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Influence of technological parameters on additive manufacturing steel parts in Selective Laser Sintering

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ABSTRACT

Purpose: The investigations have been carried out on test pieces of 316L stainless steel parts fabricated by Selective Laser Sintering technique. The effect of selective laser sintering parameters such as power output, laser distance between the points sintered metal powder during additive manufacturing as well as the orientation of models relative to the laser beam and substrate on the roughness, surface morphology and wear resistance of manufactured models were performed.

Design/methodology/approach: To fabricate 316L stainless steel parts, the method using selective laser sintering (SLS) technique, using Renishaw AM 125 machine is utilised. Wear resistance, roughness and surface morphology of SLS produced samples prepared via different process parameters are investigated.

Findings: The results show that the wear resistance and surface morphology are strongly influenced by orientation of the parts relative to the laser beam, power output of laser and laser distance between the points sintered metal powder during additive manufacturing.

Research limitations/implications: In the nearest future, studies will be conducted to establish influence of laser parameters such as scan speed, focus offset, exposure time, diameter of laser beam and hatch parameters such as hatch type and hatch distance on the quality and density of AM steel parts.

Practical implications: Stainless steel is one of the most popular materials used for selective laser sintering (SLS) processing to produce nearly fully dense components from 3D CAD models. Reduction of surface roughness is one of the key research issues within the additive manufacturing technique SLS, since one of the major cost factors is the post processing of surfaces by means of milling, turning, grinding and polishing.

Originality/value: This paper can serve as an aid in understanding the importance of technological parameters on quality and wear resistance of manufactured AM parts made by SLS technique.

Keywords: Selective Laser Sintering; Rapid prototyping; Additive manufacturing

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Among the known methods of additive manufacturing (AM) [1,2], the most accurate technology is selective laser sintering SLS, which is becoming a firmly established digital manufacturing method in the additive technology of metallic parts [3-5]. SLS technology belongs to the modern additive technology, which combines to one process the complex steps of scanning, design and fabrication where the three-dimensional model is performed layer by layer. It comes from rapid prototyping methods currently used successfully for the production of the final products [6-8]. SLS technology is developing at a very fast rate which is associated with a lot of studies being carried out systematically by many research centres, both related to the design and production of components with this method. This confirms, for example the long-term cooperation of NASA (National Aeronautics and Space Administration) with scientists from Missouri University of Science and Technology (S & T) at the forefront of prof. F. Liou, whose research conducted within the allocated grants, are contributing to progressive development of the SLS technology towards obtaining more durable materials with high mechanical properties used in the aerospace [9,10]. SLS method will enable the production of a single and series of components of very complex shapes and intricate construction, which allows for their use in many industries [4,6,7,10], among others, in the armaments industry, aerospace, automotive [11], medical [12-14], as well as the production of solar cells used in photovoltaics [15-17].

The idea of selective laser sintering technology is producing elements of layer upon layer of powders with a particle size (grain) up to 50 microns by sintering the subsequent layers using a computer controlled laser beam. SLS system consists of the laser, the working chamber and the control system. In the working chamber, a thin layer of material is distributed by powder scraper on a movable platform, and is then sintered by laser beam for a two-dimensional cross-section element, after which the platform is lowered by the thickness of the layer. The powder scraper again then spreads the powder layer which is imposed on to the previously sintered layer (Fig. 1). During the sintering process, the elements are created using a diffusion mechanism [5,7,8].

Among the available materials, titan and its alloys, iron alloys, copper alloys, nickel alloys, ceramics, polymers and for instance, tungsten carbide [18-23], are currently being successfully used in SLS technology, but the most commonly used are stainless steel [5,8,17,24,25].

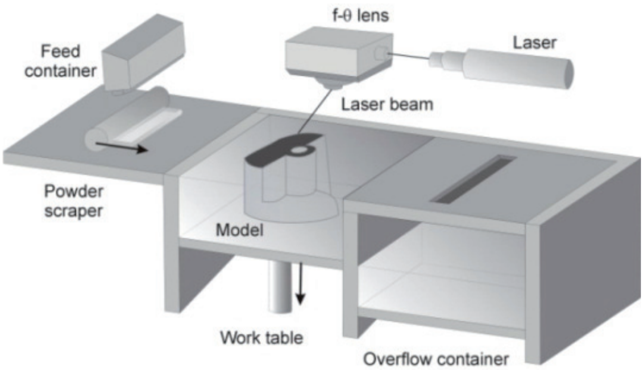


Fig. 1. Scheme of Selective Laser Sintering process

Many parameters govern the process of producing components from stainless steel, and consequently affect the quality of surface and mechanical properties of the sinter products, which can be classified according to four main categories. These are, material properties, laser parameters, the scanning process parameters and environmental parameters. More precisely, they include size of powders, laser beam power, process time, powder mass feed rate, beam patch overlap and layer thickness [8,26,27]. Powder properties and fabrication parameters have a strong influence on the roughness and wear resistance of SLS, with the latter more significantly. Therefore, in order to understand the relationship between the process parameters, roughness and wear resistance are the circumstance to improve the accuracy of the parts. It is also necessary to develop the intelligent process control and automation and to allow us to produce the parts with the desired dimensional and geometrical accuracy [3,28-30]. Due to the multitude of parameters and their possible combinations, using the method of SLS encountered certain limitations connected with producing elements with a larger surface roughness compared to the elements obtained by conventional methods, with the stresses, distortion, inaccuracy and porosity [18,26,29,31].

Many attempts have been made to improve the parts produced by SLS process, but the progress has been slow because of the complex nature of the SLS process. In recent years, various processes have been used for surface integrity of the SLS component, to obtain lesser roughness with sufficient dimensional accuracy, and increased wear resistance for the application, such as post-processing treatments and by the use of laser remelting. Shi and Gibson [32] used a robotic finishing system to improve the overall surface quality (surface roughness, dimensional accuracy and geometrical accuracy) of SLS parts. Ramos et al. [33], reported that it is possible to reduce surface roughness using a high laser power polishing technique using either CO_2 and Nd:YAG lasers. Paul et al [34] developed a methodology to calculate the laser energy of a part manufactured in the SLS process and to correlate the energy to the part geometry, slice thickness and part orientation. Olakanmi [35] reported the effect of mixing time on the homogeneity of aluminium powder blends and its SLS processed density and microstructure, concluding that high porosity in the powder inhibits effective thermal conductivity between aluminium particles, thereby leading to deterioration of the sintered density and microstructure of the SLS processed samples. There is therefore a need to optimise process parameters which have a direct impact on the final product in terms of mechanical chemical and functional properties.

Some efforts have been made in recent years to tackle the surface integrity problem through optimisation of the SLS process. Most authors correspond process parameters with the wear resistance of SLM processes. Sun, Moroz and Alrbaey [36] reported the abrasive wear performance of SLM materials including stainless steel. However, very few parameters have been taken into consideration to investigate the sliding wear behaviour and corrosion resistance properties of SLM stainless steels. These two categories of properties are important in engineering components used in wear and friction conditions, as is expected for many stainless steel components. There is limited information about the influence of the SLS process parameters on surface roughness and wear resistance of SLS metallic parts.

In present work, a study has been conducted to investigate the wear resistance, roughness and surface morphology of SLS 316L stainless steel samples produced under various laser power, point distance and orientation of models relative to substrate. Tribological testing was carried out under dry sliding condition without lubrication. Microstructural evolution was studied using optical and scanning electron microscopy. The obtained results are presented and discussed in this paper.

2. Experimental procedure and materials

The gas atomised powders of stainless steel 316L with a grain size in the range of 15-45 μm, supplied by Renishaw Company were used. This alloy is an austenitic nickel-chromium steel which is widely used in pharmaceutical, chemical, petrochemical, energy and pollution control industries and is used successfully in producing metal parts through additive manufacturing. That austenitic steel shows no phase transformations. Precipitations of secondary phases can only occur after long term tempering.

Experiments were performed by SLS machine type AM 125 (Renishaw) with the main characteristics parameters listed below:

- the maximum laser power – 200 W, in continuous mode,
- the maximum laser scanning speed – up to 2000 mm/s,
- laser beam – 35 μm diameter at powder surface,
- layer thickness – 20-100 μm.

The source of radiation is YFL continuous wave Ytterbium fibre laser with a wavelength λ=1070 nm.

A powder layer thickness of 50 μm was employed to build up the sample layer by layer in argon atmosphere. This layer thickness shows a good compromise between density and production time [4,31]. The metallic parts were produced using the SLS method in which the variables were the output power of the laser and point distance. The samples were built on a steel plate of 125 mm x 125 mm, with different power output (P) ranging from 100 to 200 W and different point distance (PD) ranging from 10 to 50 μm.

Although SLS components are known to have a relatively rough surface finish, which is expected to affect the tribological properties of the components, the main focus of present work is the wear resistance, roughness and surface morphology behaviour of SLS samples.

The samples consisted of two walls with a thickness of 1 mm (Fig. 2). One of the walls was oriented perpendicularly to substrate, and second one was oriented at an angle of 60 degrees.

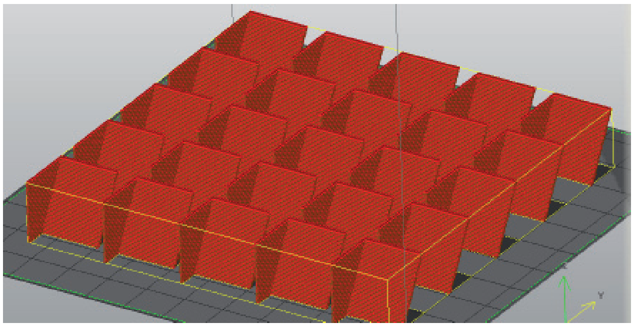


Fig. 2. Visualisation of the wall orientation in the samples

The selected technological properties of powder SS 316L like flowability, bulk density and tapped density were measured by Hall Flowmeter funnel according to ISO 3923-2.

Wear test investigations of surface samples were performed using the ball-on-plate method and obtained wear tracks were measured on profilographometer Sutronic 25 of Tylor-Hubson Company. As a counterpart a steel ball was applied with a diameter of 6 mm. The investigations were performed at room temperature (22°C), by a defined friction path distance with the following testing parameters: Fn=10 N load, friction speed 4.5 cm/s, friction path 35 m and movement rate v=0.05 m/s. All tests were conducted in ambient atmosphere and under dry, unlubricated conditions.

The depth of wear trace after wear abrasion test has been observed and measured using a confocal microscope ZEISS LSM Exciter 5.

The surface morphology was observed on 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 25 kV.

3. Results and discussion

Based on measurements of technological properties of powder SS 316L it was found that the flowability according to the PN-82/H-04935 standard was 22 s. Bulk density according to the PN-EN 23923-1:1998 standard was 4.19 g/cm^3 and tapped density according to the PN-EN ISO 3953:2011E standard was 4.92 g/cm^3.

Figure 3 shows the morphologies of the 316L stainless steel powders. As shown, the as-received SS 316L powder is dominantly regular with spherical shaped powders.

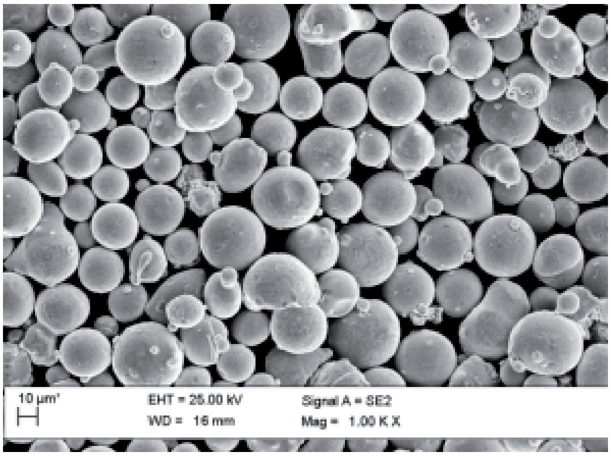


Fig. 3. SEM-SE image of the supplied Renishaw 316L powder

Figure 4(a) and (b) shows the external surfaces of perpendicular and oblique SLS samples, respectively. The external surfaces of the parts fabricated by the SLS process have different roughness because of the difference in power output, point distance and orientation of walls. The surfaces of perpendicularly built walls (Fig. 4a) are characterised being slightly pleated without any discontinuity. For obliquely built walls the discontinuities and more pleats are formed by overlapping layers.

Investigations in scanning electron microscopes confirm the effect of adhered powder particles to the surface, which is unavoidable issue in SLS process (Fig. 4). This problem generally leads to the insufficient surface quality of produced components, meaning that the surface roughness increases (this property in some cases is required, for implants consisting of a solid core and a porous, strongly developed surface layer). However, this effect is not intentionally induced but is only a side effect of a sintering process. The effect of adhered particles is caused by the occurrence of heat affect zone around the sintering place, occurring during the laser scanning of metal powder which is a cause of leaving metal powder around which is not fully sintered around the sintering area.

A disadvantage of SLS is the rough surface finish, which usually requires machining of the parts for example by grinding or sandblasting, in order to comply with the geometrical and mechanical strength requirements. An irregular surface results from the "staircase effect" of the AM process and also from powder particles sticking to the surface. A number of studies have been conducted in the field of surface roughness and wear resistance analysis of parts processed by various AM technologies (see e.g. Kumar and Kruth [18], Spierings et al. [26], Sachdeva et al [29], Ramos et al [32], Sun [36], Mumtaz and Hopkinson [37]).

Figure 5 shows the surface roughness measurement results of samples oriented parallel and inclined at an angle of 30 degrees in respect of a laser beam. In both cases, orientation of models to the laser beam, observed the increase in surface roughness during increase the point distance ranging from 10 to 50 µm. Additionally the surface roughness of the models oriented parallel to the laser beam in most cases is higher than that surface of the models orientated at an angel of 30 degrees in respect to the laser beam, except the sample made at P=200 W PD=50 µm.

The highest value of surface roughness R_a=8.3 µm was observed for parts made at P=100 W and PD=50 µm oriented parallel to the laser beam. The smallest value of surface roughness R_a=2.6 µm was observed for parts made at 100 W and 10 µm oriented at an angle of 30 degrees in respect of the laser beam.

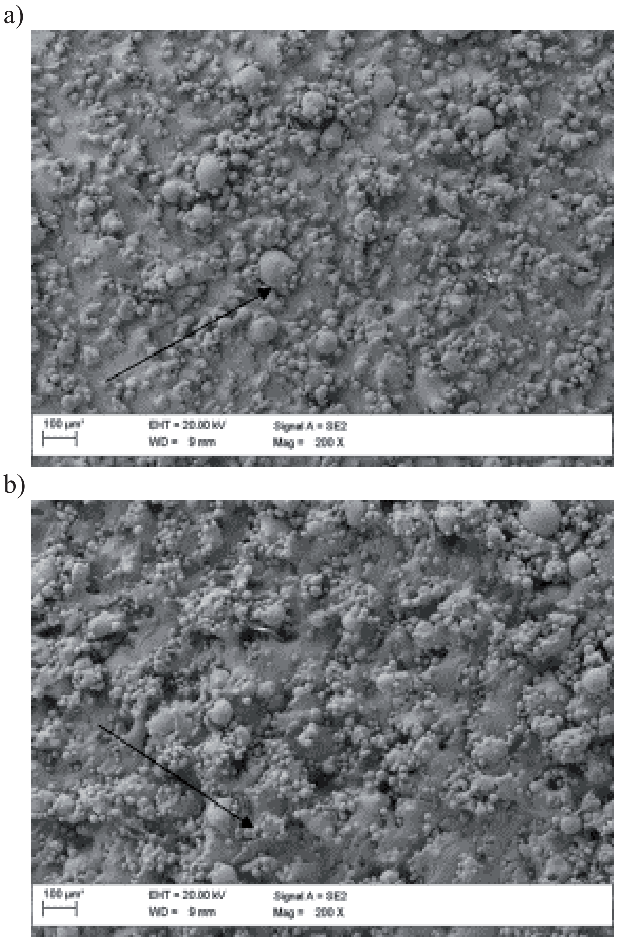


Fig. 4. a) External surface of a perpendicularly built SLS sample, b) External surface of an obliquely built SLS sample, arrow shows the build direction, P=100 W, PD=10 µm

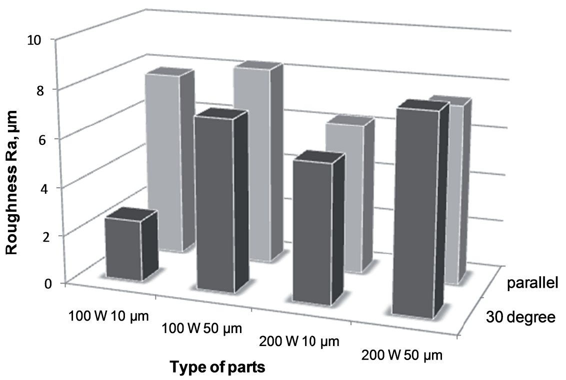


Fig. 5. Roughness of models orientated parallel and oriented at an angle of 30 degrees in respect to laser beam

It can be concluded that a strong increase in the surface roughness and a decrease in the dimensional accuracy are dependent on the deep holes and adherent semi-sintered particles on the surface. Surface conditions can have a significant effect on mechanical properties, particularly for fatigue. For many applications the parts must be subjected to machining to obtain a desired surface finish.

There exists a general correlation between roughness, power output and point distance: roughness increases with increasing power output and point distance. Thus, there is a process window at a power output 100 W and point distance 10 µm where the produced SLS samples have the lowest roughness, i.e. the best accuracy of the model.

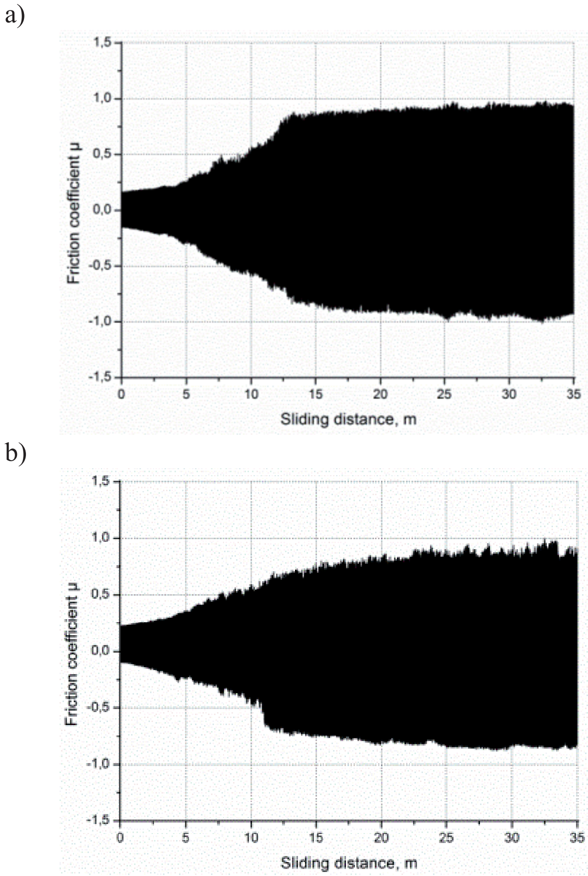
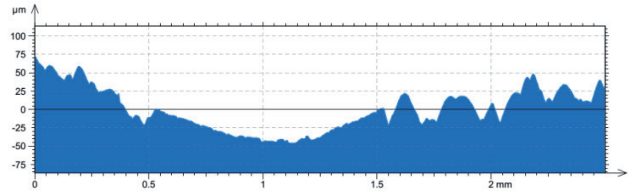


Fig. 6. Representative dependence of friction coefficient on sliding distance during the wear resistance test for part made at: a) 100 W and 10 µm (surface oriented at an angle of 30 degrees in relation to laser beam); b) 200 W and 50 µm (surface oriented parallel relative to laser beam)

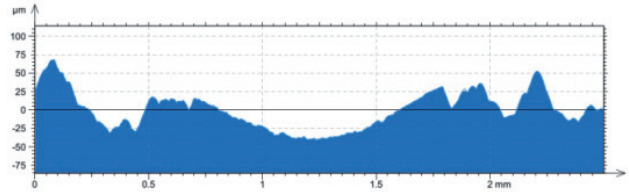
Figure 6 illustrates the diagram of changes in a dry friction coefficient µ obtained during tests of wear resistance in relation to a steel ball counter specimen at the temperature of 22°C for a wear track of 35 m. The friction curve has a characteristic shape, with the initial transient state with an unestablished curve, which a friction coefficient increases as the wear track increases until stabilising. This state takes place after approx. 12-15 m. The reason of long time of stabilisation tribological process is initialisation chipping (removing) adhered particles from the surface. The registered friction coefficient in the SLS samples ranges from 0.75 to about 0.9 depending on laser power, point distance and orientation of models.

The typical wear track profiles measured by profilometer of the SLS models deposited using the processing conditions in Figure 2 are shown in Fig. 7.

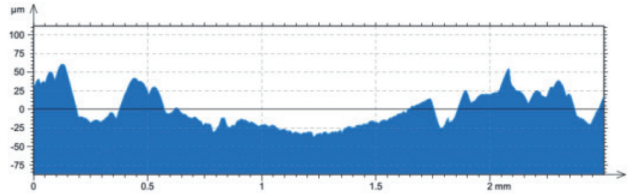
a)



b)



c)



d)

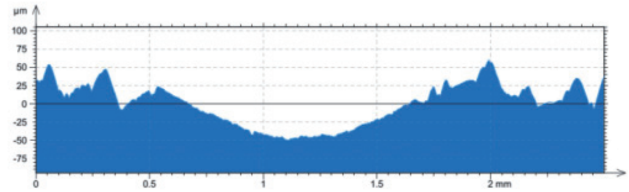
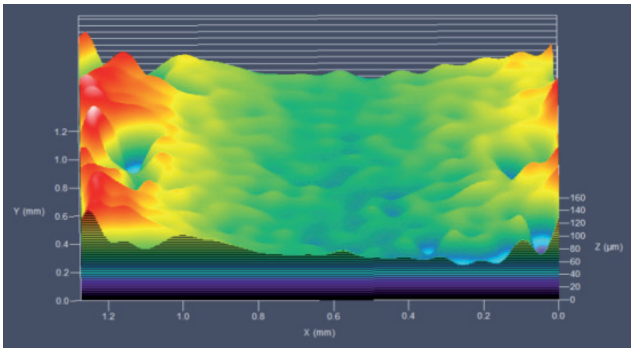


Fig. 7. Surface profiles measured across wear tracks on selected samples: a) 100 W, 10 µm (parallel); b) 100 W, 10 µm (30 deg.); c) 200 W, 50 µm (parallel); d) 200 W, 50 µm (30 deg.)

It can be found that a decreasing power output induces deeper and wider wear tracks produced on the SLS samples, as is presented in Fig. 7. In contrast to the influence of the changes of laser power on wear resistance properties of models, the change of the point's distance of the laser spot has a significant influence on changes in the geometry of wear tracks. The influence of this parameter on the wear tracks may be observed on the surface topographies obtained by confocal microscopy (Fig. 8). With the increase of the distance between the sintering points, the size of wear track increases and caused a worsening in the functional properties of perpendicular and oblique oriented surfaces.

a)



b)

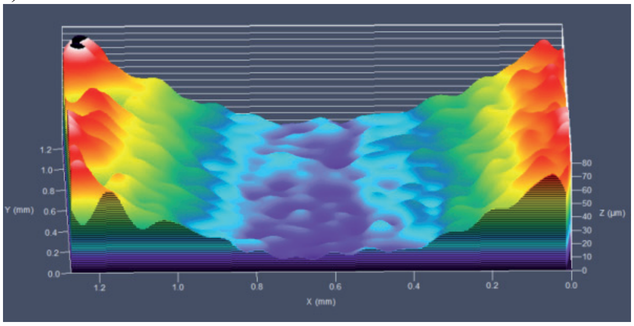


Fig. 8. a) After tribology test, SLS parameters 100 W, 10 µm, b) after tribology test 100 W, 50 µm SLS parameters

The wear depth of the perpendicular samples is about 45 µm, while that of the oblique samples is as deep as 65 µm. Changing orientation of the model from perpendicular to oriented at an angle of 30 degrees, in respect of a laser beam, induces an increase of wear resistance which can be related to the stair step effect. The surface has many sharp edges which are crumbling during wear resistance test, thereby there is increasingly rapid wear of the element. (For the elements oriented at an angle of 30 degrees in respect of the laser beam, wear track is much wider and deeper, when compared to track obtained for the surface oriented parallel to the laser beam).

Figure 9 illustrates the area cross section of the wear track after the wear test of SLS metallic models, for the assumed technological parameters. The highest value of track area, approximately 40000 μm^2, was observed for a metallic part made at a P=200 W and PD=10 μm oriented, parallel to the laser beam. The smallest value of track area, approximately 18000 μm^2, was observed for a metallic part made at P=100 W and PD=10 μm oriented parallel to the laser beam.

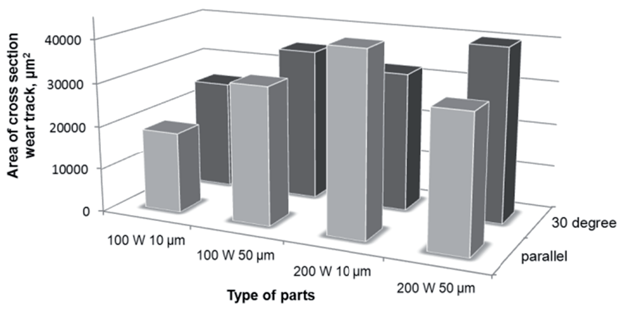


Fig. 9. Influence of the technological parameters on the value of the area of cross section wear track

As a result of the research conducted it can be concluded, that in the case of parts oriented at an angle of 30 degrees in respect to the laser beam, the increase in power output, ranging from 100 to 200 W and also the increase in the point distance, causes an increase in the area of cross section wear track and also the worsening of wear resistance. A similar situation is observed for the elements oriented parallel to the laser beam. The increase in power output and point distance causes an increase in the area cross section wear track.

Studies confirm that changes to the angle of inclination of metallic parts, relative to the laser beam, from parallel to oriented at an angle of 30 degrees, in respect of the laser beam for most of the analysed samples, causes deterioration of wear resistance.

A general correlation exists between the value of the area of cross section wear track, power output and point distance: Area of cross section wear track increases with increasing power output and point distance. Thus, there is a process window, at a power output 100 W and point distance 10 μm, where the produced SLS samples have the lowest wear volume, i.e. the best wear resistance.

The structures of elements oriented at an angle of 30 degrees in respect of the laser beam were studied using an electron scanning microscope. It was found that a very small "warping effect" exist as shown in the Figure 10. That effect occurs for all the analysed models, deflected by an angle of 30 degrees in respect of the laser beam.

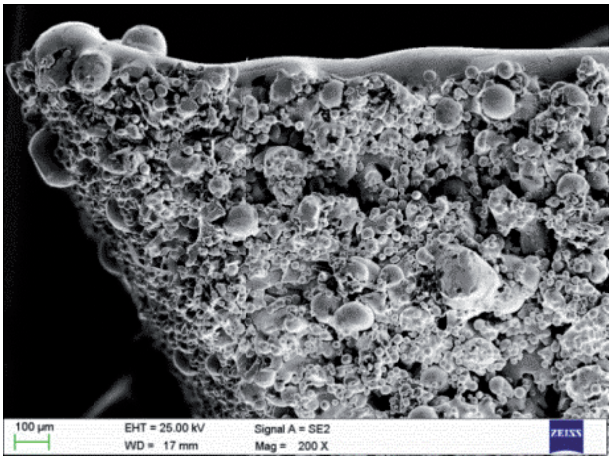


Fig. 10. Representative warping effect of the wall oriented at an angle of 60 degrees in respect of the substrate, part made at 100 W and 10 μm

The best application of properties were obtained for the samples made parallel to the laser beam, with laser power of 100 W and with 10 microns of the points sintered of metal powder during additive manufacturing.

4. Conclusions

This paper provides a method to improve the SLS parts roughness and wear resistance by choosing the correct process parameters. A clear difference in surface roughness, microstructure and wear resistance, are evident. Also it is demonstrated that full dense metallic parts can be generated by the SLS method. It was shown that changing of the power output and laser distance between the points sintered metal, as well as the orientation of the model relative to the laser beam, caused changes in geometric characteristics of wear tracks and, consequently, in the surface morphology. The results show that reduced power output and reduced point distance are favourable to improve the roughness of the SLS part.

By parametric analysis of the SLS process for SS 316L powder with particles having a size less than 45 μm, the optimal parameters of power output, laser distance between the points sintered of metal powder during additive manufacturing, as well as the orientation of the model relative to the laser beam and substrate were determined as 100 W, 10 μm and oriented parallel to the laser beam, respectively.

The study results showed that with increasing points distance of the laser spot the functional properties of parallel and surfaces oriented at an angle of 30 degrees in respect to the laser beam get worse.

The presented results of the effect of the SLS process parameters on the roughness and wear resistance can be used to analyse the artificial neural network in order to select the proper process conditions without having to perform additional research.

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