STUDY OF MICROSTRUCTURE AND PROPERTIES OF 316L STEEL AFTER SELECTIVE LASER MELTING

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Abstract

Additive technologies provide engineers with an innovative approach for design and manufacture of parts. The development of additive manufacturing technologies, such as selective laser melting, allows making metal products by melting the powder and obtaining a continuous solid-phase structure. The paper presents the results of study of selective laser melting process of steel 316L powder. Morphology and particle size distribution of the initial powder was shown. The chemical composition, microstructure and phase composition of the compact samples obtained by selective laser melting technology before and after heat treatment was investigated. The results show that the density of the samples was close to 100 %. Analysis of the microstructure of the samples before heat treatment shows a high crystallization speed, leading to the formation of the fine structure. Mechanical tensile properties for the samples before and after heat treatment were measured.

Keywords: Selective laser melting, stainless steel, 316L, powder metallurgy, additive manufacturing

1. INTRODUCTION

Additive technologies that assume manufacturing of physical models, tools, functional parts directly from a CAD-model, now attract a big interest for researchers. In one such technique, called selective laser melting (SLM) - focused laser radiation is used to melt particles of powder material and receiving solid-phase structure. This allows obtaining products with complex shape, production of which by traditional methods is significantly difficult. In this study, investigations were carried out to determine mechanical characteristics of the samples before and after heat treatment. Also, a comparison with the properties of products obtained by traditional methods were made.

2. EXPERIMENTAL METHODS

Production of samples was carried out on the SLM 280HL machine, produced by SLM Solutions GmbH. This machine is equipped with two fibre lasers (400 and 1000 Watts) with beam diameters of 81 and 700 µm, the characteristic length of radiation - 1070 nm, scanning speed up to 15 m/s. Maximum dimensions of parts are limited by build area, which is 280 x 280 x 350 mm. The process takes place in inert atmosphere (nitrogen or argon), the choice of which is determined by used powder material. A detailed description of operating principle of the machine was shown in [1-5].

Powder steel 316L was used as initial material. This powder was obtained by gas atomization of melt and provided by the manufacturer of SLM machine. Steels are a promising class of materials for use in selective laser melting [4-8] and can be used for making tools with complex shape, parts with internal cooling channels, heat exchangers, impellers, high pressure pumps elements and others.

Grain size distribution of the powder was determined by laser diffraction measurements on the unit particle size Analysette 22 NanoTec plus with a total measuring range of 0.01 - 2000 microns, equipped with three semiconductor lasers and fully meets the requirements of ISO 13320 «Particle size analysis - Laser diffraction method». Ultrasonic radiation was used in the measurement process, allowing to split small particles conglomerates. The study was conducted three times, results of these measurements were averaged, and the table and the histogram distribution of the particle diameter were made.

Tensile testing was performed at the Zwick-Roell machine. Study of microstructure of samples was carried out using an light microscope Leica DMI5000 M (x50 - x1000 magnifications). Investigation of morphology of powder particles was made by a scanning electron microscope (SEM) TESCAN Mira 3 LMU, operating at magnifications ranging from 4 to 10^6 times with accelerating voltage of 200 V to 30 kV. To study properties of specimen after homogenization heat treatment was carried out (heating up to 1200 °C, 20 min delay, quenching in water). This heat treatment also makes it possible to remove the stresses arising during the production of the parts. The study of samples microstructure was carried out by etching with the mixture of HNO_3 and HCl acids taken in the 1:3 ratio by volume.

3. RESULTS AND DISCUSSION

The predominant number of particles has a shape close to spherical. The surface of most particles is not smooth and covered with a large number of small satellite particles. These particles were solidified under conditions of collisions of large drops with smaller ones during atomising process. These satellites can affect the obtained apparent density in two ways. Firstly, it can be increased by filling the small pores if they break away from the larger particles. Secondly, they can reduce the density by preventing compaction if they are tightly connected to the core particles. Also, the satellites may influence technological properties of the powder, such as flowability, absorption of laser radiation and others.

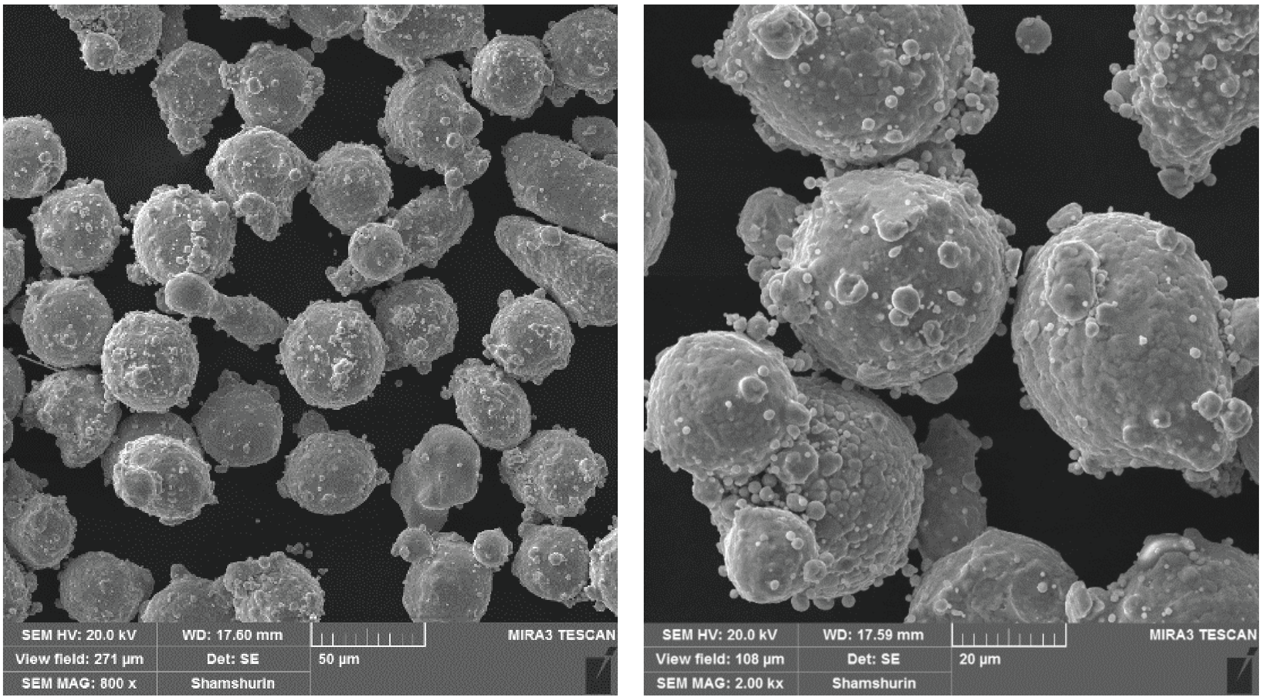

Figure 1 SEM-images of steel 316L powder particles

The results of particle size distribution measurement show that the predominant particle size is around 25 microns - see **Figure 1**. The spread is not very large, the size of more than 98 % of the particles are in the range from 5 to 60 microns. Since the amount of particles smaller than 5 microns is about 0.8 %, it can be assumed that the satellites on particles surfaces are kept sufficiently tight and do not detached from them. Further, samples were produced by obtaining selective laser melting. Following regime parameters were used: the laser beam speed - 550 mm / sec, power - 175 watts, beam diameter - 70 mm, layer thickness - 50 µm.

The study of phase composition of samples after SLM showed the presence of 100 % gamma phase (austenite). The chemical composition after SLM fully corresponds to chemical composition on the alloy in ASTM A240 (**Table 1**) [9].

Table 1 Chemical composition of bulk specimen (wt. %)

Specimen	C	Mn	P	S	Si	Cr	Ni	Mo	Fe
Mass Content, wt. %	0.01	1.20	0.007	0.016	0.342	16.4	12.0	2.48	Bal.
ASTM A240 [9]	<0.03	<2.00	<0.045	<0.030	<0.750	16.00-18.00	10.00-14.00	2.00-3.00	Bal.

As can be seen from measurements, the porosity of the obtained samples is relatively low. The etching was carried out to determine the grain and dendrite structure.

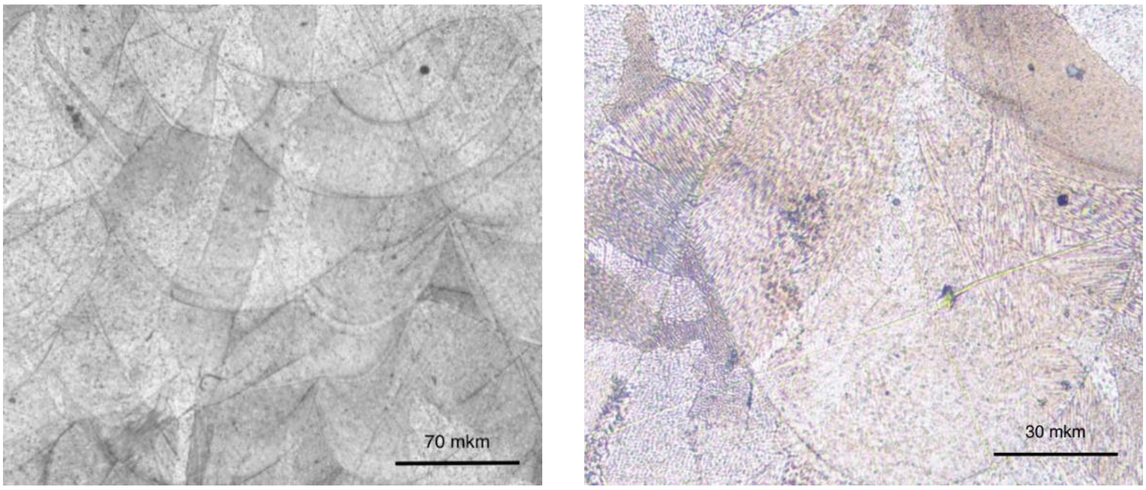

Figure 2 Microstructure of cross-section specimen after SLM

On microstructure of samples at low magnification laser tracks are visible. Curved lines that are shown in the **Figure 2** represent a cross section of melts. The height of these melts is greater than layer thickness on average by 50-70 %, indicating the repeated re-melting of lower layers. In addition, "overlaps" of neighbouring laser tracks were produced in order to avoid the formation of elongated pores. This causes partial re-melting of the neighbouring tracks. A nucleus for growth of the molten bath crystals are crystals of the underlying layer. This leads to the formation of elongated in z-direction grains.

Due to the small diameter of the laser beam, the same laser processing conditions across parts volume and localization of the area of heating - a metal structure over the entire area of section is practically the same, and distribution of impurities is possible only on the area of laser tracks.

On microstructure of frozen tracks a cellular structure with submicron distances between the cells is observed. The distance between cells varies depending on the area of the track: the minimum distance is observed at lowest part [10].

Measurement of average distances between centres of adjacent cells on obtained micrographs showed that the average size of cells in upper part of layer - 730nm; in middle part - 628 nm, at bottom - 580 nm. This is due to the fact that the heat transfer at the bottom of the molten pool occurs by conduction to the underlying layers and to previously solidified metal. Heat transfer in the upper part of the track occurs in the molten metal and to the gas medium. During the heat treatment, individual cells were disappeared, and instead of cell clusters a larger grains appeared. The structural heterogeneity, which was caused by the appearance of cellular structure, was smoothed (**Figure 3**).

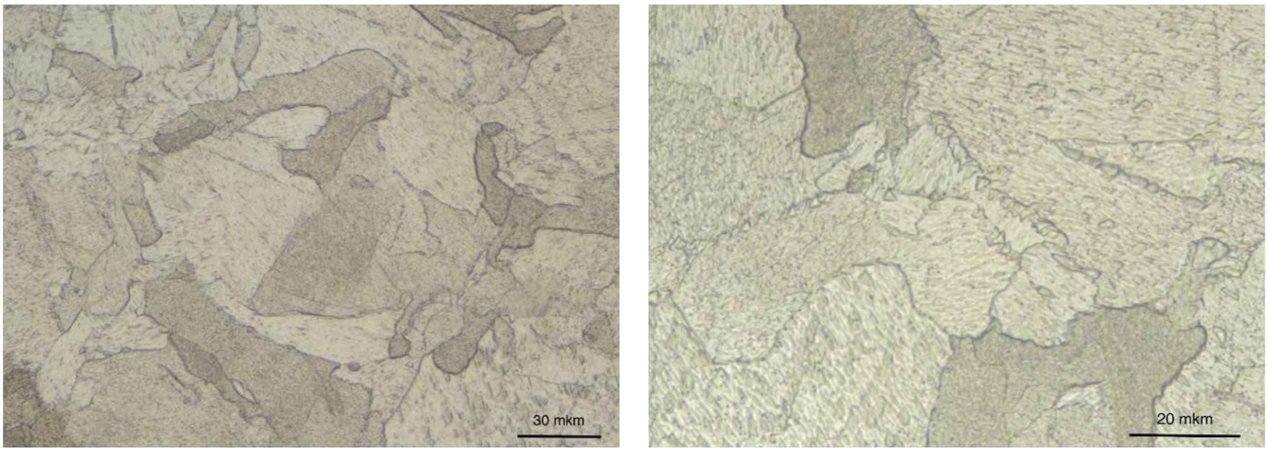

Figure 3 Microstructure of specimen after SLM and heat treatment

Further study of mechanical properties of obtained samples was made. The properties of samples were investigated without special machining. The surface of the samples remained unchanged. From results of the study of samples it was obtained, that the value of the tensile strength and elongation obtained is greater for vertically grown specimens (**Table 2**). This may be due to a rather smooth surface obtained of the vertical sample, because there was no support structure at its side surface.

Table 2 Mechanical properties of specimens produced from 316L stainless steel by SLM

Specimen	**Yield strength [MPa]**	**Tensile strength [MPa]**	**Elongation [%]**
SLM before heat treatment	427	631	56
SLM after heat treatment	368	603	75
Wrought [9]	290	517	40

Results of tensile tests after the heat treatment showed a greater elongation but lower tensile strength, which is probably due to the decrease of internal stresses and alignment segregation heterogeneity.

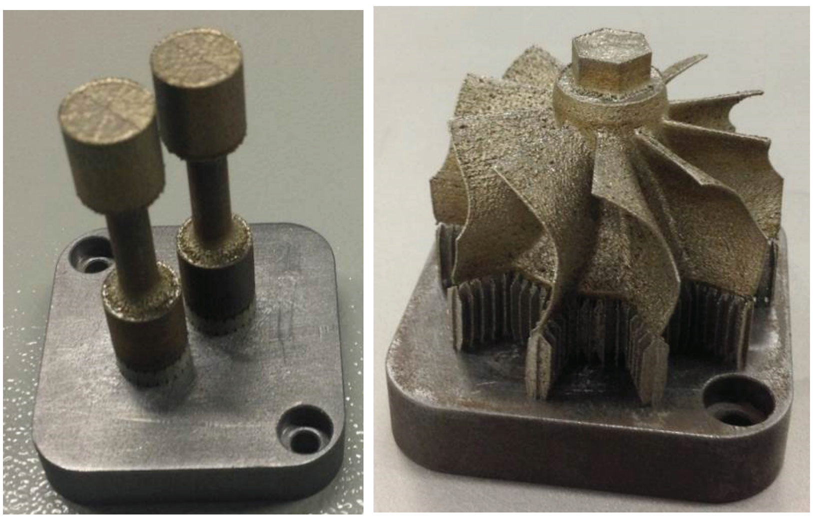

Figure 4 Images of specimens for tensile tests and turbine wheel manufactured by selective laser melting of 316L stainless steel

Compared with properties of the products produced by traditional methods, the samples obtained by the SLM technology, tensile strength and elongation are higher, due to the peculiarities of crystallization and dimensional parameters of the structure, resulting in processing of material by laser with small beam diameter and high power [10]. **Figure 4** shows the samples for the tensile tests and the turbine wheel with complex geometry on the build platform.

4. CONCLUSION

Thus, it is shown that by using selective laser melting technology products can be manufactured with high mechanical properties. The morphology of the initial powder is spherical, with small growths-satellites. Strength and ductility of samples obtained by selective laser melting are higher than that of wrought samples. The chemical composition of samples after SLM fully corresponds to chemical composition requirements of 316L steel. The microstructure of the specimens - cellular, with the size of 0.5-0,8 μm. After the heat treatment individual cells disappear, and instead of them large grains are formed. The possibility of manufacturing complex parts from 316L stainless steel powder by SLM technology are shown.

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