DESIGN AND MANUFACTURE OF PARTS WITH A TAILORED STRUCTURE BY SELECTIVE LASER MELTING

Evgenii BORISOV, Anatoly POPOVICH, Vadim SUFIIAROV, Igor POLOZOV

National Technology Initiative Center of Excellence in Advanced Manufacturing Technologies at Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation
evgenii.borisov@icloud.com

Abstract

The paper investigates the influence of the layer thickness and the laser spot diameter in the process of selective laser melting, as well as subsequent heat treatment on the structural-phase composition and mechanical properties of the manufactured parts. The possibility of manufacturing parts with a tailored structure from an Inconel 718 superalloy using selective laser melting is demonstrated by varying the technological parameters of the process. In this case, the elements of a part with different grain size and orientation are formed.

Keywords: Selective Laser Melting, Inconel 718, nickel superalloy, powder metallurgy, additive manufacturing

1. INTRODUCTION

The technology of Selective Laser Melting (SLM) is already actively used for the production of metal parts. This is due to the possibility of manufacturing parts with a complex configuration in the shortest possible time without the need for tooling. The latter is especially relevant in such areas as aviation and medicine [1-3]. In aviation, where titanium and nickel alloys are widely used, special requirements are imposed in a wide range of products [1,4].

Inconel 718, especially produced by additive manufacturing, attracts a lot of attention of researchers due to its wide application in the elements of gas turbines, aerospace parts, in the petrochemical and nuclear industry due to its heat resistance, corrosion resistance and high temperature properties [5,6].

However, there are not enough information in papers on the possibility of using the features of the selective laser melting process to control the microstructure and crystallographic texture, even less information on the relationship between the preferred anisotropy, microstructure and mechanical properties of the alloy [7-10].

In this regard, the purpose of this work is to establish patterns of structure formation depending on the initial technological parameters and to develop a manufacturing method and study the properties of compact products with tailored structure.

2. EXPERIMENTAL METHODS

Compact samples were made on a selective laser melting machine SLM280HL, SLM Solutions GmbH. As an initial material, a powder of the Inconel 718 heat-resistant nickel alloy obtained by gas atomization was used. The particle size distribution was determined using the laser diffraction method on an Analysette 22 NanoTecPlus with a full scale range of 0.01-2000 μm. Investigation of surface morphology of particles and compact samples, texture characteristics by diffraction of backward reflected electrons (EBSD) was carried out using a scanning electron microscope TESCAN Mira 3 LMU (SEM) operating at magnifications of $4\text{-}10^6$ at an accelerating voltage of 200V-30 kV, EBSD analysis was performed at accelerating voltage of 20 kV in steps of 5 μm. X-ray phase analysis was performed on a multifunctional X-ray diffractometer Bruker D8 Advance. Measurements to determine the mechanical properties were carried out in accordance with ISO 6892-1 on a

Zwick / Roell Z100 test machine with a maximum force of 99640 N. Hot isostatic pressing (HIP) was carried out in an Avure Quintus gas-state at a temperature of 1180 °C and a pressure of 150 MPa for 3 hours. The heat treatment was carried out in two stages: annealing at a temperature of 1065 °C for 1 hour with cooling in air; aging - was carried out in two stages, 1 - at a temperature of 760 °C for 10 hours, then cooling to 650 °C for 2 hours and holding at 650 °C for 8 hours, then cooling in air. A study of the microstructure on an optical and electron microscope, as well as mechanical properties at room temperature, was carried out jointly with the Delft Technical University [11].

3. RESULTS AND DISCUSSION

Investigations of the Inconel 718 powder on a scanning electron microscope (**Figure 1**) showed that the powder particles have a round, nearly spherical shape. The particle size is in the range: d_{10} = 21.1 µm, d_{50} = 37.4 µm, d_{90} = 62 µm. Some of the particles have satellite outgrowths (**Figure 1b**). The presence of such particles is typical for powders obtained with gas atomization. Investigations of the surface morphology of particles at high magnification showed that their surface has some irregularities, reflecting the cast microstructure of the material and refer to cellular-dendritic crystallization.

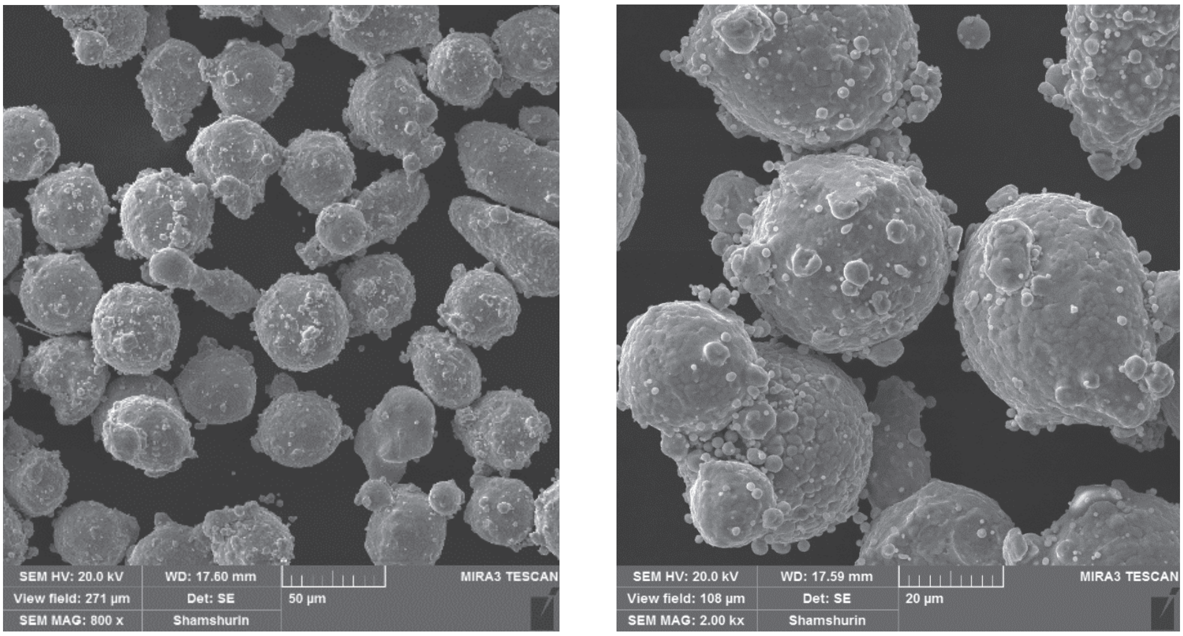

Figure 1 SEM-images of Inconel 718 powder particles

SLM process parameters with a similar energy density for the layer thicknesses of 50 and 100 µm (with laser beam diameters 80 and 700 µm respectively) were used to obtain samples for studying the microstructure, phase composition and mechanical properties. Due to the rapid solidification in the SLM process (10^4-10^6 K/s), the initial microstructure consists of cellular dendrites. The rate of solidification and, accordingly, the size of the cells depends on the thickness of the layer and the technological parameters used in the SLM process.

The measurements showed that the average cell size at a layer thickness of 50 µm is 0.9-1.1 µm and at 100 µm is 1.3-2 µm. Other differences in the formation of the microstructure for different thicknesses of the layers are shown in **Figure 2**, where a texture study performed by EBSD analysis is presented.

The microstructure of a sample made with a layer thickness of 50 µm has finely dispersed grains without a predominant orientation, whereas the microstructure of a sample made at a layer thickness of 100 µm has columnar grains with a predominant orientation <001>.

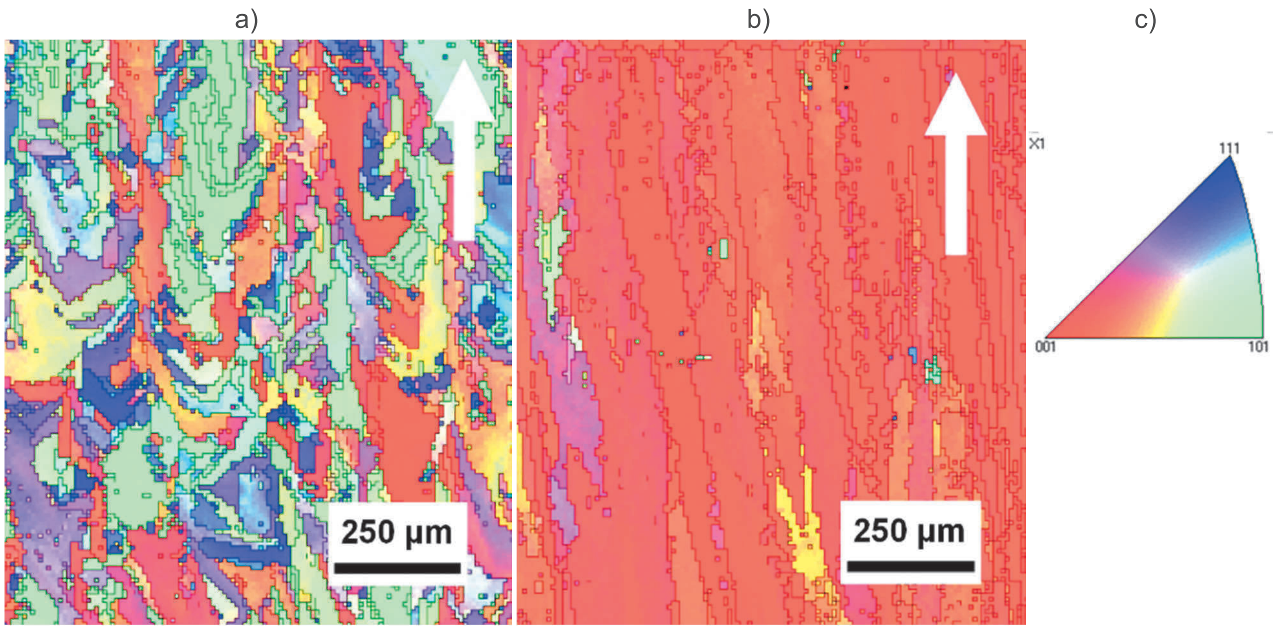

Figure 2 EBSD analysis of specimens made by SLM: a) orientation map of crystallites for a sample with a layer thickness of 50 μm; b) orientation map of crystallites for a sample with a layer thickness of 100 μm; c) index map

Differences in the microstructure should also affect the strength characteristics. For the testing of the rupture, cylindrical specimens were prepared for testing in accordance with ISO 6892-1. The yield strength, ultimate stress and elongation of the samples (shown in **Table 1**) were determined from the tensile test results.

Table 1 Tensile test results for Inconel 718 alloy samples manufactured by the SLS method

Layer thickness (μm)	**Yield strength** $\sigma_{0.2}$ (MPa)	**Ultimate strength** σ_B (MPa)	**Elongation** (%)
SLM			
30	745 ± 9	1004 ± 8	25 ± 3
50	650 ± 11	845 ± 9	28 ± 4
100	543 ± 2	782 ± 6	31 ± 6
SLM + HIP			
50	645 ± 6	1025 ± 14	38 ± 1
100	481 ± 11	788 ± 12	34 ± 3
SLM + HIP + Annealing + Aging			
30	1157 ± 8	1363 ± 12	21 ± 1
50	1145 ± 16	1376 ± 14	19 ± 1
100	1065 ± 20	1272 ± 12	15 ± 4

After annealing and aging, the mechanical properties have significantly higher values (see **Table 1**), this was due to changes in the phase composition of the material, the release of the strengthening phase γ"- Ni_3Nb. Mechanical properties after HIP decreased due to grain growth at elevated temperature, but the HIP significantly increased the elongation due to reduced porosity. When studying around grains, a network of NbC carbides is observed (**Figure 3**). The presence of carbides inhibits the growth of grains during HIP and thermal processing, and also promotes hardening of the material.

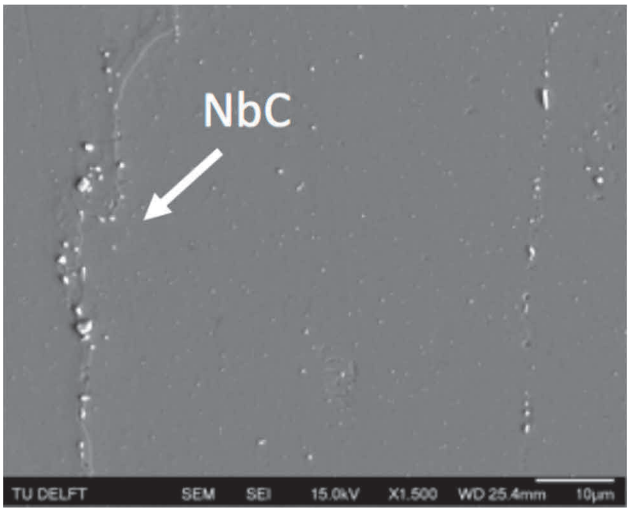

Figure 3 SEM image showing the presence of carbides in the alloy structure

At the next stage of work, a method for manufacturing samples with a given structure in individual elements was developed. For the production of different regions of samples, regimes for layer thickness values of 50 and 100 μm were used. Samples were produced with a different combination of these regions to determine whether they could be freely varied in the final product. Samples were prepared in which the regions produced with a layer thickness of 100 μm are located both in the transverse direction (**Figures 4 a, c**) and in the longitudinal direction with respect to the growing direction of the samples.

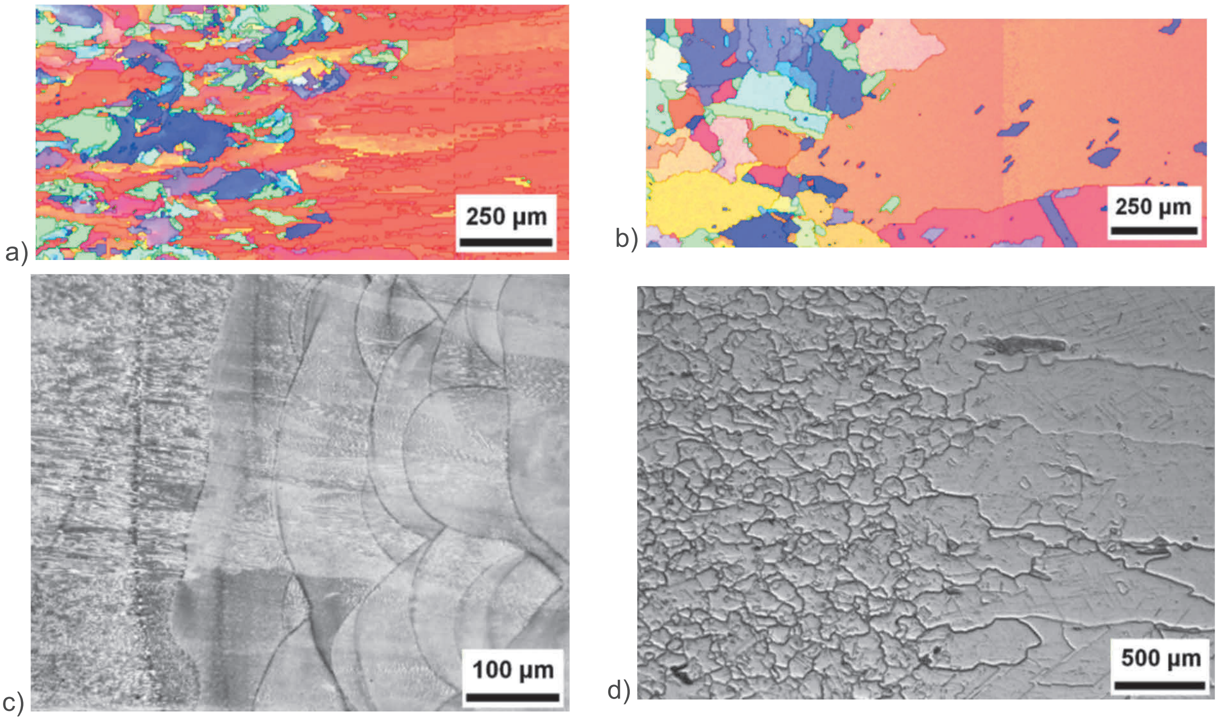

Figure 4 Microstructure of the boundary region between the sections made at a layer thickness of 50 μm (left) and 100 μm (right) after SLM (a, c) and SLM + HIP (b, d).

Figures 4 b, d also shows the effect of hot isostatic pressing on the microstructure of tailored specimen: high-temperature heating above the recrystallization temperature led to coarsening of the grains and the formation of equiaxed grains in the region of 50 μm made at a layer thickness. However, the disappearance of a clear distinction between the zones did not occur and the zone of large elongated and the zone of small equiaxed grains are clearly visible.

Thus, after the thermal treatment, two zones are formed: a region of directed columnar grains and a fine-grained equiaxed region.

4. CONCLUSION

This paper presents a comprehensive study of selective laser melting of Inconel 718 powder. It was shown that the larger the layer thickness, the larger the dendritic cell size in the structure, the EBSD analysis showed that a change in layer thickness and technological parameters leads to a change in the microstructure of grains and that the use of thickness a large layer, directed solidification with the formation of columnar grains. The mechanical properties of the samples strongly depend on the thickness of the layer, the thinner layer gives a higher strength of the samples. On the basis of the conducted researches the concept of manufacturing of products with the given microstructure is formed.

REFERENCES

[1] *Superalloys II: High-temperature materials for aerospace and industrial plants*. Moscow: Metallurgy, 1995. 385 p. (in russian)

[2] SUFIIAROV, V.Sh., POPOVICH, A.A., BORISOV, E.V. and POLOZOV, I.A. Selective laser melting of heat-resistant Ni-based alloy. *Non-ferrous Metals.* 2015. vol. 1, pp.32-35.

[3] ATTAR, H., CALIN, M., ZHANG, L. C., SCUDINO, S., and ECKERT, J. Manufacture by selective laser melting and mechanical behavior of commercially pure titanium. *Materials Science and Engineering: A*, 2014. vol. 593, pp.170-177.

[4] AGAPOVICHEV, A.V., KOKAREVA, V.V., SMELOV, V.G. and SOTOV, A.V.,. Selective laser melting of titanium alloy: investigation of mechanical properties and microstructure. In *IOP Conference Series: Materials Science and Engineering*. 2016. vol. 156, no. 1, p. 012031.

[5] JIA, Q. and GU, D. Selective laser melting additive manufacturing of Inconel 718 superalloy parts: Densification, microstructure and properties. *Journal of Alloys and Compounds*. 2014. vol. 85, pp.713-721.

[6] TROSCH, T., STRÖßNEr, J., VÖLKL, R. and GLATZEL, U., Microstructure and mechanical properties of selective laser melted Inconel 718 compared to forging and casting. *Materials Letters*. 2016. vol. 164, pp.428-431.

[7] AVERYANOVA, M., CICALA, E., BERTRAND, P. and GREVEY, D. Experimental design approach to optimize selective laser melting of martensitic 17-4 PH powder: part I - single laser tracks and first layer. *Rapid Prototyping Journal.* 2012. vol. 18, no. 1, pp. 28-37.

[8] YADROITSEV, I., KRAKHMALEV, P., YADROITSAVA, I., JOHANSSON, S and SMUROV, I. Energy input effect on morphology and microstructure of selective laser melting single track from metallic powder. *Journal of Materials Processing Technology*. 2013. vol. 213. no. 4, pp. 606-613.

[9] HOLZWEISSIG, M. J., TAUBE, A., BRENNE, F., SCHAPER, M. and NIENDORF, T. Microstructural characterization and mechanical performance of hot work tool steel processed by selective laser melting. *Metallurgical and Materials Transactions B.* 2015. vol. 46, no. 2, pp. 545-549.

[10] YADROITSEV, I., KRAKHMALEV, P. and YADROITSAVA, I.,. Selective laser melting of Ti6Al4V alloy for biomedical applications: Temperature monitoring and microstructural evolution. *Journal of Alloys and Compounds*. 2014. vol. 583, pp. 404-409.

[11] POPOVICH, V.A., BORISOV, E.V., POPOVICH, A.A., SUFIIAROV, V.S., MASAYLO, D.V. and ALZINA, L., Impact of heat treatment on mechanical behaviour of Inconel 718 processed with tailored microstructure by selective laser melting. *Materials & Design*. 2017. vol. 131, pp.12-22.