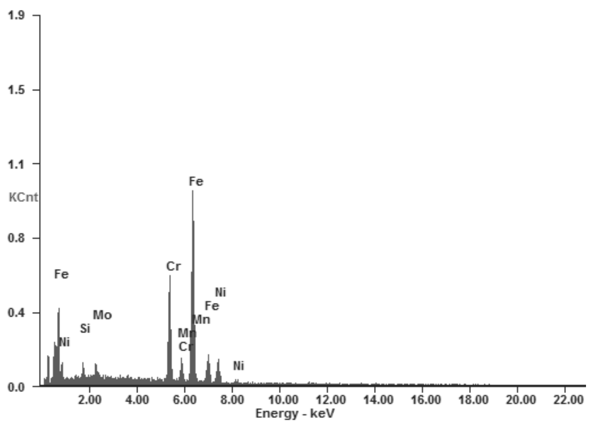


Fig. 6. X-ray energy dispersive plot of the whole area presented in Fig. 5

As a result of the degradation of the surface made of the elements and X-ray quantitative microanalysis, taken using a spectrometer energy dispersed X-ray EDS using the secondary electron, confirmed the presence of the main elements in the analyzed 316L stainless steel (Table 4).

In effect of the quantitative X-ray microanalysis was obtained information about the elements present in the selected microareas of the investigated models, and in effect of the quantitative analysis was obtained information about mass and atomic concentration of particular elements (Table 4).

Table 4.
Chemical composition analysis of whole area presented in Fig. 5

Element	The mass concentration of main elements, %	
	weight %	atomic %
Si	1.7	3.33
Mo	2.63	1.51
Cr	20.05	21.19
Mn	2.56	2.56
Fe	62.43	61.45
Ni	10.63	9.95

For technical reasons, in calculations not included information about samples made of laser power output 150 W and point distance 30 μm. Authors would like to noted that the measuring errors occurred during roughness measurements did not exceed 5%. The different surface quality can be observed by the roughness measure, as shown in Figs. 6 and 7. The surface roughness of the models orientated to the substrate at an angle of 60 degrees is obviously lower than that surface of the models orientated perpendicular to the substrate. Thus, it can be considered that the deep holes and adherent semi-sintered particles on the surface strongly increase the surface roughness and decrease the dimensional accuracy.

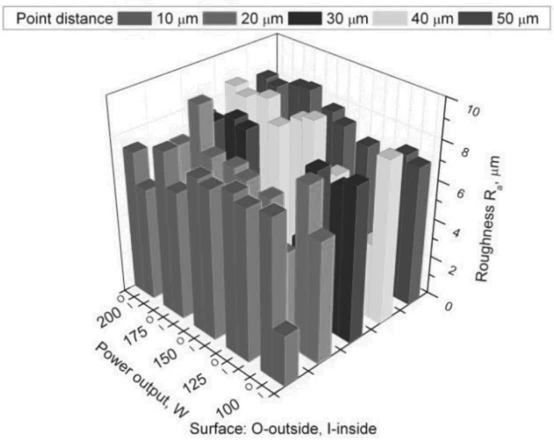


Fig. 7. Influence of the laser power output and point distance of laser beam on the roughness of the models orientated to the substrate at an angle of 60 degrees

As a result of roughness, there was no significant effect of point distance and laser power output on the value of surface roughness. The only differences between surface roughness and the effects of these parameters relate to internal and external walls the same oriented. Measurement of roughness exterior and interior walls showed significant differences in surface roughness due to changes in the laser power output and point distance. These differences in some cases are approximately 70%. For example (Fig. 7), the model made ÃÚ laser power output of 100 W and point distance 10 μm, the roughness of the inner wall was about 2.57 μm and for the same model with the same set parameters the outer wall roughness was about 7.83 μm. Analogous situation was observed for samples made by laser power output 125 W and a point distance of 50 μm. Roughness of the inner wall was about 2.45 μm and for the outer wall roughness was about 7.05 μm. In most other cases, the models that are oriented to the substrate at an angle of 60 degrees was found that the roughness of inner surface is about 15-20% less relative to the outer wall.

The lowest value of roughness the surfaces oriented at an angle of 60 degrees relative to the substrate was noted for the inner wall of the model performed by laser power output 125 W and the point distance 50 μm was 2.45 μm. The highest value noted for the roughness of the outer wall of the model made by laser power output 175 W and point distance 20 μm where the value of this parameter was 9.1 μm.

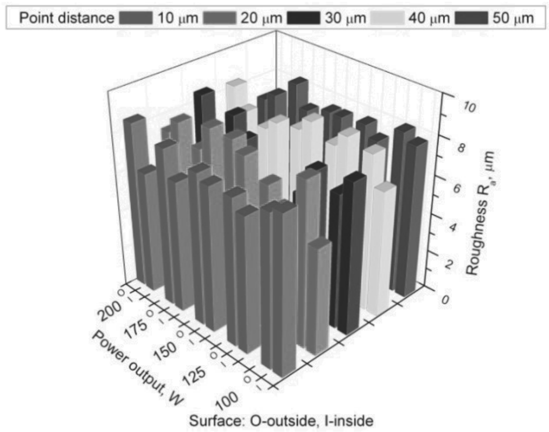


Fig. 8. Influence of the laser power output and point distance of laser beam on the roughness of the models orientated perpendicular to the substrate

For samples with walls oriented perpendicular (Fig. 8) to the substrate was found the similar correlations as for models oriented at an angle of 60 degrees, but the difference between the roughness of the inner wall and the outer is slightly less and is approximately 10%, and in some cases is within the limit of measurement error which indicates a steady the performance and reproducibility of the ongoing process. In some cases, the roughness measurement is within the limit of measurement error which indicates evenly performance and repeatability of the current process. The lowest value for the surface roughness oriented perpendicular to the substrate was observed for the inner wall made by laser power output of 100 W and the distance point 20 μm was 5.49, and the highest value noted for the roughness of the outer wall made by laser power output of 150 W and a point distance of 20 μm where the value of this parameter was 8.59 μm.

4. Conclusions

Completed research aimed at selecting the optimal parameters for performance models in order to obtain the smallest possible surface roughness. The study included the following parameters affect the performance quality i.e. laser power, laser distance between the points sintered metal powder during selective laser sintering process as well as the orientation of the model relative to the laser beam and substrate.

On the basis of studies it was found that the surface quality models using 316L stainless steel with the assumed parameters of the experiment depends on the process parameters used during the selective laser sintering method as well as the orientation of formed walls of the model relative to the substrate and thus the laser beam. For models made at an angle of 60 degrees relative to the substrate, the difference between the roughness of the outer and inner wall is approximately up to 70%. It is recommended to reduce the roughness of the surface model and thus improving the accuracy of its production to be positioned so that the largest possible surface area to perform was at an angle of 30% relative to the laser beam.

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