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ANALYSIS OF SELECTED PROPERTIES OF AN ARTICLE MADE FROM METAL POWDER USING LASER ADDITIVE MANUFACTURING

Key words: incremental production, Selective Laser Sintering-SLS, Selective Laser Melting-SLM, metal powders, porous structures, laser.

Abstract: The article points out the need for knowledge about the relationships of many technological features for items produced by selective laser melting of metal powders. The importance of the orientation of the produced element relative to the work table of the machine both in terms of the effect on the mechanical properties and surface quality of the product is shown. Inaccuracies in shape and representation of the real dimensions of the internal and external outlines are presented.
The anisotropy of the structure and the resulting differentiation is shown. Attention is paid to different conditions in the incremental production in the area of one layer where the consolidation of the metal powder takes place in one impact of the laser beam, and the connection with the next layers is carried out by thermal effect from the preceding layer, in a much lower temperature. The ability to remove the anisotropy of the structure by homogenizing annealing is shown.
Knowledge of the characteristics of the articles produced with incremental technologies is extremely important when selecting production parameters, especially in case of designing responsible machine parts subjected to higher loads.

Analiza wybranych właściwości wyrobu wykonanego z proszków metali metodą laserowego wytwarzania przyrostowego

Słowa kluczowe: przyrostowe wytwarzanie, selektywne spiekanie laserowe – SLS, selektywne stapianie laserowe – SLM, proszki metali, struktury porowate, laser.

Streszczenie: W artykule wskazano na potrzebę wiedzy o zależnościach wielu cech technologicznych dla elementów wytwarzanych na drodze selektywnego stapiania laserowego z proszków metali. Określono znaczenie zorientowania wytwarzanego elementu względem stołu roboczego maszyny, zarówno w aspekcie wpływu na właściwości mechaniczne wyrobu oraz jakość powierzchni wykonanego kształtu. Wskazano na niedokładności kształtu oraz odwzorowanie wymiarów rzeczywistych wykonanych zarysów wewnętrznych i zewnętrznych.
Wykazano anizotropię struktury i wynikające z tego zróżnicowanie. Zwrócono uwagę na różne warunki wytwarzania przyrostowego w obszarze jednej warstwy, gdzie konsolidacja metalicznego proszku przebiega w trakcie jednego oddziaływania wiązki laserowej. Natomiast połączenie ze sobą kolejnych warstw odbywa się poprzez wpływ cieplny powstającej warstwy na poprzednią, w znacznie niższej temperaturze. Wykazano możliwość usunięcia anizotropii struktury przez wyżarzanie ujednorodniające.
Wiedza o właściwościach wyrobów wytwarzanych w technologii przyrostowej jest niezwykle istotna przy doborze parametrów wytwarzania, szczególnie w przypadku projektowania odpowiedzialnych części maszyn poddanych większym obciążeniom.

Introduction

Additive manufacturing of the metal powder elements may be obtained by a number of technologies, and the following are the most common: selective laser sintering – SLS, and selective laser melting – SLM. The difference is in the choice of the appropriate technological parameters of the manufacturing process that affects the binding mechanism of metal powder, which is decisive for obtaining a variety of structures. In the process of selective sintering powders (SLS), porous structures are made. They have lower density and strength than in the selective melting process (SLM), which allows them to receive up to 100% density and mechanical properties similar to, or better than, items made by traditional methods [1]. Depending on the requirements imposed on elements, both SLM and SLS technology will be used, because there are products which may be both beneficial for porosity and the laminated structure.

Additive manufacturing of metal elements is to apply thin uniform layer of the powdered metal over the surface of the moving tablewhere the detail is formed. The table lowers with the value of the thickness of the powder layer. The laser beam acts on the metal powders within a specific cross-section of the produced item and combines them by full penetration to form a continuous film of metal as in the hardfacing process. When carrying out the process layer by layer, one gets the complete structure of the product.Diagrams of the laser manufacturing process of the elements in an additive technology are shown in Figures 1 and 2.

All metals may be combined by melting. However, there are factors which allow easier laser processing, such as the absorption of the laser beam, surface tension, the viscosity of the liquid metal, etc. For each material, process parameters must be determined experimentally in order to avoid the drawbacks of tracks scanned (spheroidization liquid lakes), also called *balling* and *porosity*. For this reason, the market has a limited number of materials [2].

The use of SLM technology with metal alloys opens up new possibilities for many industries, particularly for aerospace, automotive, and medical industries [3, 4, 5].

Individual layer thicknesses may be different, and they are in the range from 20 μm to 150 μm and are associated with the gradation powder [6]. The thickness of the layer depends on the mechanical properties and the surface quality of the produced product.

Prototype thicker layers are used for manufacturing, which significantly reduces the production time and costs.

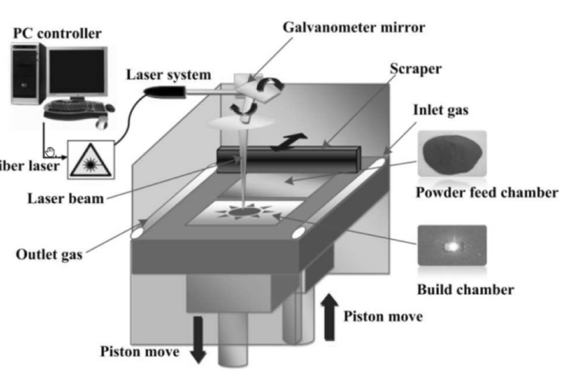

Fig. 1. Schematic diagram of the selective laser melting process [7]

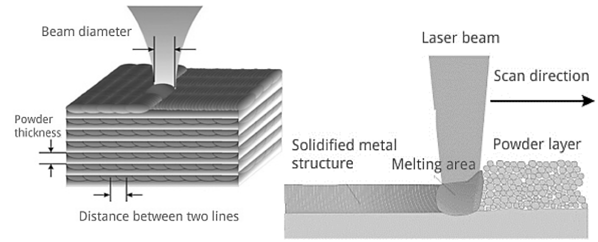

Fig. 2. Schematic diagram of the process of melting the layer of metal powder [8]

The metal powders used for sintering or melting laser processes are in different gradations. The diameters range between a few to about 100 μm [9].

Even if the powders have the same chemical composition, they may have differences in the thermophysical properties of the powder, and thus may produce different densities, surface qualities, and mechanical properties [9]. Density and thermal conductivity of an evenly distributed powder layer are two main characteristics which substantially affect the process of sintering or laser melting. The course of solidification and consolidation (composite) of metallic particles depends on them, and it directly affects the quality of the resulting element [10, 11].

Effective use of technology in additive manufacturing of metal powders is associated with a proper matching of a number of parameters. Their proper selection is a key factor in obtaining good quality components according to established requirements. The scientific publications show the results of the research on the influence of the particular parameters on process effects. One can find the recommended combinations of laser power and scanning speed for a particular material, which is extremely important to prevent undesirable effects such as insufficient penetration (occurs at too low laser power) too much remelting (low speed scanning and high power laser) or irregular remelting, and balling effect, which is the formation of globules of melted material [12].

Many parameters such as laser power, scanning speed, the distance between the scan lines, scanning strategy thickness, grading metallic powder, protective atmosphere, and the temperature of the platform have an influence on the physical and mechanical properties of the elements.

1. Own research and analysis of the results

1.1. The research material

Elements to be processed have been designed so that it was possible to determine the strength properties, structural correctness, and mapping dimensions. 3D models created in Autodesk Inventor 2015 were made by using the machine Renishaw AM250 by selective laser melting (SLM).

Stainless steel 316Lwas used in the study. AISI steel 316L is determined according to European standards as X2CrNiMo17-12-2/1.4404 and belongs to the group of austenitic steel. The starting material used to make the powder sample was grit 15 to 45 µm.

1.2. Technology of samples

To prepare the samples,a Renishaw AM250 machine was used. The device allows one to produce metal components either by sintering or laser melting. It has a hermetic vacuum chamber, so that the process takes place in a controlled atmosphere. Before the process starts, the air is withdrawn and inert gas-argon is pumped in, so that there is no risk of oxidation of the metal during the process, which could significantly impair the properties of the element.

For automatic or manual selection of process parameters,dedicated software is used: Quanta or processor program Magics Company Materiallise [6].

The orientation of designed samples to the machine table is shown in Figure 3. The orientation of details was imposed by their geometry. Gradients are turned according to the movement of distributing the element powder (Wiper Blade), so it has the best conditions for the proper distribution of powder, i.e. the minimum approach angle on the emerging elements. The platform where the building process starts is a plate of 15 mm thickness made of the same type of material as the currently used powder.

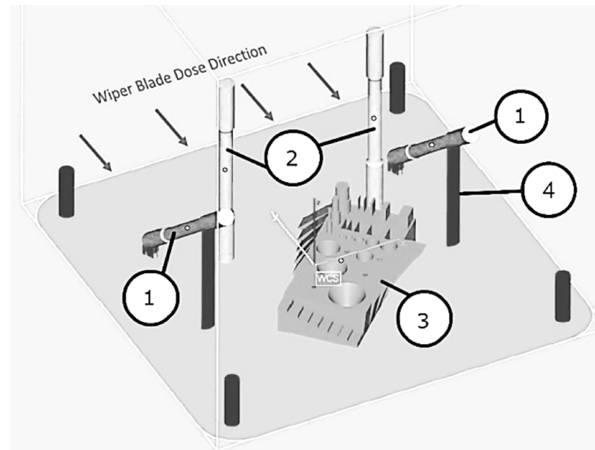

Fig. 3. The sample orientation relative to the machine table 1 – sample at an angle of 45 degrees, 2 – Samples vertically, 3 – dimensional inspection sample, 4 – the sample support automatically generated (SLS technology)

Automatically selected technological process parameters of the preparation of the samples are shown in Table 1.

Table 1. Technological parameters of incremental samples production [13]

Machine type	AM250
Laser power	200 W
Material	316L
Gradation powder (particle size) [µm]	15 – 45
Layer thickness [µm]	50
The number of layers	2820
Total height [mm]	141
The total volume [cm^3]	128.3
Estimated duration of the process [h]	19
Post-process machining	Cut off parts at the base using EDM cutting
Strategy scanning, stripes width [mm]	5
The distance between the scan lines [µm]	120 – 170
Base thickness [mm]	15
Approximate weight [kg]	8.5

1.3. Testing samples

The project of the samples and static tensile tests were performed in accordance with EN ISO 6892-1: 2009.

Testing of the produced samples were at 45° and 90° relative to the machine table. Two different sample orientations in the machine working space allow one to determine the reliance of the tensile strength of the samples with the angle of inclination to the machine table, i.e. fused layers of different inclination to the tensile powder force.

The samples at a 45° angle had the support system generated by the machine software shown in Figure 4.

These supports are formed by laser sintering (SLS), while the same sample, as well as any other, are made by a laser melting (SLM).

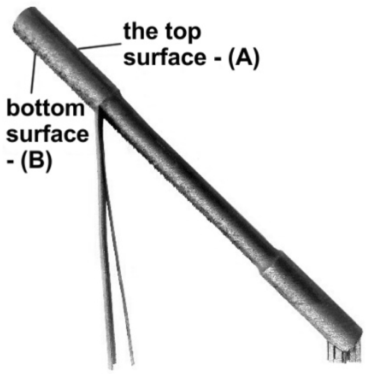

Fig. 4. Sample at an angle of 45 degrees relative to the base surface. Visible support, automatically generated

The surface of steel samples at a 45 degree angle is characterized by uneven quality on the perimeter and a significantly poorer surface quality in comparison to the samples produced vertically. This is particularly visible on the bottom of the surface (inverted) (Fig. 5).

A single layer thickness of 50 micron with easy adhesion of unnecessary material to the surface of the hanging section and the thermal conductivity of the material have a negative influence on the surface quality. A better surface quality of the vertically produced samples is shown in Figure 6.

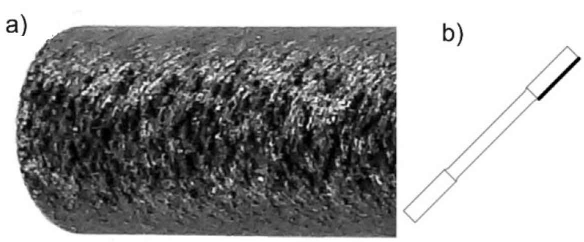

Fig. 5. a) the sample made of steel 316L with a very rough bottom surface (hanging) made at an angle of 45°, b) photographed place marked with a thick line

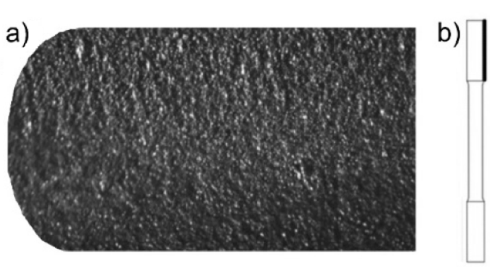

Fig. 6. a) the surface of the vertical sample made of steel 316L has a uniform surface roughness over the entire length and circumference, b) photographed place marked with a thick line

Differences in the surface roughness of the samples generated vertically and at a 45 degree angle are shown in Table 2. Roughness on the surface of the samples was measured around the perimeter of the samples handle.

Table 2. The measured values of roughness Ra of steel samples

The sample material	316L		
Sample Type	**Vertical**	**Angled 45°**	
Place/surface measurement	Every 90°	Top	Bottom
Average measured value of Ra [μm]	7.88	8.04	10.06

1.4. The tensile strengths of prepared samples

Static tensile test was performed on the testing machine LFM 20 – 125 kN, Walter+Bai AGCompany. Samples and attempts have been made according to EN ISO 6892-1: 2009.

Parts made by melting metal powder oriented to the machine table at a 90° angle and 45° angle show anisotropy of the structure caused by the application of the layered material, which simultaneously affect the values of tensile strength. The results are shown in Table 3.

The strength of the samples produced at a 45° angle is significantly higher than that produced vertically. The strength difference depends on the direction of force action in relation to the laid layers, and it results from the improved fixation within the same powder layer. Linking the powder particles in a single scan line is stronger than that which exists between the layers, as occurs in one impact of the laser beam. However, the connection with the sequence layer is carried out by thermal effect of the resulting layer on the preceding one at much lower temperature.

Table 3. Summary of the results obtained on the basis of the static tensile test of the steel 316L samples [14]

The values Rm	Orientation sample	Rm MPa	A5 %	Z %
Measured	Vertical	615	44	68
Measured	Angle45°	650	45	67
Measured	Angle45°	651	43	67
According to Renishaw	Vertical	574±10	–	–
	Angle45°	662±2	–	–
According to EN 10088 (traditional manufacturing technology)	–	500–700	–	–

1.5. The structure and micro hardness material tests

The analysis of the tested structures of the materials were made with the help of a microscope Nikon Eclipse MA200 cooperating with a PC equipped with software NIS-Elements 4.10.

The porosities of the specimens were evaluated on samples prior to etching. To show the structure of the surfaces, the samples were etchedwith $C_3H_8O_3$+HCl+HNO_3 (3:2:1) at about 60° C for 6 minutes.

Figure 7 shows the etched surface with visible pores (mostly spherical) with very different diameters ranging from about 1µm to 60µm. The overall porosity of the samples is rated at 2%.

The structure of the samples was revealed after etching, and they are shown in Figures 8 to 10.

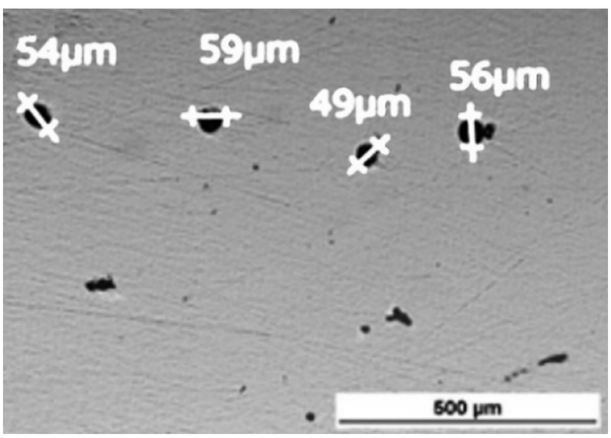

Fig. 7. The pores in the structure of steel 316L before etching

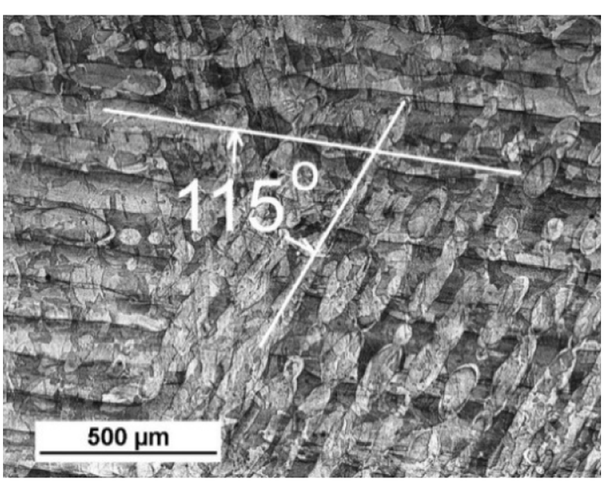

Fig. 8. The angle between the scan lines of adjacent layers was about 115° – view on the plane layer, steel 316L, vertical sample

The etching of the layer shows the scan lines which represent a single layer. Figure 8 shows a normal view to the layer and selected angle between the scan lines of contiguous layers at approximately 115°. Its value made it possible to designate the next layer as visible.

It was also possible to identify and verify the distance between the scan lines in relation to the figures in the program for the development of manufacturing technology, as shown in Figure 9. The distance values of the samples read in different places amounted to 96 to 120µm, and they are lower than those specified by the manufacturer Renishaw (130 to 170 µm).

The structure of the sectional plane perpendicular to the layers is shown in Figure 10. Furthermore, a stack of layers combined together as a result of the impact of heat into the material can be seen. A structure resembling fish scales (best seen in outline of the samples on the right side) represents a single scan line with the heat affected zone.

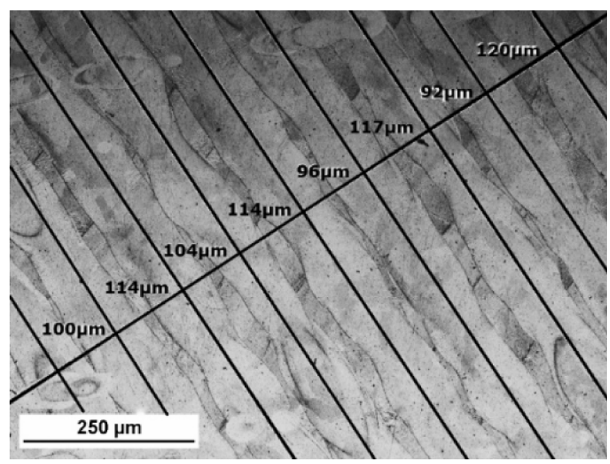

Fig. 9. The distance between the vertical scan lines of the sample of 316L steel. On the visible area, these values ranged from 96 to 120 µm

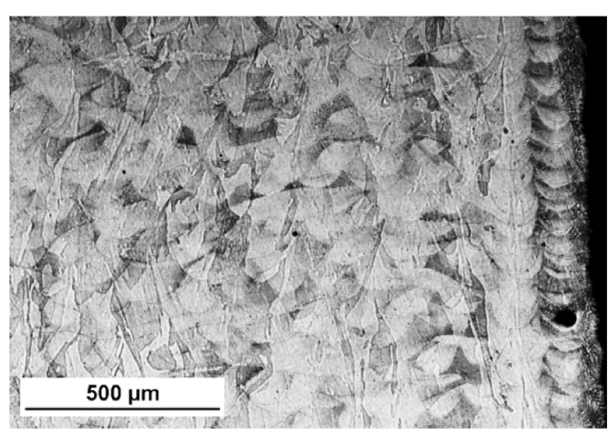

Fig. 10. View of the stack of layers of steel sample formed at an angle of 45°. The apparent "husk" forming the outer surface of the product

Micro hardness samples tests were performed on a machine Wilson Wolpert MicroVickers Analog 401MVA. To see the differences in micro hardness depending on the position of the indenter relative to the scan lines, a range f measurements were taken. All the read values HV0.1 for a tested steel 316L ranged from 232HV0,1 to 278HV0,1 for the sample from the vertical longitudinal section (through the layer). Differences in the hardness to a horizontal section (in the plane of one layer) of the vertical samples ranged between 245HV0,1 to 252HV0,1.

This may indicate a greater heterogeneity of the material in the direction of the layer where the connection zones of the material take place through the influence of heat between the layers as opposed to a single layer structure which is under the action of a laser beam.

The heterogeneity of the structure can be removed by homogenizing annealing. An example of the structure of the sample produced at a 45 degree angle after annealing is shown in Figure 11. Heat treatment consisted of heating the sample in a furnace at 1030°C for 2 h 50 min and cooling within the furnace. A metallographic section was etched with a solution of 3x glycerin, 2x hydrochloric acid, and nitric acid 1x. The micro hardness of the surface of the sample was 203HV0,1±5.

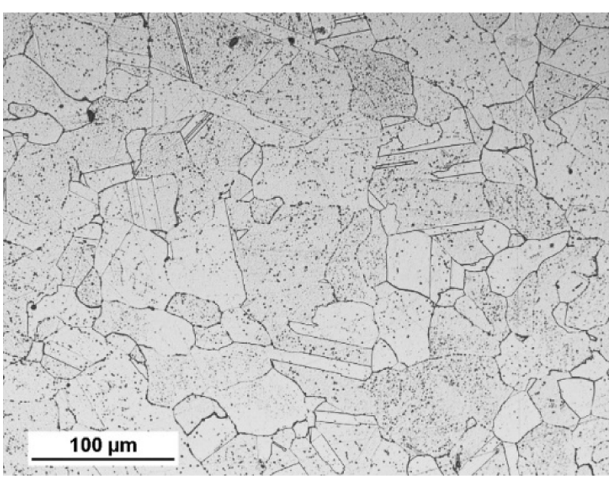

Fig. 11. The surface structure of the sample (of Figure 10) produced at an angle of 45 degrees after the homogenizing annealing

1.6. An assessment of accuracy of the dimensions of designed elements in the technology of selective melting (SLM)

To determine the accuracy of the mapping dimension in the SLM device, Renishaw AM250, model control was designed. By using a coordinate measuring machine, the detail was subjected to a series of measurements. On this basis, it was possible to know the dimensional accuracy of the obtained components. The measurements were carried out by using a coordinate measuring machine Mitutoyo Crysta Apex C7106 and GEOPAK software included in the packet MCOSMOS-3 v3.2.R9.

The control model had a lot of geometry, which was designed to give the most extensively and accurately analyse of the possibility of SLM technologies offered by one of the commercially available devices.

The resulting models clearly indicate the effects of using the layer technology. This was clearly visible on the lateral surface (Fig. 12a). On the surface of the model (Fig. 12b), parallel to the XY plane, one can observe the effect of the strategy scan stripes. Parallel lines are visible, as well as a less visible series of parallel lines oriented at a different angle. Strategy scraps are characterized by variability in the angle of the scan line at another layer. The thickness of the single layer is so small that the surface of the last layer is shown heavily outlined by dominant lines that form the parallel strips of the previous layer. Angular orientation of the sections that form the belt during production changes at each successive layer in order to balance the stresses better; therefore, two lines of the belts are seen (visibility of the previous layer).

The measurement results of the shape is indicated in Figure 12 and shown in Table 4.

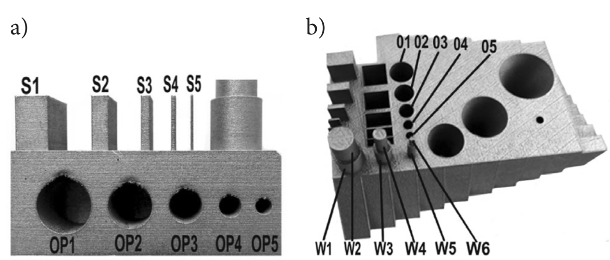

Fig. 12. Model for quality control of production with marked places of measurement: a) vault holes defects OP1-OP5 product of steel 316L. Multilayer structure visible in the side surface; b) visible effect of the application of the stripes strategy on the surface of the component and the two directions of the outlines (visibility of the previous layer)

Table 4. Selected measurements indicated in Figure 12

No.	Designation dimension	Nominal dimension [mm]/ [degrees]	Measured dimension [mm]	Error [%]
Blind holes on the horizontal axis (in line with the axis X) – the measurement of internal diameters				
1.	OP1	10	9.806	-1.937
2.	OP2	8	7.803	-2.458
3.	OP3	6	5.734	-4.439
4.	OP4	4	3.703	-7.417
5.	OP5	3	2.845	-5.167
Walls – measurement of wall thickness				
6.	S1	6	6.133	2.211
7	S2	3	3.194	6.456
8.	S3	1.5	1.677	11.778
9.	S4	0.6	0.827	37.889
10.	S5	0.2	0.452	126.000
Holes on the vertical axis (in line with the axis Z) – the measurement of internal diameters				
11.	O1	10	9.787	-2.133
12.	O2	8	7.803	-2.463
13.	O3	6	5.802	-3.294
14.	O4	4	3.803	-4.917
15.	O5	3	2.866	-4.467
The vertical cylinders (in line with the axis Z) – the measurement of external diameters				
16.	W1	10	10.079	0.790
17.	W2	8	8.092	1.144
18.	W3	6	6.110	1.825
19.	W4	4	4.129	3.212
20.	W5	3	3.196	6.517
21.	W6	2	1.668	-16.625

Conclusions

Completed tests and measurements allowed the observation of many of the characteristics and characteristic relationships of the elements produced by laser melting metal powders. SLM allows the production of parts for almost any shape, which to some extent is shown in the example of completed items. During the design of elements, one should consider the important role of their orientation relative to the machine table. This same body, depending on the orientation of the working space, may vary in size and shape to some degree. This was clearly noticeable in the case of endurance tests of samples oriented at a 45° angle and a 90 °angle to the table surface of the machine. These types of hanging elements are subjected to deformation caused by forces of gravity and the creation of varying surface roughness. The loose powder is not an adequate support in this technology, so additional support should be added. It should be noted also that the size of the deformation depends on the type of material, its density, and the thickness of the formed layer.

Another aspect is the issue of mapping dimensions. The machine manufacturer indicates the approximate tolerance with which the dimensions of the product are carried out, which is ±70 μm for steel 316L. These figures only partially show the expected effect of the process, because the geometry of the part also affects the obtained effect. The differences between real and nominal dimensions are dependent on the type of material used (heat conductivity coefficient) and the grading of the powder, which shows the thickness of a single layer. Large inaccuracy relates to the manufacture especially of small dimensions of both the interior and exterior construction elements. To obtain precision parts, it is essential to use finishing processing before taking into account relevant surplus.

A very important issue related to additive manufacturing is the anisotropy of the structure and the resulting mechanical properties caused by layered application of material. Components produced by this technology have different mechanical properties (e.g.,tensile strength) in a perpendicular direction to the plane of the layers and the other parallel to them. Higher strength in a direction parallel to the plane of the machine table (layer planes) is caused by better consolidation conditions of metal powder within each layer extending in one impact of the laser beam,whilethe connection with the sequence layer is carried out by thermal effect of the resulting layer on the preceding one at a much lower temperature.

Although the anisotropy properties are not large, knowledge on this subject is extremely important for the responsible design of machine parts subjected to higher loads.

Moreover, the study of the structure and micro hardness show its heterogeneity, especially in the areas between the layers. Removal of inhomogeneity occurs after annealing.

Details obtained by incremental powder technology have a relatively uniform structure with low porosity (density reaching almost 100%), and the resulting high strength properties are comparable to and sometimes higher than the components produced by other technologies.

Time fabrication is one of the most important factors strongly limiting the widespread use of technology SLM. The execution of details may take tens of hours, which is unacceptable for many industries. Additionally, the high initial costs that have to be incurred to start the production and preparation of facilities to work with metal powders do not work in favour of this technology. However, there are industries for which the presented possibilities are irreplaceable. Aircraft, space, and automotive industries are willing to invest in technologies to reduce the weight of components, thereby reducing the operating costs of aircraft and vehicles. The ability to personalize medical components significantly affects the effects of their use. "Tailor-made" prostheses or implants have better compatibility with the human body, as a result, better treatment results.

Technology of selective melting metal powder is more widely used, and this trend is likely to be maintained. However, it will not completely replace machining.

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