The investigation of microstructure and mechanical properties of tool steel produced by selective laser melting technology

A V Agapovichev[1, 3], A V Sotov[1], R R Kyarimov[1], V P Alexeev[1], V G Smelov[1], V S Sufiiarov[2], D V Masaylo[2]

[1] Samara University, 34, Moskovskoe sh., Samara, 443086 Russia
[2] National Technology Initiative Center of Excellence in Advanced Manufacturing Technologies at Peter the Great St. Petersburg Polytechnic University, 29, Polytechnicheskaya, St. Petersburg, 195251 Russia

[3] E-mail: Agapovichev5@mail.ru

Abstract. This paper presents study of microstructure of the material (tool steel 150Cr14) produced by the selective laser melting (SLM) technology. The chemical composition analysis and grain size measurements of the initial powder tool steel 150Cr14 were performed. The bulk density and flowability of the powder were investigated. Specimens were built under various building parameters such as laser scanning speed and laser power and tested on uniaxial tension. In this study, the effect of the SLM parameters on the mechanical properties of tool steel is investigated. Due to less surface quality limitations of SLM technology compared with conventional production techniques specimens were subjected to set of tests including measurement of surface roughness, inspection of inner structure which are influenced from building parameters.

1. Introduction

The implementation of new technological processes in blanking and basic production gives an amazing possibility of material and time resources saving for design, development and manufacture of gas turbine engines components [1, 2].

Selective laser melting (SLM) is one of the new additive production methods using high power lasers (typically ytterbium fiber lasers) to create three-dimensional physical objects by fusing metallic powders [3, 4].

Technology of selective laser melting makes it possible to manufacture parts from stainless steels, tool steels, aluminum and titanium alloys, superalloys, cobalt-chromium metal powders [5, 6]. SLM technology uses a high power laser to melt a thin layer of powder in accordance with the 3D model [7, 8]. The SLM method is a promising method for manufacturing parts from materials, the processing of which by traditional methods is complex and very costly. Currently, SLM is a unique technology for manufacturing objects of complex shapes, including the grid structure [9, 10].

The cost of a modern metal stamp often exceeds the cost of the part made with it, and the labor intensity of designing and manufacturing of technological equipment makes up to 80% of the total labor intensity of new product technological preproduction [11]. In the face of increasing global competition in the manufacture of gas turbine engines components, manufacturing time is becoming a key factor in the choice of production technology. Such world tools manufactures as Sandvik Coromant, Kennametal, IMC Group, etc., have created scientific divisions that study the possibilities of additive technologies implementation in the production of cutting tools and complex tooling. This article is shown the influence of the layer construction strategy during powder melting on the strain values. Moreover, the manufacturing time and the amount of consumed materials are determined. Also, results of optimization of internal structure of melting materials are resulted, the best strength was shown by samples with cellular internal structure.

To obtain the required mechanical characteristics of the stamp, it is necessary to obtain a dense internal structure by selecting the optimal technological parameters and layers constructing strategy. Thus [12] this paper deals with establishing of building parameters for tool steel H13 processed using SLM technology with layer thickness of 50 and 30 μm with different part building orientation. In the article [13] the questions of the effect of layer thickness at SLM.

The main benefits of SLM technology using in the manufacture of stamps is the possibility of obtaining complex cooling channels. The paper [14] presents the results of CAD / CAE modelling and the production of dies cooling channels from tool steel H13 by the EBM method and tool steel P20 by the SLS method.

In the article [15] questions of manufacturing of samples of dies with cooling channels from tool steel H13 were discussed. The heat treatment processes for residual stresses elimination and properties modelling were investigated.

It is important to design and evaluate the residual stresses in the dies cooling channels. The authors of the work [16] carried out numerical experiments to determine the influence of the SLM parameters and the lattice designed structure on the surface roughness of the cooled channels; coefficient of stress concentration and uniformity of cooling; structural and thermal insulation channels properties.

Thus, one of the promising areas of SLM technology application is manufacturing of tooling. In this case, the cost of an enterprise is eliminated the cost of expensive serial tooling, since the SLM technologies make is possible to make an individual light alloy dies with less resources. One key aspect of SLM implementation is the elimination of as many intermediate processing steps as possible.

In the manufacture of technological equipment, tool steels with special properties are used, the steels which are normally used in engineering.

The most important requirement for all types of die steels is the combination of hardness with high viscosity [17]. Die steels should also have special technological properties, which include:

- good workability, i.e. ability to accept cutting and cold and hot pressure treatment well;
- good hardenability, i.e, the possibility of obtaining a high and uniform hardness, a uniform fine-grained structure to a great depth;
- low sensitivity to overheating, i.e, the possibility of quenching with heating in a sufficiently wide temperature range; - slight sensitivity to decarburization during heating, which reduces the hardness of the surface (working) metal layer;
- high temperature strength, high temperature toughness and, thermal conductivity;
- good grinding, which determines the high quality of polished and polished surface.

To determine the possibility of SLM technology using for tooling manufacturing, a complex of tool steel 150Cr14 structure and mechanical properties studies were carried out.

2. Research methods and equipment

During the experiments 150Cr14 tool steel powder and SLM produced specimens were used. The experiments aimed to investigate the microstructure and mechanical properties of a selected steel powders at various process parameters.

The test specimens were manufactured using the SLM 280HL. The equipment is designed for single and small batch production of various parts, and has a building camera with a size of 280x280x350 mm. The SLM 280 HL is equipped with an ytterbium fiber laser (wavelength of about 1 mm) with a power of 400 W. The laser has a Gaussian intensity distribution with respect to the center of the laser radiation, also denoted by the transverse electromagnetic mode TEM_{00}.

Investigation of powder particles morphology and chemical composition was made by a scanning electron microscope Tescan Vega.
The flowability and bulk density of the 150Cr14 tool steel powder investigation was determined with a volumeter.
The hardness of the samples was measured on a hardness modifier ITBRW-187.5-M. In order to investigate the effect of the process parameters on hardness, macro and micro scale hardness measurements were conducted on the side cross-sections of specimens produced with different settings of scan speed and layer thickness.
Tensile testing was performed at the INSTRON 8802 machine.
Study of microstructure of samples was carried out using an optical metallographic microscope METAM LV-32.
The surface roughness of the as-processed samples was measured on horizontal top surfaces using a Hommel-Etamic W55 profilometer. Samples for the study of roughness were made at different sections of the laser radiation power, the scanning speed of the displacement of the scanning contour.

3. Research methods and equipment

The results of the 150Cr14 powder elemental composition X-ray spectral analysis are presented in table 1.

Table 1. Results of the tool steel powder elemental composition analysis 150Cr14

—	Fe	C	Si	Mn	S	P	Cr	Ni	Mo	Ti	O	Cu
Research results	88.77	-	1.44	0.54	-	-	1.14	0.40	-	-	4.08	
DIN 150Cr14	Base	0,95	1.60	0.60	0.030	0.030	1.25	0.4	0.2	0.030	-	0.3

Figure 1 shows scanning electron microscope (SEM) images of the150Cr14 powder.

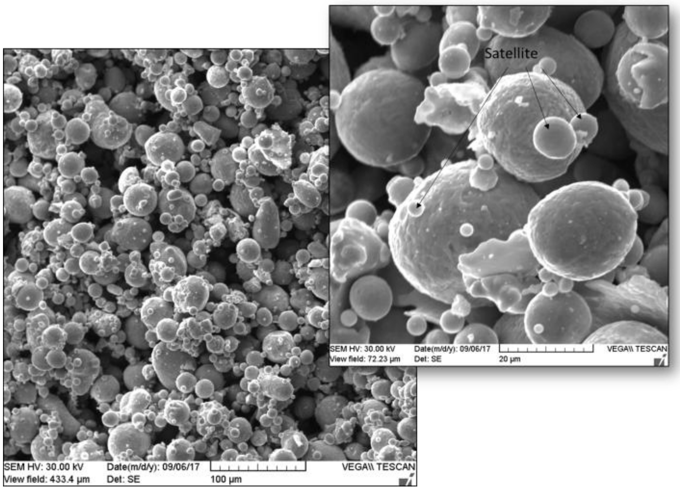

Figure 1. SEM-images of 150Cr14 tool steel powder particles.

The results of particle size distribution measurement show that the predominant number of particles has a shape close to spherical. Some particles are covered with a large number of small satellite particles which are specific for powders obtained by gas atomization [18].
One of the most important parameters of the metal powder used in SLM technology is the particle size distribution. The layer thickness of SLM is changing between 20 and 100 μm. Consequently, the

maximum size of the used powder particles should not exceed the minimal layer thickness [19]. The grain size distribution of 150Cr14 powder particles is shown in figure 2.

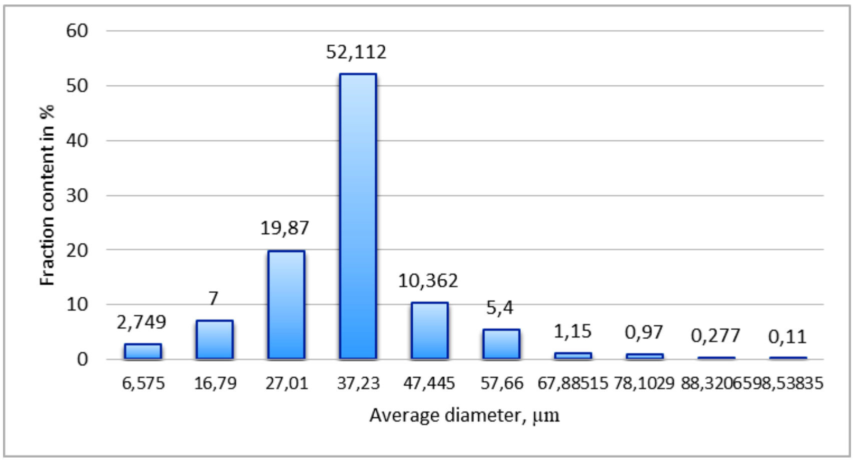

Figure 2. Grain size distribution of 150Cr14 powder particles.

The grain size distribution showed that the amount of 150Cr14 powder particles size up to 12 μm does not exceed 2.749%. The amount of 150Cr14 powder particles size from 10 μm to 40 μm is 79%. The results of the flowability and bulk density investigation of 150Cr14 tool steel powder are presented in table 2.

Table 2. Results of the elemental composition analysis of the 150Cr14 metal powder

Powder grade	Weight, g	Volume, cm^3	Time, s	Flowability, g / s	Apparent density, g/cm^3
150Cr14	137	123.088	52	2.63	1.11

For tensile tests, a batch of 150Cr14 powder samples was produced under various building parameters, taking into account the mathematical experimental design techniques.
Following regime parameters set were used:
- Laser power (P): 125, 175, 228 W.
- Scan speed (V): 400, 550, 700 mm/s.
- Scanning step (t): 50, 100, 150 μm.

The results of uniaxial tensile tests of the SLM manufactured specimens are shown in figures 3 and 4.

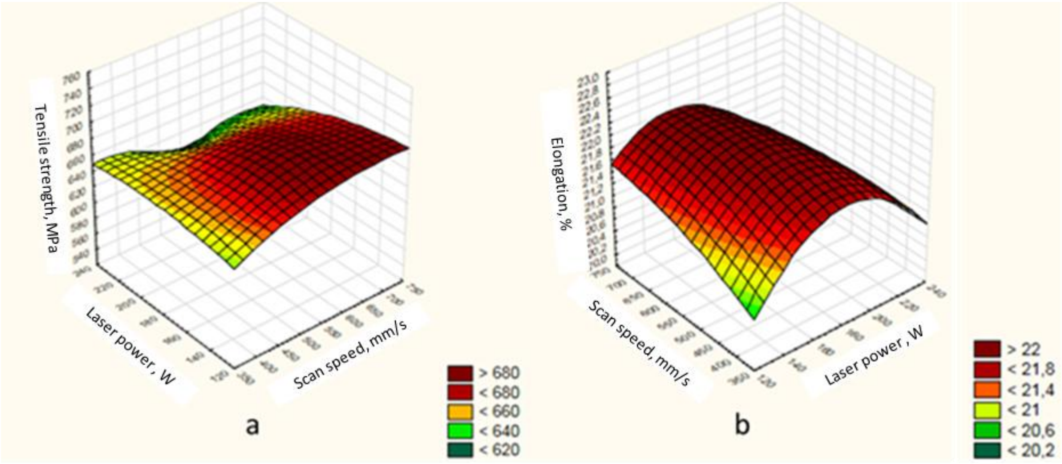

Figure 3. Effect of laser power and scan speed on the tensile strength and elongation: a – the influence of the scanning parameters on the ultimate strength; b – the influence of the scanning parameters on the relative elongation.

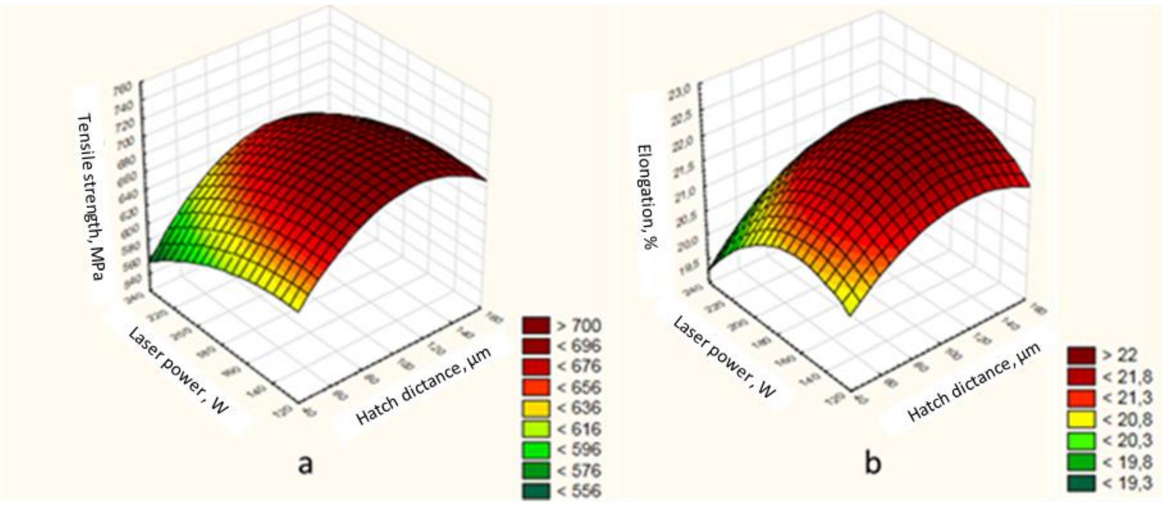

Figure 4. Effect of laser power and scanning step on the tensile strength and elongation: a – the influence of the scanning parameters on the ultimate strength; b – the influence of the scanning parameters on the elongation.

It can be noticed that the best mechanical properties are obtained at a scan speed of 750 mm/s and a laser power of 120 W. The highest value of the investigated parameter is 736.28 MPa is obtained at a scan speed of 700 mm/s and a laser power of 125 W.
The results of hardness measurements of SLM samples are shown in figure 5.

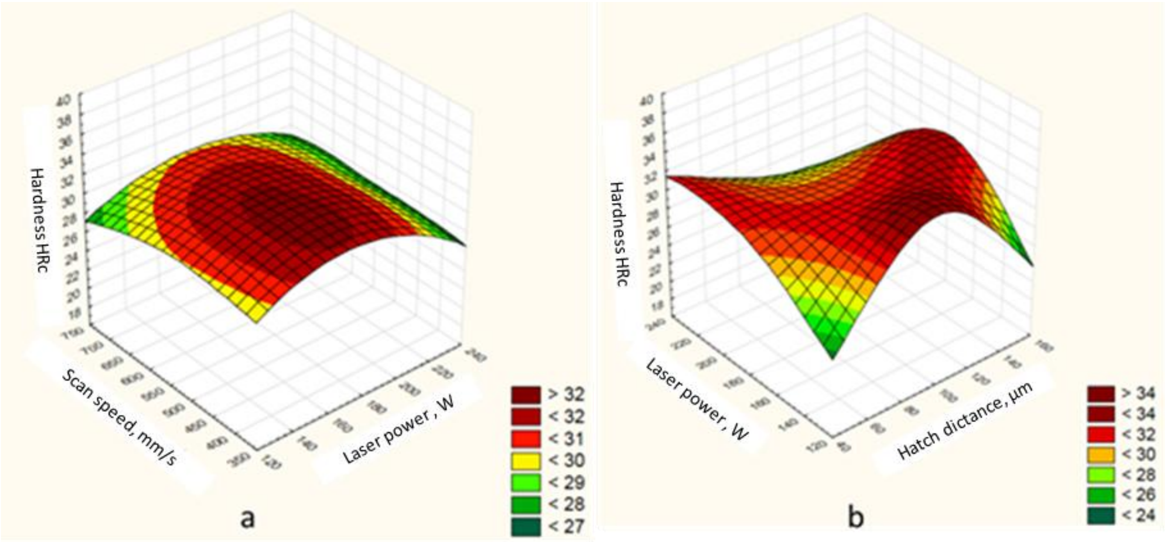

Figure 5. Effect of technological parameters on specimens hardness: a – the influence of laser power and scan speed; b – the influence of laser power and scanning step.

As can be seen from hardness analysis, the specimens hardness reaches 35-38 HRC units. The heat treatment conditions: heating, holding at a temperature of 860°C for an hour, oil quenching, tempering of 180°C for an hour. Based on the measurement results, the specimens hardness after heat treatment reaches 57-61 HRC values at the following SLM process parameters: laser power 125 W, scan speed 550-700 mm/s and scanning step 100 microns.
A study of the roughness of the samples was performed on the samples shown in figure 6.

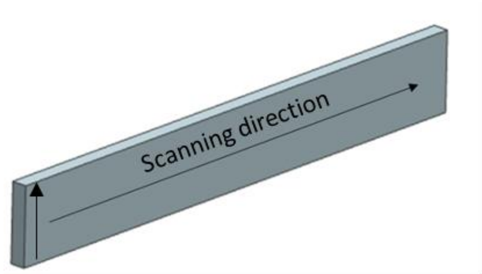

Figure 6. Roughness measurement line.

The results of measuring the SLM samples roughness are shown in figure 7.

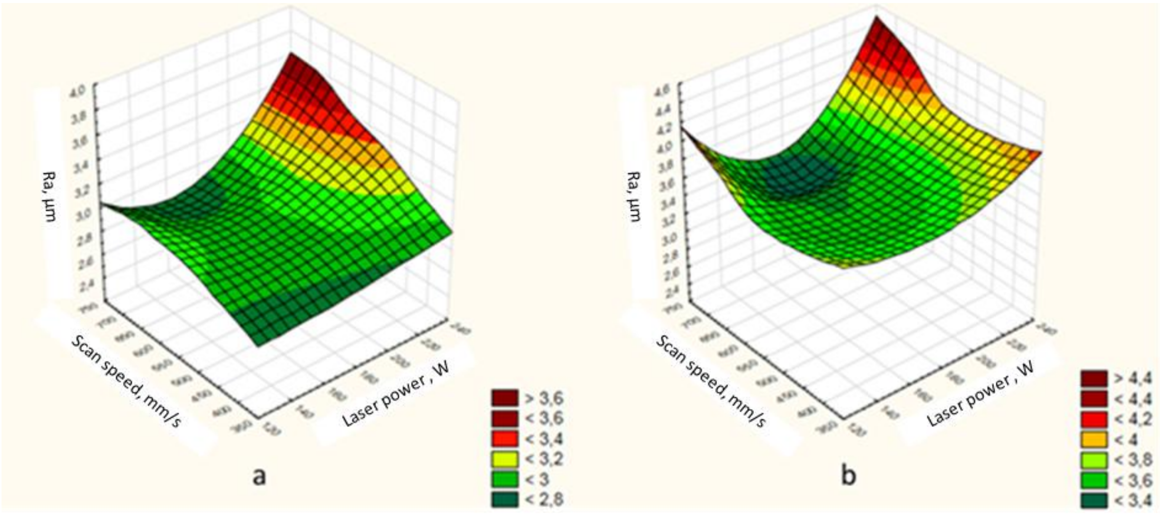

Figure 7. Influence of technological parameters of scanning on roughness of samples: a – roughness of the samples along the scanning direction; b – roughness of samples across the scanning direction.

Based on the conducted researches, it can be concluded that the smallest roughness measured along the scanning direction (figure 7a) is achieved at scan speeds in the range of 400 and 700 mm/s and a laser power range from 125 to 180 W. The lowest roughness is observed at a scanning step of 100 μm.
The smallest samples roughness measured across the scanning direction (figure 7b) is achieved at scan speeds in the range from 600 to 7500 mm/s and a power range of 160 to 200 W. The lowest roughness is observed at scanning step of 100 μm.
The results of metallographic researches carried out using optical metallography methods showed that the structure of materials obtained using SLM technology is not uniform in all samples. In some samples there are defects in the form of microcracks. There are also defects in the form of pores. The structure of a sample produced by a laser power of 175 W, a scan speed of 550 mm/s and a scanning step of 150 μm is shown in figure 8. Analysis of the microstructure showed that the particles of the metal powder that retained their spherical shape are not observed. The unmelted particles of metallic powder are absent. In the structure of the material, there are not significant defects of cavities and cracks. Cracks are mainly observed between melting particles.

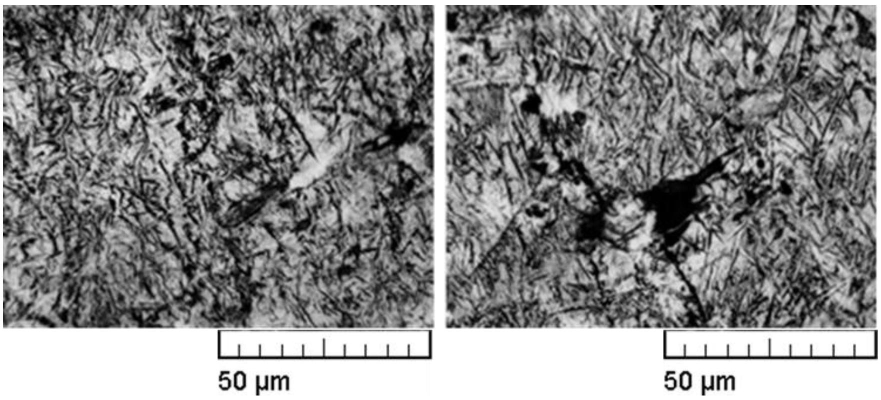

Figure 8. Specimens microstructure.

The microstructure of a sample produced by a laser power of 125 W, a scan speed of 550 mm/s and a scanning step of 150 μm is shown in figure 9. Analysis of the microstructure showed no defects in the form of lack of fusions and cavities. A small number of cracks were found in the microstructure of the material. There is a sandwich structure is characterised for SLM manufactured materials.

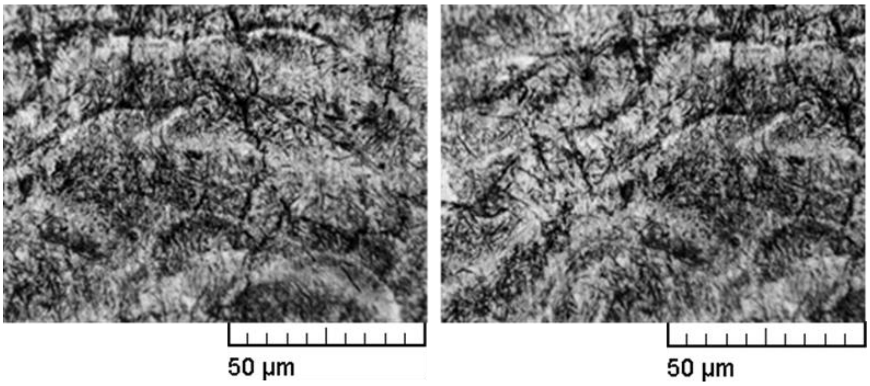

Figure 9. Specimens microstructure.

The parts of the die tooling were manufactured using SLM technology from 150Cr14 tool steel (figure 10). The best values of the material strength and hardness were obtained by following regimes: power 125 W, speed 550 mm/s, scanning step 100 μm. The possibility of manufacturing
die parts from 150Cr14 tool steel powder by SLM technology are shown.

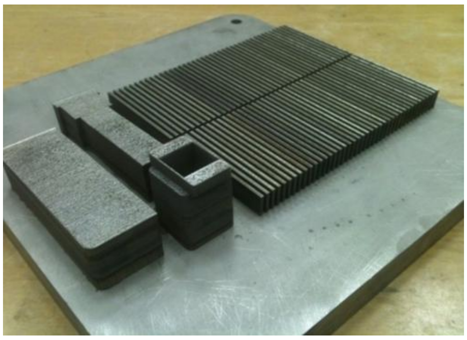

Figure 10. Details of die equipment manufactured by SLM technology.

4. Conclusion

The 150Cr14tool steel powder of the investigated grain size distribution and elemental composition can be used for SLM manufacturing. It is established that the morphology of the initial powder is spherical with small growths-satellites. But after the heat treatment individual cells disappear, and instead of them large grains are formed.

In SLM technology, it is possible to use metal powders with different bulk density. For the engineering production, it is advisable to use metal powders with a greater bulk density.

Strength and ductility of samples obtained by selective laser melting are higher than by traditional manufacturing methods. According to the requirements for die steels, the hardness of the working surfaces and the cutting edges of the die parts must correspond to the values of HRC 54-64, so it is necessary to provide heat treatment after SLM technology.

The effect of building regimes on the roughness showed that, in assigning optimal technological regimes, it is possible to obtain a surface roughness Ra 3.2.

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