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INVESTIGATION OF CONDITIONS OF DEEP PENETRATION IN MANUFACTURE OF SAMPLES OF HEAT-RESISTANT ALLOY Inconel 718 BY THE METHOD OF SELECTIVE LASER MELTING

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The relationship was established between the parameters of selective laser melting process (laser power and distance between tracks) and microstructure of samples of alloy Inconel 718 at the condition of applying a small diameter beam (0.05 mm). Using the method of selective laser melting, the samples of alloy Inconel 718 were manufactured in the installation ALT Alfa-150 of the LLC «Additive Laser Technology of Ukraine» production. For the first series of samples the alternating laser power was preset in the range of 150–250 W, and for the second series the distance was changed between tracks in the interval of 0.09–0.13 mm. Examination of microstructure was made in optical microscope AXIOVERT 200M MAT. The problems of effect of parameters of selective laser melting process (laser power, distance between tracks) on structure of Inconel 718 material were considered. From the results of work the relationships between the parameters of selective laser melting process and depth and width of the melt pool were determined. The conditions of a deep penetration with a formation of large pores were determined. 20 Ref., 1 Table, 6 Figures.

Keywords: *additive technologies, selective laser melting, powder materials, heat-resistant nickel alloys, Inconel 718, melt pool, conditions of deep penetration*

The technologies of 3D printing of products of metallic powders appeared in the middle of the 1980s [1] and differed from the traditional methods by that the manufacture of products occurs by a successive layer-by-layer growing of powder material under the action of a high-energy source [2]. The wide spreading during recent years was found by the technology Selective Laser Melting (SLM), i.e. selective laser melting due to the feasibility of manufacture of intricate-profiled products according to the computer model of almost any metallic powders (zinc, bronze, steel, titanium and titanium alloys, aluminium and aluminium alloys, precious metals, etc.).

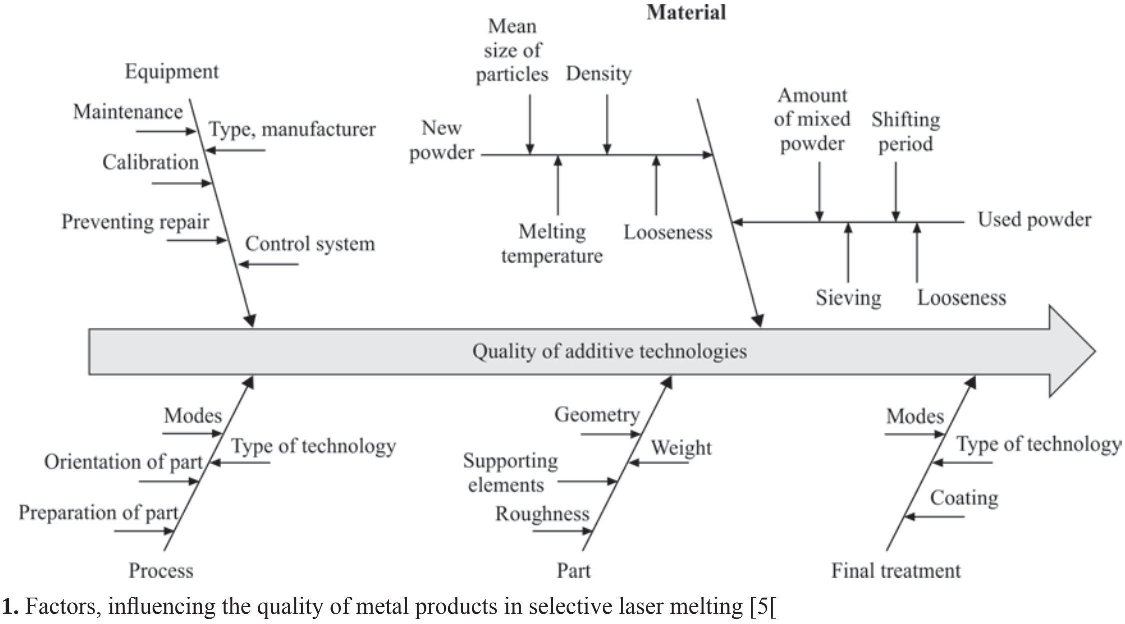

Figure 1. Factors, influencing the quality of metal products in selective laser melting [5[

This technology is capable to replace the classic industrial processes, allows manufacturing products, superior by the physical-mechanical properties to metal products manufactured by standard technologies. Using the selective laser melting it is possible to produce the unique intricate-profiled products without application of mechanical treatment and expensive rigging. Nowadays, the SLM technology found the application in defense industry, medicine, aircraft industry and rocketry. However, the manufacture of any products by this technology is rather expensive due to a high complication of the process.

In production of aircraft and rocket-space hardware a special place is occupied by complicated technological processes, used in manufacture of rocket engines and highly-loaded units of pneumo-hydraulic system of the rocket carrier, made of heat-resistant alloys. Technology of the selective laser melting allows several times reducing the time and number of technological operations, and the quantity of required main equipment, calculated in tens, decreasing to several ones [3].

At the present time, the urgent task is the design and improvement of equipment for realization of the selective laser melting process and development of the process rational modes, depending on the tasks: material, geometry, properties.

Aim of investigations is to establish the relation between the parameters of the selective laser melting (change in laser power and distance between tracks at constant speed laser movement at the condition of using the relatively small beam diameter: 0.05 mm) and microstructure of samples manufactured of alloy Inconel 718 at the deep penetration modes.

Problem statement. Except the technological properties of powder materials, used in SLM technology, a large number of parameters of the laser melting process itself has an effect on the quality of final products (Figure 1). They include the laser power, distribution of energy in laser spot, rate and trajectory of laser beam scanning, distance between scanning tracks, thickness of powder material layer, preheating of platform, type of shielding gas [4].

A large number of works were devoted to investigation of effect of technological characteristics of

Printing parameters, porosity and parameters of melt pools of test samples

Number of sample	Laser power, W	Laser movement speed, mm/s	Porosity, %	Width of basin, μm	Depth of basin, μm
1	150	800	0.5	58.1	193.5
2	175	800	0.3	70.6	225.8
3	200	800	0.7	83.9	258.1
4	225	800	2.1	90.3	322.6
5	250	800	3.2	96.7	351.8

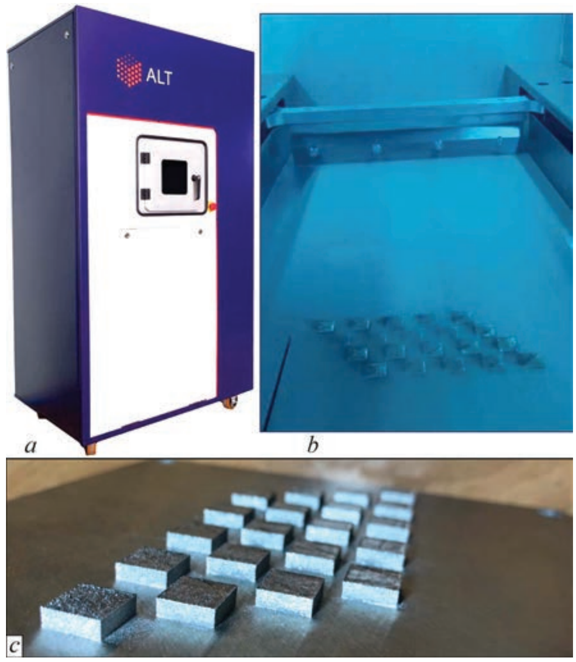

Figure 2. General view of installation ALT Alfa-150 LLC «Additive Laser Technology of Ukraine» (*a*), working zone (*b*) and general view of samples on the building-up platform (*c*)

powders [5–11] and manufacturing conditions [12–14) on properties of products.

It follows from the results of analysis of the mentioned investigations that the main factors, influencing the formation of fused layer in realization of SLM technology, is the power of laser radiation, rate of scanning and trajectory of beam movement (law of filling the part inner area).

Description of experiment conditions and discussion of results. Samples of 10x10mm size were manufactured at 50 μm thickness of powder mixture layer, 60 layers were printed. Samples were fused in argon. As a substrate, the plates of stainless steel were used. Substrate with powder was heated up to 80 °C. Argon was supplied to the chamber during the whole process of melting, amount of oxygen in chamber did not exceed 0.09 %. Figure 2 presents the general view of installation, working zone, where building-up of object takes place, and general view of ready samples on platform. Strategy of scanning by a laser beam in

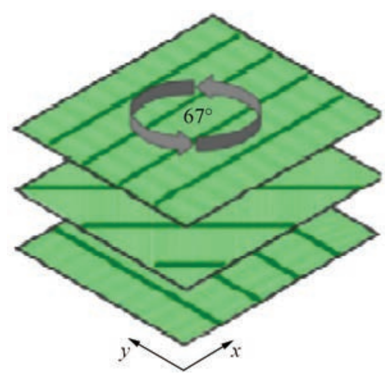

Figure 3. Scheme of layers rotation relative to the previous one

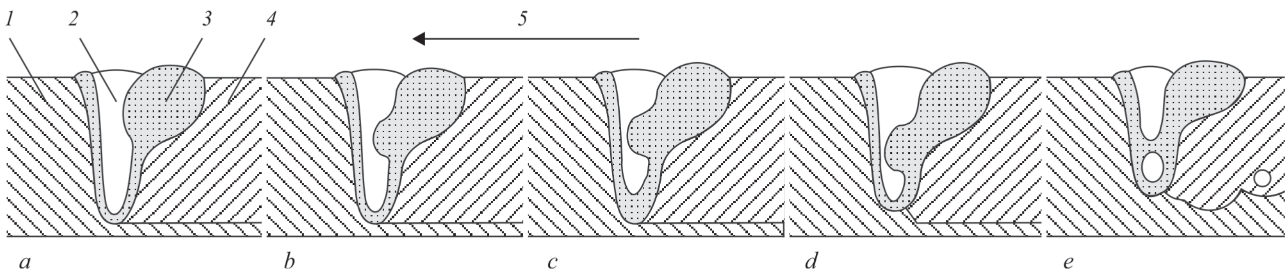

Figure 4. Scheme of porosity formation inside melt pool of track, made with parameters of deep penetration [18] (*a*–*e* — correspond to test samples Nos 1–5): *1* — substrate; *2* — crater; *3* — melt; *4* —fused track; *5* — direction of laser movement

filling the part inner area is line by line with a zigzag. The building-up was made from the platform. Experiment was performed in installation ALT Alfa-150 of LLC «Additive Laser Technology of Ukraine» manufacture. The examination of microstructure was made in optical microscope AXIOVERT 200M MAT.

To study the effect of laser power on the geometry of molten pool, five samples of alloy Inconel 718 were manufactured, keeping the scanning rate of 800 mm/s, interval between the tracks was 0.1 mm and alternating laser power was preset, respectively, 150, 175, 200, 225 and 250 W. Angle of rotation of layers relative to

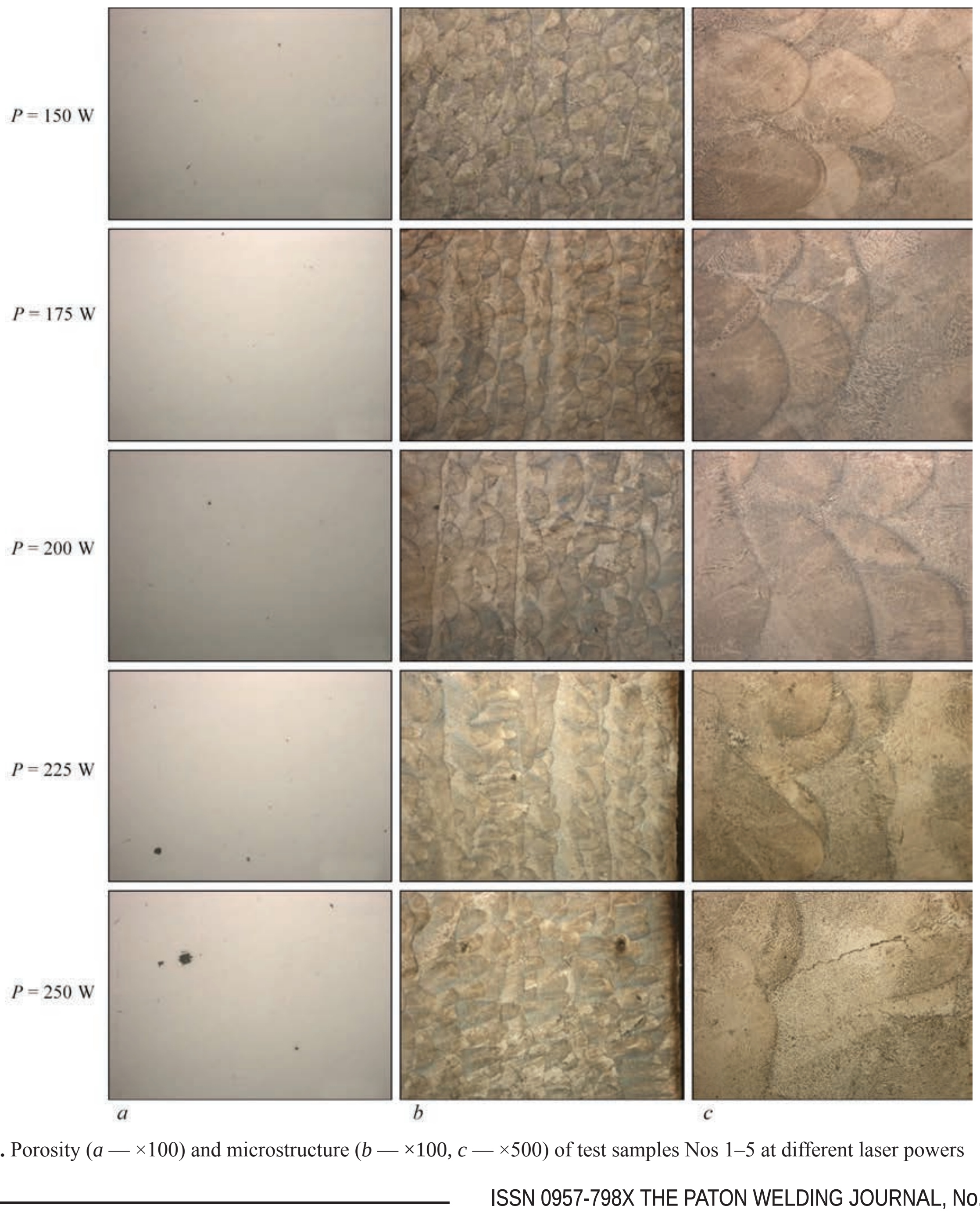

Figure 5. Porosity (*a* — ×100) and microstructure (*b* — ×100, *c* — ×500) of test samples Nos 1–5 at different laser powers

the previous one was 67° (Figure 3). Figure 4 shows the microstructure of test samples Nos 1–5.

Definite sizes of molten pools in the upper part of each sample were measured and mean value of width *w* and depth *h* of one pool of melt for each laser power were determined. Results of measurements are shown in Table.

It is seen that values *w*, *h* and laser power *P* are correlated that corresponds to the results obtained for other alloys [15]. It is seen that values *w* and *h* were increased with increase in the laser power, but the intensity of change was successively decreased. Probably, it is connected with the fact that the increased laser energy cannot be completely absorbed by powder and molten matrix due to a limited convection of melt and heat transfer. Therefore, the depth and width of a basin show the relation with laser power *P*, but they are not directly proportional [16, 17].

Thickness of coating layer, used in this experiment, was 50 μm. When the laser power was 150 W, the depth of molten pool was 193.5 μm, that is larger than thickness of three layers, and when the laser power reached 250 W the basin depth of melt was 354.8 μm, exceeding the layer thickness by seven times. As a result of experiment it was found that at laser power of more than 175 W, speed of laser movement of 800 mm/s, layer thickness of 50 μm and 0.05 mm beam diameter the conditions of deep penetration are created. At the further increase of this parameter the pool depth is increased, the crater collapse is occurred, which leads to the formation of large pores, which is a non-repairable rejection for the printed part. Such section of the track is called «key hole». Externally the track, made in this region, looks stable and almost has no external defects. However, in the track section depth the large pores are formed, dissipating along the whole track, caused by incomplete filling of crater volume with melt and developing of shrinkage processes in it. Scheme of porosity formation inside the melt pool is shown in Figure 4.

In addition, the area of regions with a rough microstructure is increased and microcracks are observed, forming as a result of microstresses, occurring in solidification and cooling of melt due to a significant overheating.

It was determined in work [19] that at certain values of scanning interval, the reducing of porosity is observed at other equal parameters. Therefore, it is necessary for each alloy to find this optimum and this is one of possible ways to improve the structure.

Interval between the tracks is the distance between two neighboring trajectories of laser scanning (Figure 5). This distance has a direct effect on the quality of formation of each layer [20] and on the process efficiency. In addition, adjustment on inter-track interval also has an effect on the part appearance quality.

If the scanning step is too small in spite of increase in continuity of material between neighboring tracks, and pores formation will be less, the secondary remelting increase the tendency to formation of coarse-grain structure. If the scanning step is too large, the overlapping between two tracks will be insufficient.

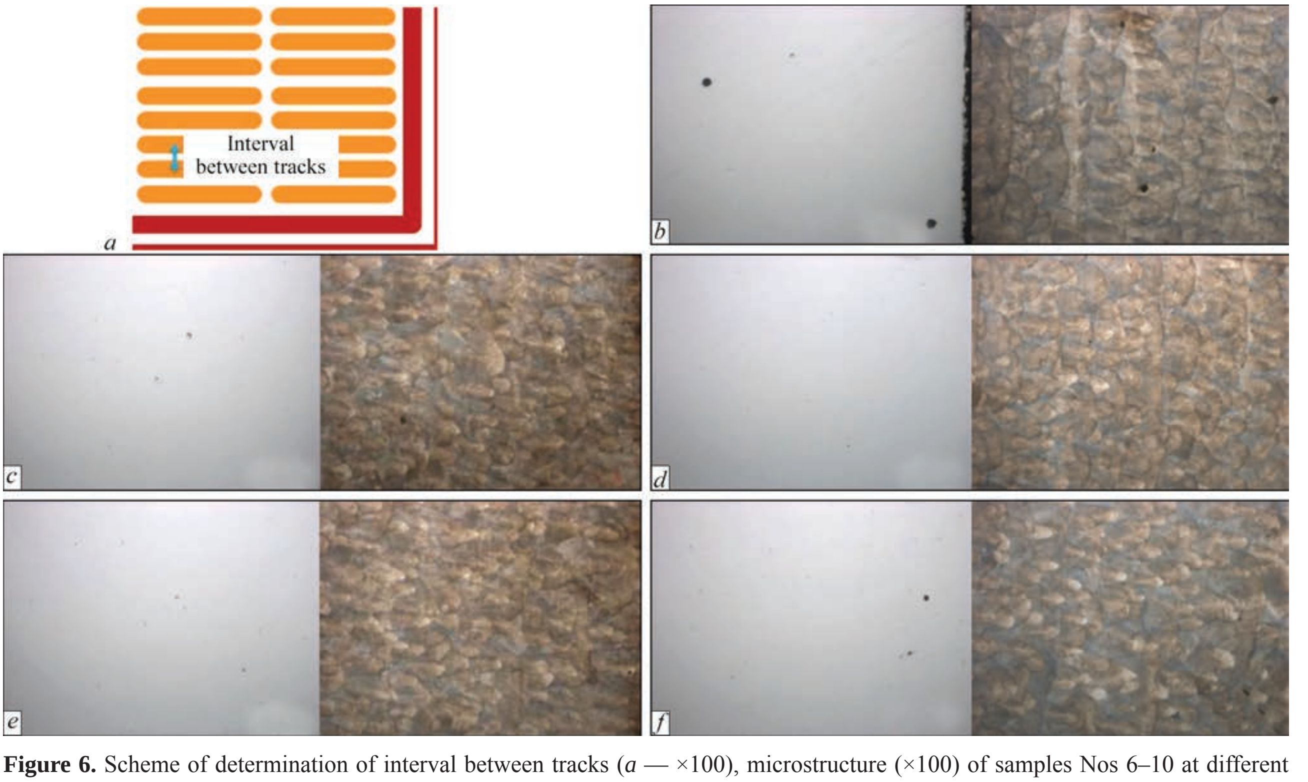

Figure 6. Scheme of determination of interval between tracks (*a* — ×100), microstructure (×100) of samples Nos 6–10 at different distances between tracks: *b* — 0.09; *c* — 0.10; *d* — 0.11; *e* — 0.12; *f* — 0.13 mm

There will be no relation between the neighboring tracks. This generates a large number of pores, thus decreasing the density. But the rise in intertrack interval increases the area of remelting, thus increasing the coefficient of laser utilization and rate of production.

To study the effect of distance between tracks on morphology of metal structure of heat-resistant alloy Inconel 718, the samples were manufactured with change in the mentioned parameter from 0.09 up to 0.13 mm. Figure 6 shows the microstructure at different modes of scanning. It was found within the scope of this experiment that at the distance between tracks of 0.09 and 0.1 mm the local overheating is occurred, due to which the porosity is increased, regions with a coarse-grain microstructure are formed. With increase in this parameter up to 0.11 mm the number of pores was decreased. However, with increase in interval between tracks up to 0.13 mm the gaps between melting pools were formed, repeated recrystallization, favorably influencing the final microstructure, was not occurred. It was established as a result of experiment that optimum values of interval between the tracks at the condition of a thin beam of laser (of 0.05 mm order) are 0.11–0.12 mm.

The further investigations will be directed for establishing the optimum modes in changing the scanning rate and better combination of speed and power of laser with account for radiation density to attain the high quality of metal and efficiency of installation.

Conclusions

It is shown as a result of investigations that morphology of molten pool is connected with laser power and distance between the scanning lines. Determined are the values of scanning parameters for alloy Inconel 718 from the point of view of decrease in porosity and creation of the dispersed microstructure: distance between tracks is 0.1 mm, laser power is 175 W at laser movement speed of 800 mm/s, 50 μm layer thickness, 0.05 mm beam diameter. It was established that at laser power of more than 175 W the conditions of deep penetration with formation of large pores are created.

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