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INFLUENCE OF TECHNOLOGICAL PARAMETERS OF SLM-PROCESS ON POROSITY OF METAL PRODUCTS

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Selective laser melting is one of the modern methods of manufacturing parts and assemblies of complex geometry, which are difficult or impossible to reproduce in the conditions of traditional manufacturing. The problem of this manufacturing is that a product quality depends on many factors, which can be divided into such main groups as equipment, material, process, part and finishing. The influence of the specific energy density of scanning the heat-temperature Inconel 718 alloy in the 3D printer Alfa-150 (ALT Ukraine) of the Ukrainian production was investigated. The influence of SLM-technology parameters on the quality of final products is shown and the analysis of the influence of technology factors on the quality of finished products is performed. As a result of metallographic examinations, it was found that the distance between the passes of the laser, at which the estimated overlap of a single track is 25 %, the conditions of deep penetration are created and at the root of the track as a result of collapsing holes (so-called keyhole), large elongated pores are formed. At the estimated overlap of a single track of 17 %, a small number of tiny rounded pores is formed. At the calculated overlap of 0–8 %, a structure with a minimum number of pores is formed. When the distance between the passes of the laser exceeds the width of a single track at a given combination of power and laser scanning speed, the cases of partial fusion of adjacent tracks are observed, pores with sharp edges are formed, which are stress concentrators — the most dangerous in terms of a product reliability. Thus, a rational overlap of tracks during selective laser melting was established, which ranges from 0 to 8 % of the width of a single track at specific process parameters. 21 Ref., 2 Tables, 4 Figures.

Keywords: selective laser melting, technological factors, quality system, Inconel 718, specific energy density

The modern method of additive manufacturing, called selective laser melting (SLM), allows manufacturing 3D-products in layers [1]. Preparation for printing begins with 3D-modeling of the object built in the CAD system in the STL format*. As a result, we receive the element split on the voxel structure [2] with a certain set of parameters suitable for printing. At digital processing the model is divided into layers from 20 to 100 μm thickness and vectors of a laser beam movement are formed.

The manufacturing process begins with applying a layer of metal powder required for printing one layer on a metal substrate, which is attached to the support structure and moves in the vertical direction along the *Z* axis. The printing process takes place inside the chamber with inert gas (usually argon or nitrogen is used), which maintains a strictly controlled atmosphere. Also, this allows printing using powder of aluminium and titanium alloys, because oxygen does not get into the chamber, which allows avoiding oxidation of the used material. Each 2D-layer of the object is sintered together, copying the shape of a digital STL drawing. The metal powder melts under the influence of a laser beam directed along the *X* and *Y* axes by two surfaces that reflect the beam at a high speed. The power of the laser emitter is usually in the range of 200–1000 W.

With the help of SLM process, samples with a complex geometry can be manufactured that are impossible or difficult to fabricate by other traditional methods of manufacturing. [3].

While realizing SLM technology, metal powders in the layer melt quickly [4] and solidify in the melt pool (cooling rates range from 10^3 to 10^8 K/s) with a short-term nonequilibrium phase transition and a highly dispersed microstructure is formed [5, 6]. This leads to some significant differences in mechanical properties between products manufactured by the

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methods of casting, forging and SLM [7, 8]. The microstructure during the conventional manufacturing process, such as casting and deformation, has coarser grains with a high liquation because of a low cooling rate during solidification and significant defects of shrinkage origin caused by a large volume of crystallizing melt. In addition, in cast and wrought alloys, the management of the microstructure is complicated, whereas it is easier to be controlled during the SLM process by changing manufacturing parameters [9].

The melt pool of one track has an arc configuration. Such a shape is a consequence of the energy distribution of the laser beam according to Gauss. The shape and overlap of the melt pools is seen in the microstructure of the material, manufactured by selective laser melting. Small dendritic and cellular structures with the size of structural elements having some micrometers are revealed within each track.

However, the surface of these samples as compared to the processes of precision forging and machining operation shows a large surface roughness (Ra), which is about 10–20 μm. In some fields, such as medicine, the high value of Ra can demonstrate good biological properties. For example, the implant Ti–6Al–4V manufactured by SLM process with a high value of Ra can be preferred for the growth of a bone. In a dental prothesis made of the Co–Cr alloy manufactured by the SLM method with a high value of Ra, the adhesion between the metal and ceramic may increase. Worldwide, the values of Ra range from 6 to 11 μm and tend to decrease.

Thus, SLM technology allows providing a high quality of products (accuracy and uniqueness of geometry, high complex of mechanical properties, high density, homogeneity of microstructure and chemical composition) and a wide range of the used materials allows it to find application in such fields as medical, dental, machine-building, automobile and aerospace industries.

The need for a systematic approach to quality management of products is explained by the diversity and interrelation of external and internal factors influencing the quality, and also by the continuity of its formation and provision. The quality of products manufactured applying SLM-technology depends on many factors, which can be divided into such main groups as equipment, material, process, part and finishing.

The quality of final products is significantly affected by the parameters of the SLM process. The main among them include laser power, speed and trajectory of laser beam scanning [10–15], distance between the scanning tracks and thickness of the layer of powder material.

The quality of a product, including the final density of the metal and the surface roughness, first of all, depends on the characteristics of the melt pool (shape and size), which are largely controlled by changes in the specific energy density of the laser beam, which is essentially a measure of energy, which is supplied in the process of printing [15, 16]. The control of the specific energy density can be achieved by changing the relevant controlled parameters. Laser power P (W), scanning speed V (mm/s), distance between the tracks (melt pool overlap), d (mm) and layer thickness t (mm) are the most important parameters and are related to specific energy density of the laser as:

$$E = P/(Vdt).$$

Rational modes of the process should stably provide a positive result. The level of power and speed of the laser beam scanning at a certain thickness of the powder layer for a certain material and equipment should provide the formation of a stable track.

In essence, the distance between the laser passes regulates the amount of overlap of adjacent tracks. The effect of the distance between the laser passes is often investigated without taking into account the size of the tracks [17]. Such results have a narrow scope of application and do not have a general nature, as far as depending on the power and speed of scanning the laser beam, the geometric parameters of the melt pool change. An approach for estimating track overlap is also known. However, there is no single opinion on the rational value of the overlap of adjacent tracks. Usually scientists are of the opinion that this value is in the range of 30–50 % [18, 19]. Others believe that the distance between the laser passes should be close to the track width to provide a minimal porosity [20].

Aim of the work is to determine the rational modes of SLM-process when using metal powder of high-temperature Inconel 718 alloy in the equipment «ALT-Ukraine» at a working layer thickness of 50 μm.

Material and procedure of investigations. The material for the manufacture of samples was the powder of Inconel 718 alloy of the H.C. Starck AMPERPRINT 0181.074 manufacturer with a particles size of 45 + 15 μm.

The source material was examined using a scanning electron microscope REM-106 (Figure 1, *a*) to determine the shape and size of the particle. Figure 1, *b* shows the results of the analysis.

Samples with a size of 10×10×5 mm of high-temperature nickel Inconel 718 alloy at a layer thickness of 50 μm were manufactured, the actual chemical composition of the finished product is presented in Table 1. The control of the chemical composition was performed using the precision analyzer «EX-

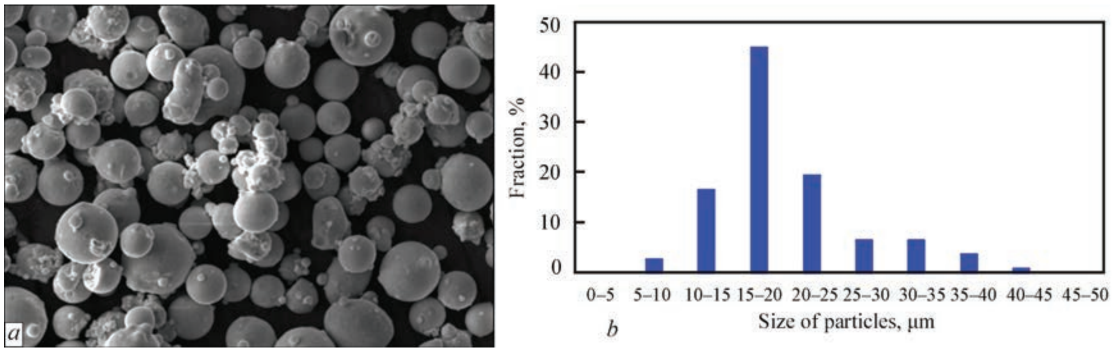


Figure 1. Particles of source material INCONEL 718 at a magnification of 500 (*a*) and results of grain-size analysis (*b*)

Table 1. Actual chemical composition of Inconel 718 alloy

Chemical element	Ni	Cr	Mo	Nb	Mn	Co	Cu	Al	Ti	Si	C	Fe
Content, wt.%	52.5	19.5	3	5.1	0.7	0.2	0.6	0.8	0.2	0.2	0.08	Balance

PERT 4L». The samples were grown in argon, in the «ALFA-150» installation of «LLC Additive Laser Technology of Ukraine» production. As a strategy for building a solid body, a zigzag (end of the previous track next to the beginning of the next track) printing process with a 67° rotation of the next layer relative to the previous one was used (Figure 2). The study of the microstructure was performed using an optical microscope AXIOVERT 200M MAT. Metallographic examinations of the microstructure of the metal were performed after $CuSO_4$ + HCl etching in a plane parallel to the direction of growing the sample (*X*–*Z*).

In the process of sample manufacturing, the parameters of the process of tracks overlapping between

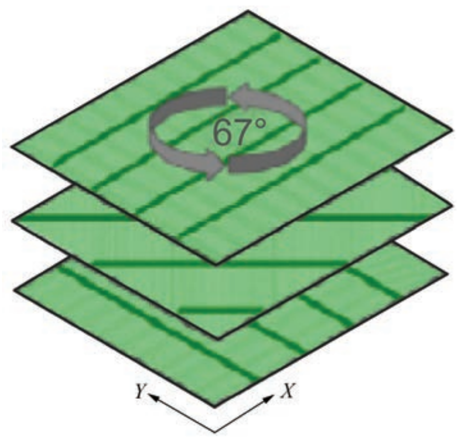


Figure 2. Scheme of scanning for reproduction of solid body

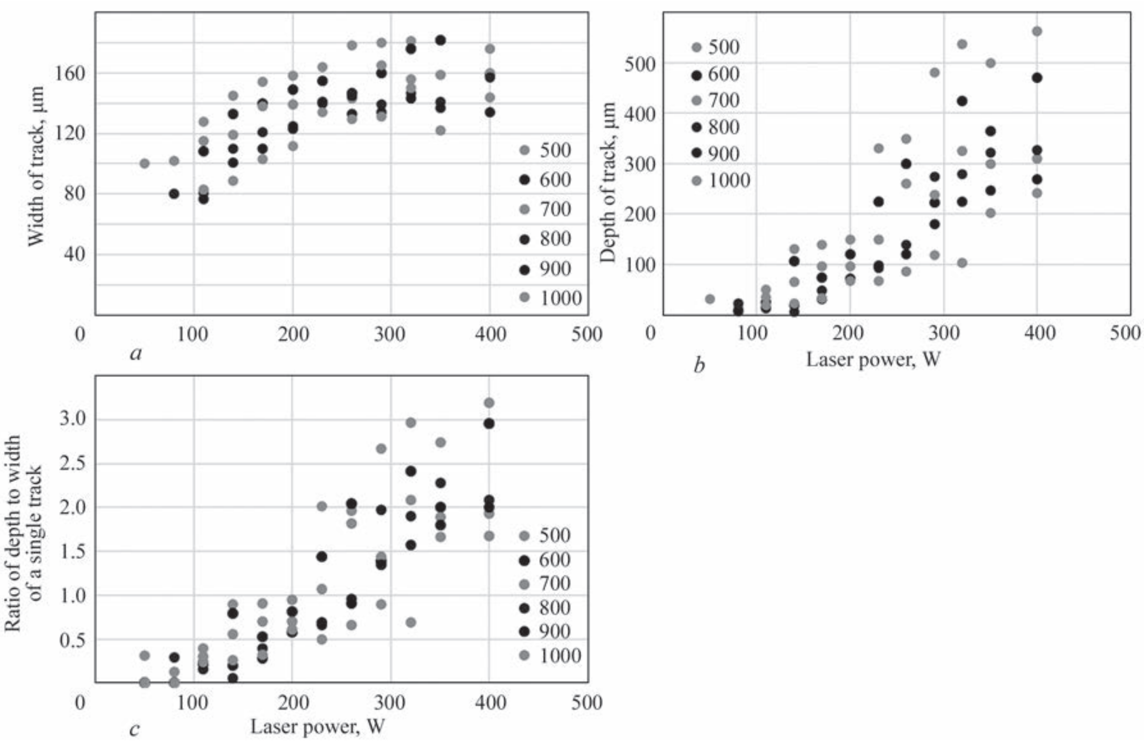
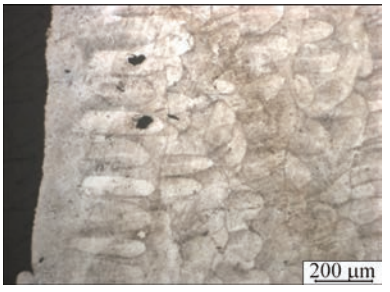
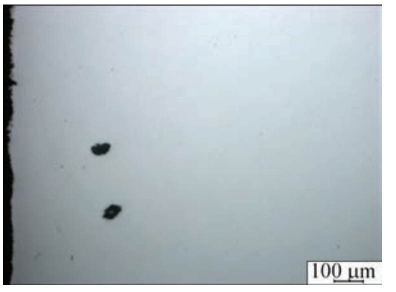
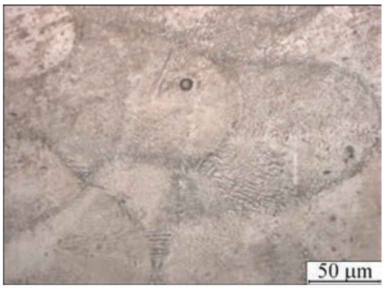
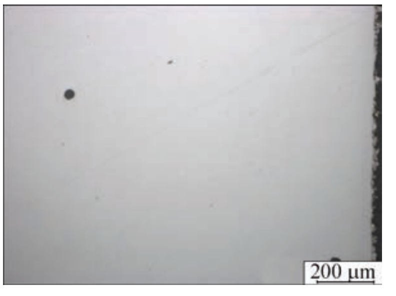
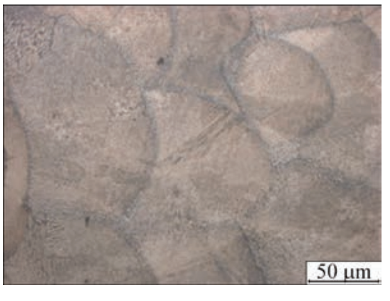
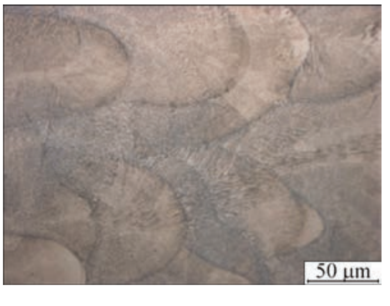
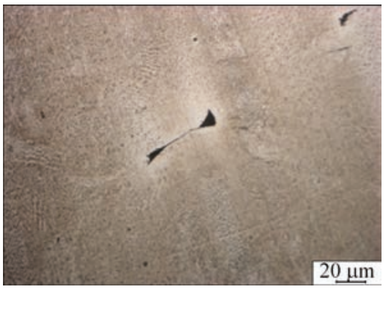


Figure 3. Geometric parameters of single tracks at different level of laser power (50–400 W) and scanning speed (500–1000 mm/s): *a* — width of a single track; *b* — depth of a single track; *c* — ratio of depth to width of a single track

Table 2. Microstructure of investigated samples depending on distance between laser beam scanning

Distance between the tracks, mm (calculated overlap, %)	Microstructure of investigated sample (etched by $CuSO_4$ + HCl)	Microstructure of investigated sample in the polished state	Porosity of samples, %
0.09 (25)			1.75
0.10 (17)			0.48
0.11 (8)			0.02
0.12 (0)			0.02
0.13 (–8)			0.87

the boundaries of the melt pools produced by the SLM process were changed.

In the calculation, the Microsoft Office software, Excel module was used.

Results of investigations. On the example of high-temperature Inconel 718 alloy, investigations of the influence of power and printing speed on the geometric dimensions of the melt pool of a single track were carried out [21].

According to the results of the experiment, the modes were established, that provide the formation of the melt pool of optimal geometry: the depth of the melting zone should exceed the thickness of the layer by about one and a half to two times, the ratio of the depth to the track width should be from 1.0 to 1.5.

As is seen from Figure 3, at an increase of power by more than 200–230 W the width of a single track ceases its monotonical growth (Figure 3, *a*), at the same time the depth of a track at an increase of power by more than 200–230 W for lower scanning speeds begins to increase sharply (Figure 3, *b*). This, in turn, results in a change in the ratio of the depth of a single track to its width (Figure 3, *c*), i.e. the process goes beyond the rational modes of the working window.

If the scanning pitch is too small, although the continuity of the material between adjacent tracks will be increased and the pore formation will be smaller, the secondary remelting increases the tendency before the formation of a coarse-grained structure. If the scanning pitch is too large, the overlap between two tracks will be insufficient and there will be no connection between the adjacent tracks. This generates a large number of pores, thereby reducing the density (Figure 4). However, an increase in the interval between the passes of the beam increases the remelting area, thereby increasing the utilization factor of the laser and the speed of production.

For further investigations of the influence of the value of a track overlap, one of the modes was chosen, which according to the results of previous investigations was defined as rational: P = 180 W, V = = 800 mm/s. The width of the pool of a single track at such process parameters is 120 μm. Within the frame of the experiment the samples of 10×10×5 mm were produced, for which the distance between the passes of the laser beam was changed from 90 to 130 μm, which should provide an overlap from 25 to 0 % and the absence of overlap is possible if the distance between the tracks exceeds the track width.

As a result of metallographic examinations, it was established (Table 2) that at an overlap of 25 % the conditions of deep penetration are created, and as a result of collapsing a hole (so-called keyhole), large extended pores in a track root are formed.

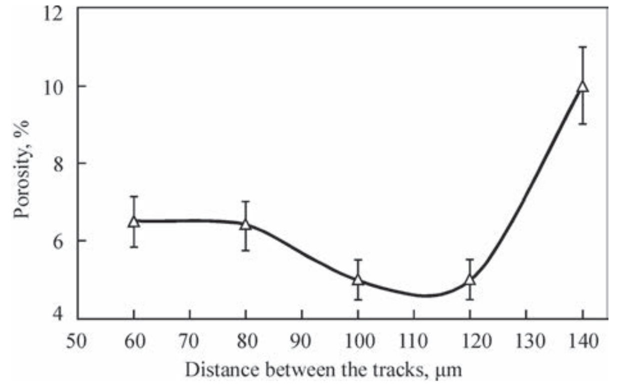


Figure 4. Influence of distance between the tracks on the porosity of Inconel 625 alloy [21]

At an overlap of 17 % a small number of tiny rounded pores is formed, the formation of which is probably associated with the capture of gas by the melt metal during crystallization, at an overlap of 0–8 % a structure with a minimum number of pores is formed. When the distance between the tracks exceeds the width of a single track at a given combination of power and laser scanning speed, the cases of a partial fusion of adjacent tracks are observed, the pores with sharp edges are formed, which are stress concentrators and the most dangerous in terms of product reliability. Thus, the optimal overlap of the tracks in selective laser melting was established, which ranges from 0 to 8 % of the width of a single track for specific process parameters.

Conclusions

The influence of SLM-technology parameters on the quality of final products is shown and the analysis of the influence of technology factors on the quality of finished products was performed.

The rational interval of values of tracks overlap at selective laser melting was established, which amounts from 0 to 8 % of the width of a single track at specific parameters of the process, that provides the minimum porosity of volumetric samples.

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