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Surface Morphology in Selective Laser Melting of Metal Powders

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Abstract

Selective Laser Melting (SLM) is a powder-based additive manufacturing capable to produce parts layer-by-layer from a 3D CAD model. Currently there is a growing interest in industry for applying this technology for generating objects with high geometrical complexity. To introduce SLM process into industry for manufacturing real components, high mechanical properties of final product must be achieved. Properties of the manufactured parts depend strongly on each single laser-melted track and each single layer, as well as the strength of the connections between them. In this study, effects of the processing parameters such as hatch distance on surface morphology are analyzed.

Keywords: Additive manufacturing; Selective laser melting; Metal powders

1. Introduction

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 [1]. Among AM technologies, selective laser melting (SLM) is a unique technology to produce objects from metal powders with complex geometry and mechanical properties comparable to those of bulk material.

SLM is widely used in various industries ranging from aerospace to biomedical. Nowadays, interest in biomedical applications of SLM increases greatly, implants and prostheses with desired shape, internal structure and engineered composition including the appropriate protective coating are produced; final shape functional bone ingrowth materials are elaborated. SLM is also a suitable technique to create micro-objects [2-3]. A lot of publications describe the creation of porous materials, materials with structured surfaces; specially structured SLM surfaces enable to manufacture objects with enhanced and unique properties and functionality [4-6].

The essential operation in selective laser melting (SLM) is the laser beam scanning over the surface of a thin powder layer previously deposited on a substrate. The forming process proceeds along the scanning direction of the laser beam. Each cross-section (layer) of the part is sequentially filled with elongated lines (tracks) of molten powder, i.e. SLM part is the superposition of tracks and layers. Since the 3D objects in SLM are built layer-by-layer, the layer morphology substantially determines the final product properties.

A number of factors (including direct and indirect parameters) affect on SLM process [7–9]. Principal process parameters in SLM are laser power, wavelength, spot size diameter, scanning speed, hatch distance, powder layer thickness [10-12]. Material-based input parameters are powder granulomorphometry, chemical composition,

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thermal, optical, metallurgical, mechanical and rheological characteristics [13-17].

Physical behaviour of "laser radiation–powder–substrate" system includes absorption, reflection, radiation and heat transfer, phase transformations, a moving interface between solid phase and liquid phase, fluid flow caused by surface tension gradient and mass transportation within the molten pool, and chemical reactions. This system has non-linear response when the process parameters are modified: changing laser power or scanning speed can lead to various undesirable effects as irregularity and balling effect [18]. Therefore it is important to establish links between the principal SLM parameters and surface morphology. The purpose of this study is to analyze the influence of the hatch distance and thickness of powder layer on morphology of the first layer and the surface structure of thin walls produced by SLM from metal powders. Obtained data can be used in surface structuring and micro-part manufacturing characterized by a small number of layers within a part and, thus, sensible to the geometric dimensions and the shape of surface.

2. Experimental procedure and materials

Experiments were carried out on SLM machine PM 100 (Phenix Systems). The source of radiation is YLR-50 continuous wave Ytterbium fiber laser (IPG Photonics) with a wavelength of 1075 nm. The main characteristics of PM 100 machine are as follows: the maximum laser power is 50 W; the maximum laser scanning speed is 3 m/s; the laser spot size on the surface of the powder bed is about 70 µm. The process chamber provides a closed environment filled by nitrogen as a protective gas, operational temperature of the process chamber was fixed at 80ºC.

The powders of stainless steel (SS) grade 904L produced by Sandvik Osprey and of SS grade 316L from TLS Technik were chosen as basic materials for the experiments. These alloys are an austenitic nickel-chromium steels which are widely used in chemical, pharmaceutical, petrochemical, energy and pollution control industries. Molybdenum and copper increase resistance to pitting and crevice corrosion and to general corrosion in reducing acids; the higher nickel content provides good resistance to chlorides. The low carbon content provides resistance to intergranular corrosion in the laser treatment or stress relieved condition [19].

Granulomorphological analysis of the particles was carried out by an optical granulomorphometer ALPAGA 500 NANO (OCCHIO s.a.) which is a real-time optical sieving system. Both materials are pre-alloyed gas-atomized powders, and most of the particles have high sphericity and smooth surface with a negligible quantity of satellites. Particle size and chemical composition of the powders employed in this study are presented in Tables 1 and 2.

Table 1. Powder characteristics *

Powder characteristics \ Materials		SS grade 316L	SS grade 904L
Equivalent diameter (weight by volume), µm	*p*10	5.3	5.1
	*p*50	14.5	11.2
	*p*90	25.2	18.5

* *p*10–*p*50–*p*90 are 10th, 50th and 90th percentiles of studied indexes. 10–50–90 percentiles are the values below which 10–50–90% of the observations may be found.

Table 2. Chemical composition (% wt.) of powders SS grade 316L and 904L

	Fe	Ni	Cr	Mo	Cu	Si, max.	P, max.	Mn, max.	S, max.	C, max.
316L	Balance	11.0-12.0	17.0-18.0	2.0-3.0	0.00	1.0	0.045	2.00	0.030	0.02
904L	Balance	23.0-28.0	19.0-23.0	4.0-5.0	1.0-2.0	2.0	0.045	0.55	0.035	0.02

3. Results and Discussion

The general purpose of the experiments is to study the effect of hatch distance on surface morphology during selective laser melting. Based on previously experimental results [8], the laser irradiation parameters are fixed as follows: the laser power *P* is 50 W, the scanning speed *V* is 0.14 m/s. The hatch distance (shift between tracks in the plane of the beam scanning) varied from 60 up to 280 µm with a step of 20 µm. For the given process parameters at 50 µm layer thickness (SS grade 904L) on steel substrate (SS grade 304L), the single track width is 120 µm. Therefore, the hatch distance 60 µm yields tracks with 50% overlapping each other. A gap between single tracks appears at shifting distances greater than 120 µm. The further increasing hatch distance accordingly increases the gap between two neighbouring tracks and leads to their isolation. The powder, which has been not involved in the process of the tracks synthesis, has appeared at the hatch distance about 240 µm (Figure 1).

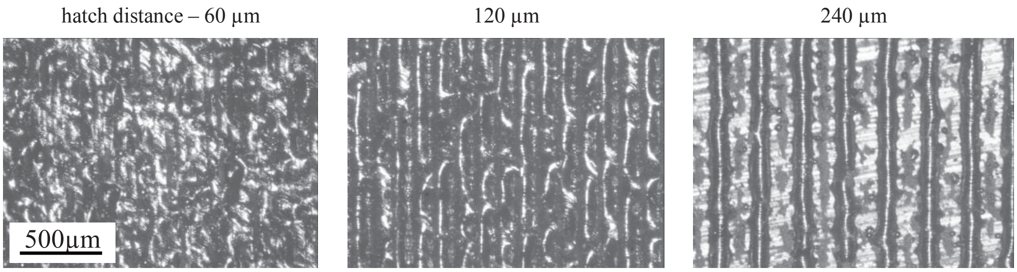
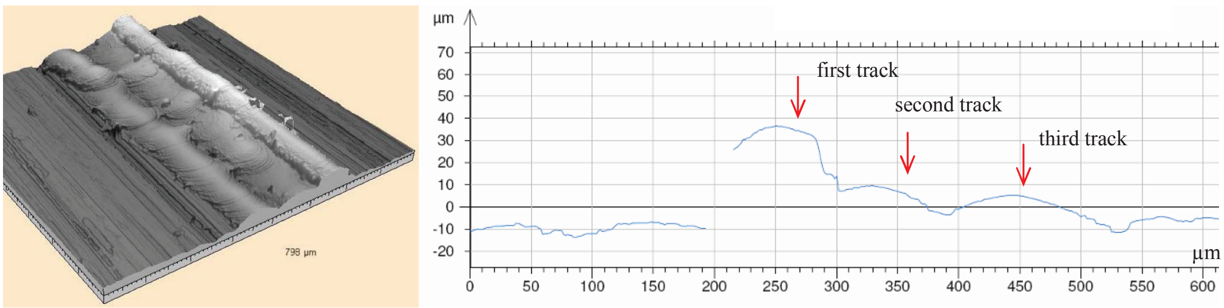


Figure 1. Surfaces of the first layer from SS grade 904L powder obtained at different hatch distances (60, 120 and 240 µm). Powder layer thickness on steel substrate is 50 µm, laser power is 50 W, and scanning speed is 0.14 m/s.

At a hatch distance more than 120 µm and ~70 µm laser spot diameter, SS grade 904L powder is melted in a sequence of tracks with the same geometric characteristics (excluding the first track). The decrease of the hatch distance leads to changes in the thermo-physical conditions of the synthesis: the laser beam directly interacts with the powder, the substrate (effect of substrate denudation) and the previously synthesized track or only with the substrate and the previously synthesized track. A molten pool has higher levels of reflectivity than loose powder [7, 20]. The absorbed energy reheats the previously synthesized track or the substrate, the heat is conducted further through the substrate causing sintering/melting of the powder particles. Owing to the substrate denudation, the second track is lower than the first one, and the zone of powder consolidation also diminishes (Figure 2, 3).



(a) (b)

Figure 2. Three synthesized tracks from SS grade 904L powder on substrate at 100 µm hatch distance: (a) 3d image, (b) profile of the tracks.

Experiments and modeling reported by Taylor et al. [7] confirm that the amount of melted material decreases with the decrease of the hatch distance. Previously processed material can act as a heat sink for laser energy, and this effect increases with the reduction of the hatch distance. Furthermore, rescanned solid metal absorbs less incident laser energy than loose powder. These two effects mean that the first laser scan melts more material than the following scans do, i.e. the first scan is always the largest in the case where the hatch distance is smaller than the powder consolidation zone.

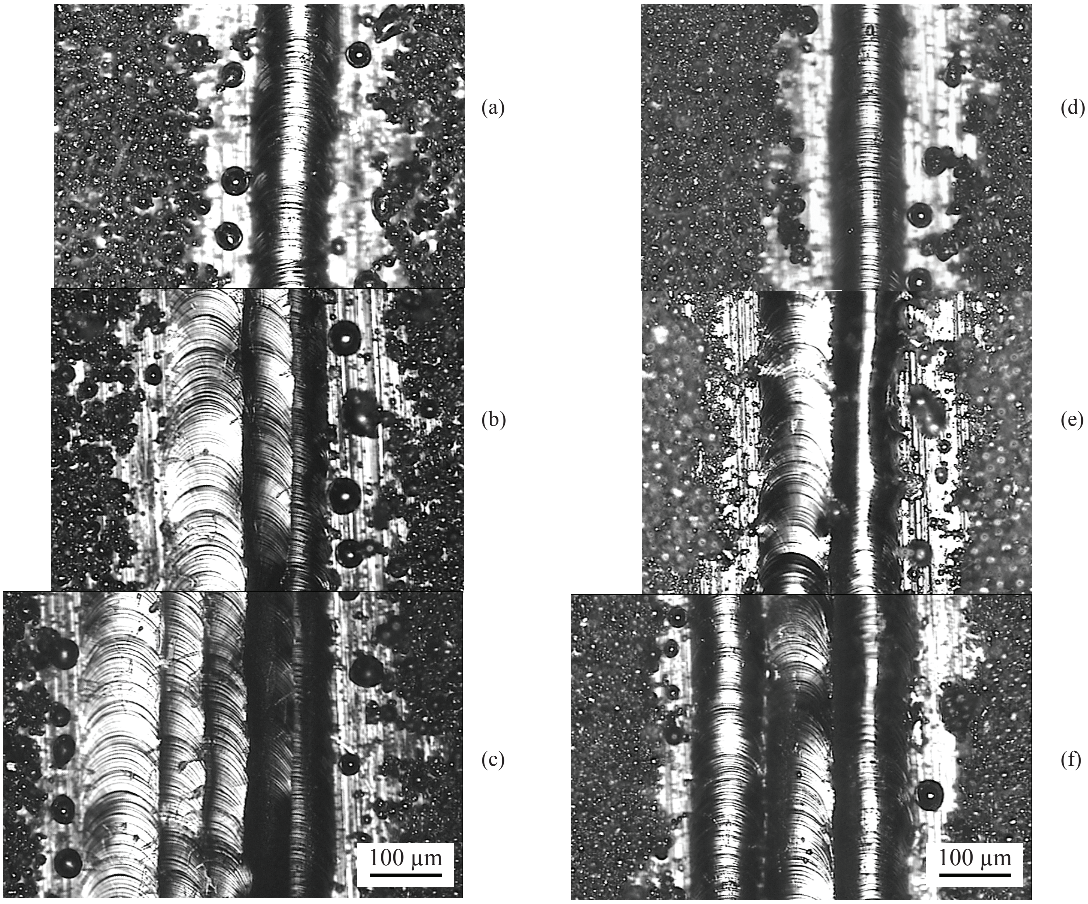


Figure 3. Top view of tracks synthesized from SS grade 904L powder on substrate at different hatch distances: (a), (b), (c) – one, three, and five tracks at 60 μm hatch distance; (d), (e), (f) – one, two, and three tracks at 100 μm hatch distance.

A series of experiments was carried out with SS grade 316L powder: the layer thickness was 50 μm, $P = 50$ W and $V = 0.10$ m/s. At hatch distance less then tracks width, a consecutive reduction of the powder consolidation zone leads to the situation when the laser beam again to start interacts directly with the powder (as in the case of the first track) and the previously synthesized track instead of an indirect interaction through heat conductivity of the substrate and convection phenomena (Figure 4). Analysis of the cross-sections of the tracks synthesized on the substrate (Figure 5) and the profile of a continuous sequence of tracks (Figure 6) showed the difference in height of these tracks: the tracks in the beginning and the end of the sequence (indicated by the arrow) are higher than the internal tracks.

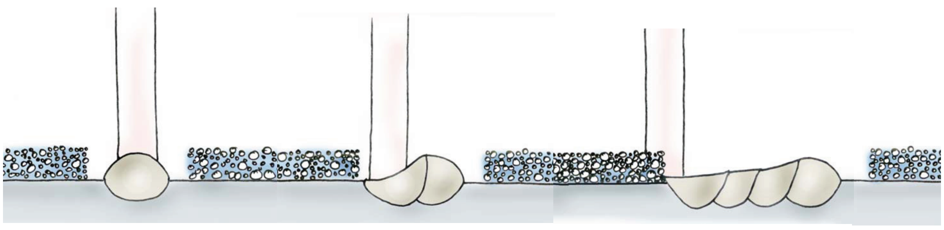


Figure 4. Scheme of consecutive reduction of the powder consolidation zone during SLM.

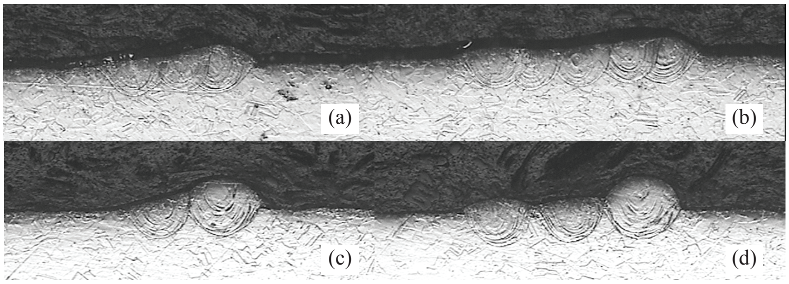


Figure 5. Cross-sections of sintered tracks from SS grade 316L powder on steel substrate at different hatch distance: (a), (b) – 3 and 5 tracks at hatch distance 60 µm; (c), (d) – 2 and 3 tracks at hatch distance 100 µm.

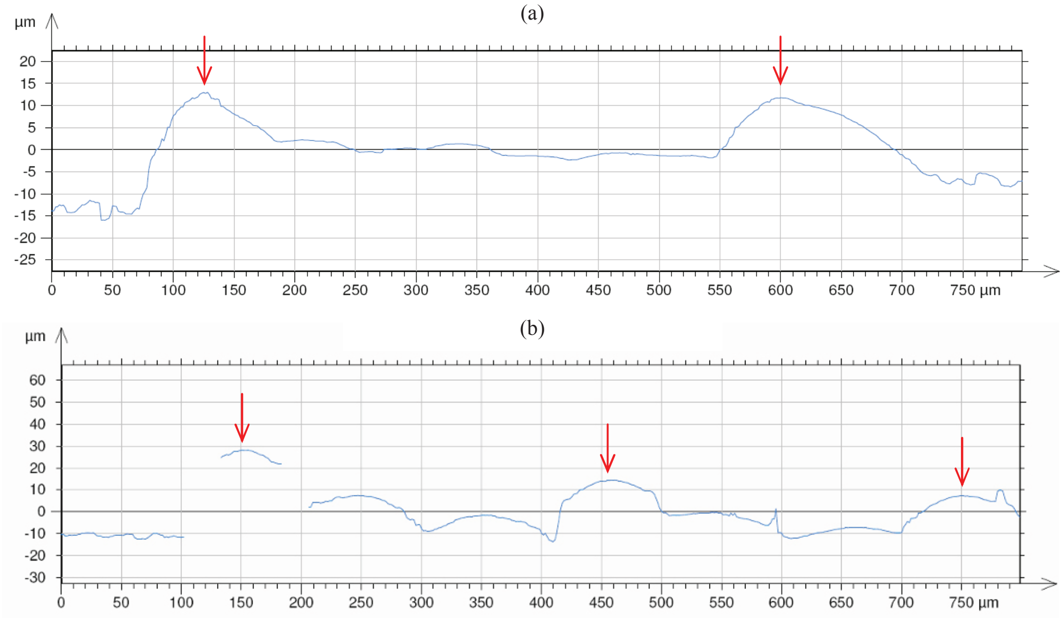


Figure 6. Profile of a continuous sequence of tracks produced from SS grade 316L powder with 60 µm (a) and 100 µm (b) hatch distances.

A difference in tracks height should be to take into account both the surface structuring and manufacturing of 3D parts. Because this type of surface morphology can lead to regular internal porous structure [21], that can be avoided by applying a special strategy of manufacturing [21-23].

Another important question is a surface morphology of one-pass thin wall manufactured by SLM. In Figure 7 presented of the surface obtained at gradual increase layer thickness from 40 µm up to 80 µm with step 10 µm (SS grade 316L powder, 20 layers for each thickness, scanning speeds is 0.04÷0.18 m/s and laser power is 50 W). Thin wall had no pores up to the scanning speed V= 0.12 m/s for all the range of layer thickness.

Smoothness of the surface formed is a particularly significant characteristic of the additive manufacturing process [24-26]. For V= 0.04–0.06 m/s for all the range of layer thickness, the surface of the wall was rough. Surface imperfections resulted from irregularity and distortions of single vectors due to power excess. For V= 0.14 m/s and layer thickness h= 70 µm and greater, small irregular pores appeared. With increase of the scanning speed, pores became regular and large, and they appeared at smaller layer thickness (h= 60 µm for V= 0.20 m/s). Pores are elongated and perpendicular to the sintering direction. With increase of scanning speed and layer thickness pores became more oriented (Figure 7). For smaller layer thickness (h= 40÷50 µm) the surface of the wall is smoother as a result of fine structure of the sintered tracks (the height of the track is smaller and the remelted depth into underlying track is bigger).

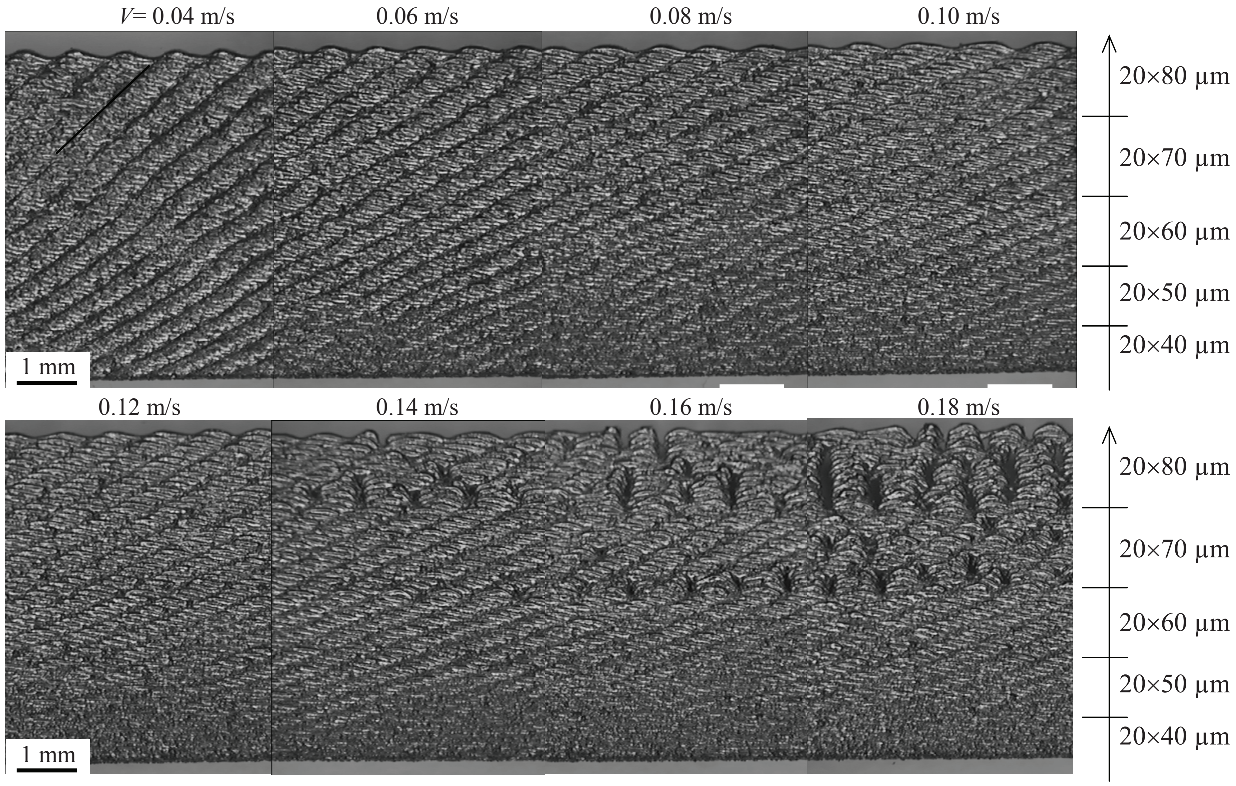


Figure 7. Laser sintered thin walls from SS grade 316L powder. Thickness of powder layers varied from 40 to 80 µm with a step of 10 µm and 20 layers for each thickness; scanning speed is 0.04÷0.18 m/s; laser power is 50 W.

4. Conclusions

It was shown that changing of hatch distance caused modification in geometric characteristics of tracks and, consequently, in the surface morphology. A track width and effect of substrate denudation shall be jointly considered when choosing the hatch distance. Analysis of the influence of the hatch distance on forming the first layer from metal powder showed that the value of the maximum shift distance should not exceed average width of the continuous track in order to manufacture a smooth surface. For fabrication of a one-pass thin wall by SLM (at fixed laser power) both parameters, layer thickness and scanning speed, are important. The surfaces have a very specific morphology. What could probably be explained by the shape of molten pool, which is elongated with the scanning speed, but this requires further study.

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