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Influence of selected parameters of Selective Laser Sintering process on properties of sintered materials

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ABSTRACT

Purpose: Presented researches aimed at determining the influence of parameters of Selective Laser Sintering (SLS), such as: laser power, point distance, scanning speed and exposure time on the density and compression strength of sintered material.

Design/methodology/approach: Researches were performed using EOS 250XT (with maximum laser power of 250 W) and Renishaw AM 250 (with maximum laser power of 400W) systems for additive manufacturing. Investigated material was EOS - DirectSteel H20. There was prepared plan of the experiment incorporating above mentioned parameters of the sintering process. According to the DOE, samples for 25 sets of parameters were built, and later on investigated in order to measure and observe their densities and compression strength.

Findings: Results of the performed studies enabled to work out the basis of the methodology for finding and optimizing parameters of the SLS process depending on the optimization criteria (i.e. physic-mechanical properties of the sample, sintering time, quality of the sintered surface). Basing on the knowledge gained during performed investigations, it can be stated that the sintering technologies supplied by the manufacturers of additive manufacturing systems can be significantly improved by modifying selected parameters.

Practical implications: As the additive manufacturing allows to produce almost any shape, without limits existing in case of subtractive machining methods, it might be applied in the tooling industry for manufacturing moulds for injection moulding. Results of performed studies will find its application in making moulds with conformal cooling channels of durability comparable with solid / base materials.

Originality/value: Selective Laser Sintering and Selective Laser Melting processes the additive manufacturing methods, are booming with its possible application fields, however it is still limited due to the main limitations of the process concerning durability and strength of sintered elements. The paper presents approach and test methodology enabling relatively simple and low cost (due to not large number of samples) optimization of SLS process enabling reaching properties of sintered elements comparable with those built of solid materials.

Keywords: Additive manufacturing; Process optimization; Selective Laser Sintering/Melting

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1. Introduction

Additive manufacturing methods are among the technologies which are being the most intensively developed in recent years. The most popular and available technologies concern 3D printing using polymers and plastics. Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) are among additive manufacturing technologies enabling building components from metallic powders. Invention of the powder sintering technique is dated back to 1979, when it was developed and patented by R.F. Housholder [1]. In his patent application, Housholder described for the first time the idea of sintering powders using moving (on powder surface) focused heat source (i.e. laser light), as well as subsequent deposition and consolidation of powder layers. This moving heat source causes melting/sintering and joining of neighbouring powder grains in the melt pool. Schematic diagram of the SLS process (from 1979) is presented in Fig. 1.

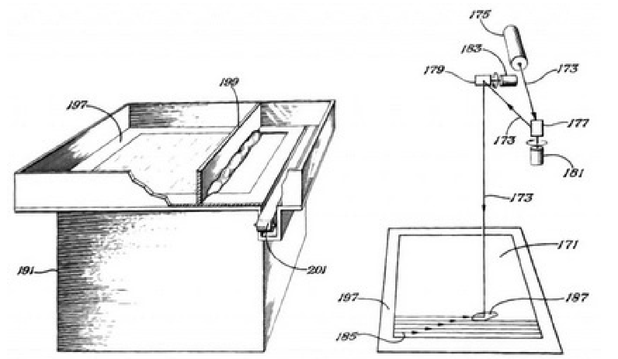
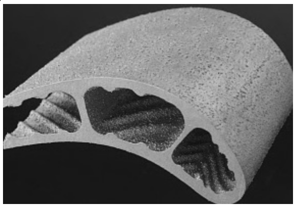


Fig. 1. Schematic diagram of powder sintering method introduced by R.F. Housholder [1]

a)



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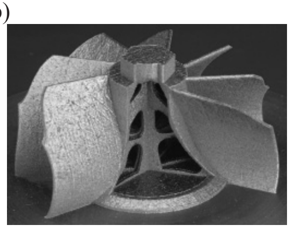

Fig. 2. Aerospace elements manufactured by SLM technology: a - turbine blade for PW4000 HTP engine, b - blade integrated disk (image source: Fraunhofer ILT, Aachen)

Modern SLS/SLM systems for sintering metallic powders consist of computer controlled laser (CO_2 or fiber laser), galvanometric scanner with laser optics and powder delivery and levelling system. These systems (supplied i.e. by Renishaw, EOS, Phoenix Systems, SLM Solutions) allow to build elements from low cost powders (like brass, tool steel), as well as sophisticated materials used in the aerospace (Inconel alloy 718, Ti6Al4V) or medicine (cobalt-chrome, nitinol). The variety of materials and possibility of manufacturing freeform elements, cause that SLS/SLM technology find widens its application fields in the industry. This technologies, as well as LENS (laser engineering near-net shape) are already in use for manufacturing components for:

- Medicine:
  - production of implants and scaffolds;
  - manufacturing of surgery tools and structures;
- Automotive:
  - production of motor and fuel pump covers and test elements;
  - production of heat exchange plates of sophisticated shape;
- Aerospace:
  - production of turbine blades with internal cooling (Fig. 2a);
  - production of BLISKs - Blade Integrated Disks (Fig. 2b);
  - component mass vs strength optimization (Fig. 3);
- Electronics:
  - production of components for sensors;
  - covers for electronic devices with sophisticated shapes;
- Tooling industry:
  - moulds for injection moulding;
  - precise metal components with wall thickness of 0.6 mm and more (Fig. 4).

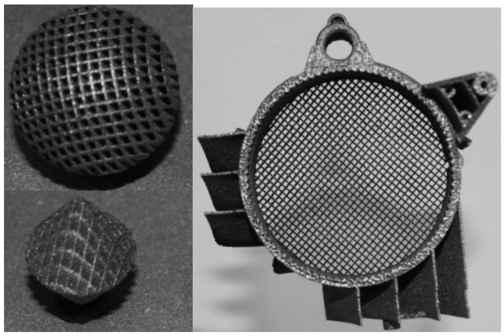

Fig. 3. High strength low weight components

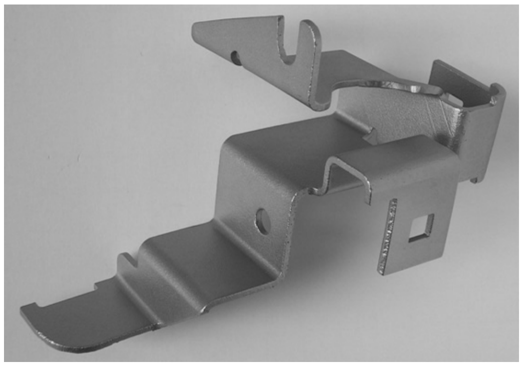

Fig. 4. Thin wall elements

Above mentioned additive manufacturing techniques play important role in the development of new elements and subsystems used in production of implants and components of sophisticated geometrical structure. They are also crucial in the research works aimed at optimization of elements when the high endurance and low mass is required (i.e.: testing apparatus for spacecrafts).

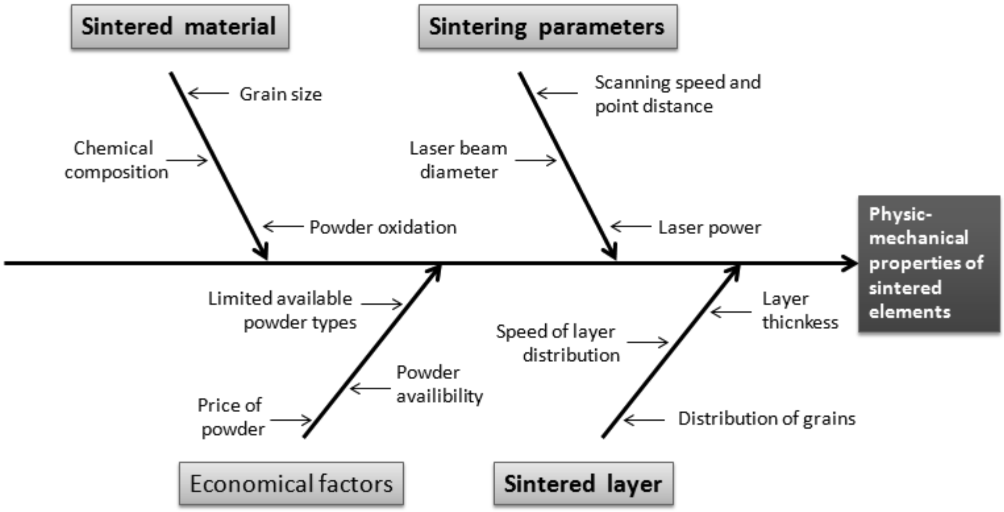

Fig. 5. Factors influencing physic-mechanical properties of SLS manufactured elements

SLS/SLM technology allows to manufacture components without need of any additional operations (apart finishing, which is also necessary in case of subtractive manufacturing techniques). It is especially important from the economical point of view, reducing time and total costs of manufacturing of elements with complex geometry (i.e.: moulds or mould inserts).

Due to wide area of application, technology of SLS/SLM is still being developed by leading research centres, institutes and universities around the world [2-6]. Researches are focused on optimization of process parameters towards improvement of physic-mechanical properties of sintered elements (density, porosity, strength) in order to obtain properties like elements manufactured from solid materials.

Economical effectiveness of the sintering of components by the means of SLS/SLM technology depends on number of various factors (Fig. 5). Apart factors closely related to technology, grouped as “Sintering parameters”, “Sintered layer” and “Sintered material”, important role play “Economical factors”. They mainly concerns the macroeconomic environment related to the SLS/SLM and powder metallurgy markets.

The purpose of performed and presented in this study researches, is to analyze the influence from “Sintering parameters” from Fig. 5 on the properties of build components.

2. Materials and methods

Experiments were carried out using two types of SLS/SLM machines:

- Renishaw AM 250: equipped with the YFL continuous wave Ytterbium fiber laser (wavelength of 1070 nm), allowing sintering and melting of elements with maximum power of 400 W and maximum laser scanning speed of 2000 mm/s. Laser beam diameter equals to 70 µm.
- EOS 250xt: equipped with the CO_2 laser (wavelength of 10600 nm), allowing sintering of elements with maximum power of 250 W and maximum laser scanning speed of 2000 mm/s. Laser beam diameter equals to 100 µm.

Sintered material was tool steel - Direct Steel (DSH20). This is small grain (20-40µm) mixture of steel based of composition presented in the Table 1. This material has composition similar to materials used in the tooling industry for manufacturing of moulds for injection moulding.

Table 1.
Chemical composition of DSH20 powder

Chromium	Nickel	Copper	Silicon	Iron
4-5%	10-12%	0.2-0.5%	0.2-0.5%	balance

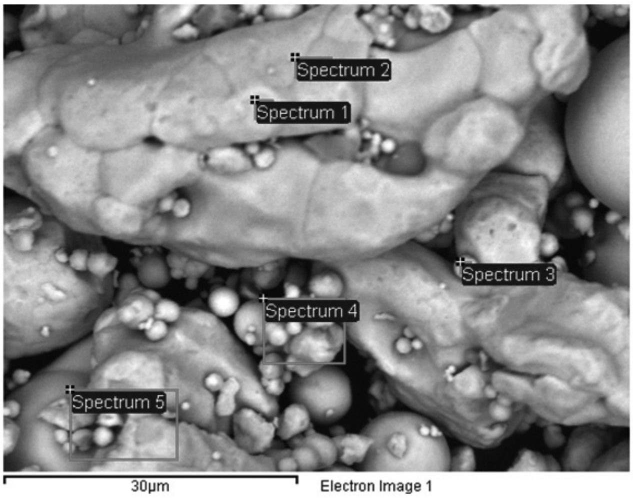

Fig. 6. SEM picture of DSH20 powder before sintering

For investigations, basing on the results of the previous researches [2], group of technological parameters of the sintering process and their range were selected - presented in Table 2.

Table 2.
Investigated parameters of SLS process

Laser power	(P)	200-400 [W]
Scanning Speed	(SP)	100-130 [mm/s]
Exposure Time	(ET)	75-100 [µs]
Point Distance	(PD)	45-75 [µm]

Although for human eye process of SLS/SLM looks like continuous, it is in fact discrete process, where:

- Scanning Speed is the speed of laser spot between heating points (Fig. 7a):

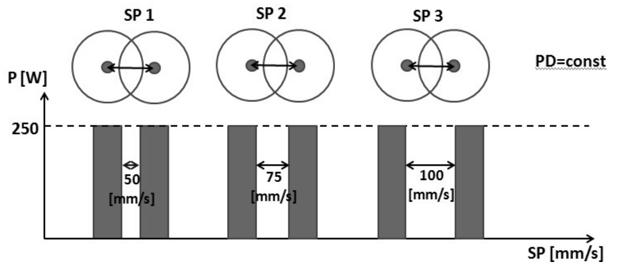

Fig. 7a. Schematic illustration of Exposure Time parameter

- Exposure Time is the length of time when laser spots in one/single point (Fig. 7b):

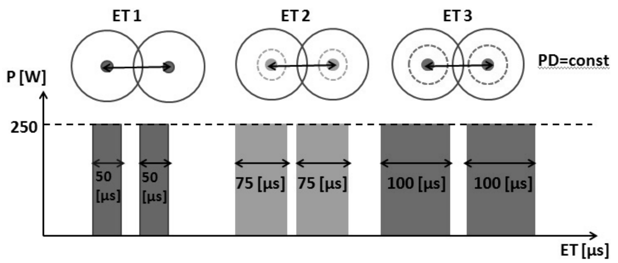

Fig. 7b. Schematic illustration of Exposure Time parameter

- Point Distance is the distance between laser spots (Fig. 7c):

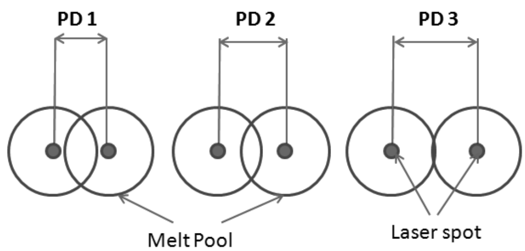

Fig. 7c. Schematic illustration of Point Distance parameter

Researches were performed for the fixed powder layer of 50 µm. Test samples were sintered in the inert gas atmosphere of nitrogen (EOS machine) and argon (Renishaw machine).

Experiments were conducted according to the derived plan (DOE). The researches were performed according to static, determined selective-orthogonal plan: PS/DS-P:(α=1) with four independent variables (listed in Table 2). Output, examined parameters were:

- Hardness [HV];
- Density [g/cm^3];
- Compression strength [MPa].

In order to perform necessary measurements and investigations , 5x5 matrices of samples was sintered (Fig. 8). In case of measurement of hardness and density, samples were cuboids of 15x10x15 mm. Compression strength was measured using cylindrical samples of diameter of 10 mm and height of 15 mm (with grounded faces of the samples) - Fig. 9. Samples were prepared according to Saint-Venant rule and standard: PN-57 H-04320.

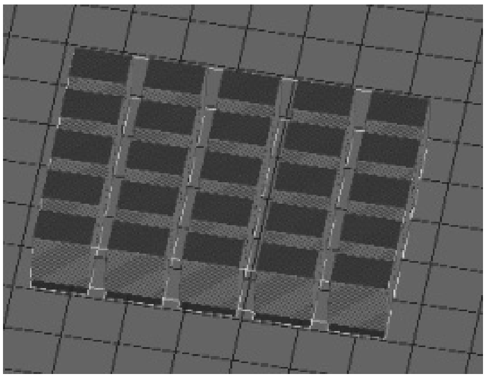

Fig. 8. Samples (in AutoFab) for measurement of hardness and density

3. Results of performed experiments

Initial researches for laser power of 100-250 W were performed using EOS system. Experiments with the laser power in the range of 200-400 W were done using Renishaw machine. When the process conditions were similar for both machines, there was no significant difference in the properties of sintered samples observed. Below are presented results achieved with the Renishaw AM 250 machine system.

3.1. Compression strength

During measurements, samples (Fig. 9) were axially compressed with constant feed rate in the room temperature (10-35°C), until they were shortened by 0,2% of initial length. For sintered material - DirectSteel H20, initial load was set at 3900N. Analysis of the obtained results (measurement of yield strength) proves that in case of sintered samples, compression strength is within the range form 752-823 MPa for the optimal process conditions.

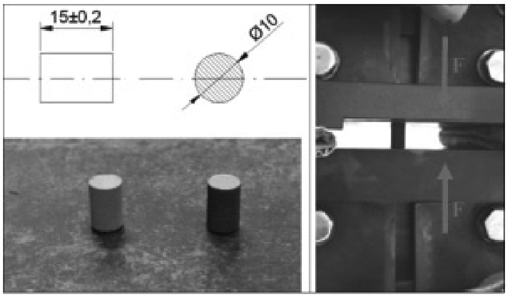

Fig. 9. Samples for measurement of compression strength

In Fig. 10 is presented compression strength as the function of point distance and laser power. In the presented figure, exposure time was constant, equal to 92 µs and scan speed was equal 87 mm/s.

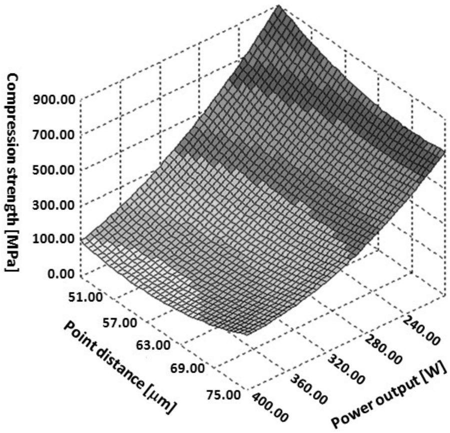

Fig. 10. Compression strength vs Point distance and Laser Power with constant exposure time and scan speed (ET = 92 µs, SP = 87 mm/s)

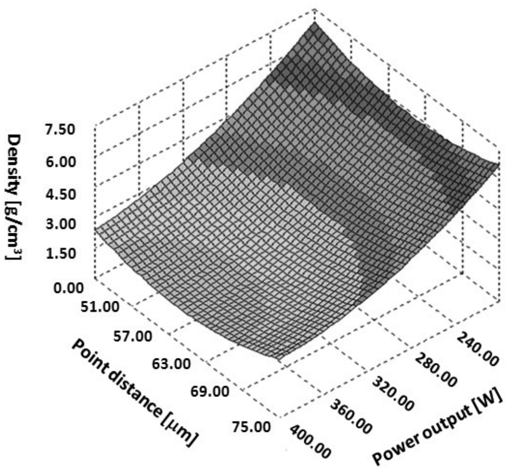

Fig. 11. Density vs Point distance and Laser Power with constant exposure time and scan speed (ET = 100 µs, SP = 84.5 mm/s)

3.2. Density

Density was measured using saturation in vacuum method, according to the Polish Standard PN-EN 623-2 (Archimedes method). Densities of sintered elements were within the range of 6.73-7.45 g/cm^3. Achieved results are very similar to density of respective steel (solid material) - tool steel H13 (density of 7.8g/cm^3), which has similar application field as used powder.

Figure 11 presents density as the function of point distance and laser power. In the presented figure, exposure time was constant, equal to 100 µs and scan speed was equal 84.5 mm/s.

Porosity of the samples was measured. For samples of the highest density equal to 7.45 g/cm^3 (Point Distance = 50 µm, Laser Power = 200 W and Exposure Time = 100µs), sintered sample had porosity not exceeding 2.5%. Results of measurements were proven by the SEM photo of microstructure - Fig. 12.

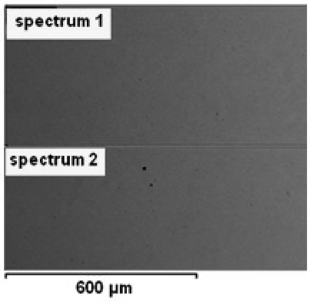

Fig. 12. SEM photo of samples microstructure with visible small pores of diameter not exceeding 10 µm

3.3. Hardness

For measurement of hardness, Frankoskop universal optical hardness meter was used. Measurements were performed with the load of 294,2N. As in case of materials used for tooling industry it is important that there would not appear significant differences in hardness among various areas of the tool, samples were prepared (grounded) in the form presented in Fig. 13.

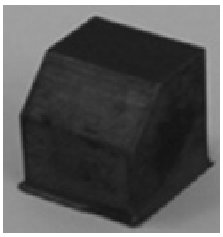

Fig. 13. Sample prepared for hardness measurement

Figure 14 presents hardness as the function of point distance and laser power. In the presented figure, exposure time was constant, equal to 100 µs and scan speed was equal 100 mm/s.

Analysis of the results of hardness measurements proves that the highest value is reached for the sample sintered when PD = 50µm, P = 200W and ET = 100µs. The best results were obtained for the flat surface parallel to the surface of base plate.

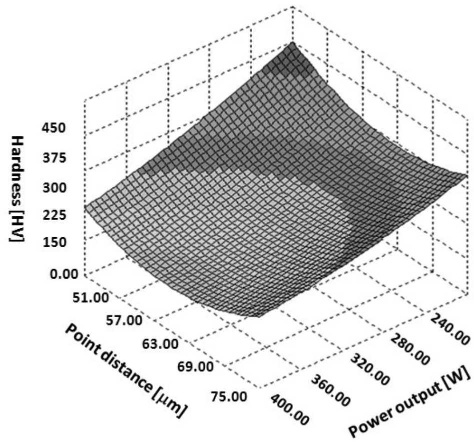

Fig. 14. Hardness vs Point distance and Laser Power with constant exposure time and scan speed (ET = 100 µs, SP = 100 mm/s)

4. Conclusions

Basing on the results of performed experiments it can be stated that elements sintered of Direct Steel 20 powder are of significant properties in comparison to elements build of solid material - tool steel H13. Sintered freeform elements may be used in the same way/conditions as those made of solid materials, for example as moulds and mould inserts used for injection moulding.

The best results (high hardness, high density, high compression strength) was achieved when the: PD = 50 µm, ET ≈ 100 µs and P = 200W - similar results (density, hardness and compression strength) were achieved for both used machines (EOS 250xt and Renishaw AM250).) machines.

Results of performed experiments prove that the most significantbiggest influence for investigated properties of sintered sample have:Laser power;

- Point distance;
- Exposure time.

When the power of the laser was set at below 200 W, the samples were not sintered properly, when exposure time was within the specified range. To achieve satisfactory results (in the means of density, porosity and compression strength) with low power systems it would be necessary to increase significantly the exposure time and the same lengthening time necessary for manufacturing desired element.

Scanning speed did not have significant influence on the performance of the process (sample properties) - it might be possible to reduce significantly time of machining by maximizing scan speed, in case of building large elements.

Acknowledgements

Measurements of hardness and density, as well as SEM photographs of sample microstructures and raw powder were done by specialists from the Materials Science Department of the Institute of Advanced Manufacturing Technology in Kraków, Poland.

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