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REGULARITIES OF INFLUENCE OF SLM PROCESS PARAMETERS ON THE FORMATION OF SINGLE LAYER FROM THE HIGH-TEMPERATURE NICKEL ALLOY Inconel 718*

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In the work the varieties of additive technologies, their advantages and disadvantages were analyzed. The experiments on selective laser melting (SLM) are described in more detail in order to provide the required microstructure of the synthesized material. The modes that provide stable printing of a single layer were experimentally established. The optimal values of scanning speed and laser power for the alloy Inconel 718 were determined. 12 Ref., 6 Figures.

Keywords: *SLM process, alloy Inconel 718, laser power, single track, specific volume power, maximum layer density*

Additive technologies is a generic name for a group of technologies involving manufacture of products according to digital models using the method of layer-by-layer addition of material. At the same time, a product is manufactured step by step by forming a layer of material, its solidifying or fixing in accordance with the data of 3D-model and joining with the previous layer. The power source may be an electron or laser beam.

There are various additive manufacturing processes, such as selective laser melting, direct laser deposition, electron beam melting, wire feed, shaped metal deposition, ultrasonic compaction, vortex interweaving and free shape friction for the manufacture of metal components.

First of all, an interest to additive technologies and direct printing or growing of metal parts as an alternative to traditional technologies arose in aviation, space industry, medicine and power engineering. In this case, the main driving factor was economic feasibility. This applies especially single complex products, the manufacturing of which by traditional methods is much more expensive than with the use of additive technologies.

Advantages of additive technologies are the following:

● improved properties of finished products. Due to the layered building, the products have a unique set of properties. For example, the parts created in a metal 3D printer by their mechanical properties, density, residual stresses and other properties surpass their analogues produced by casting or mechanical treatment;

● big economy in raw materials. Additive technologies use that amount of material in practice, which is needed to manufacture a product, whereas during traditional methods of manufacturing, the losses of raw materials can amount up to 80–85 %. The building takes place with the help of layer-by-layer addition of the required amount of material to the «body» of a product. 97–99 % of the powder, not involved in the building is recyclable after sieving. 3–9 % of the material involved in the building of supports is utilized together with a rejected non-fused powder that did not undergo a sieving operation;

● possibility of manufacturing products with a complex geometry. Equipment for additive technologies allows manufacturing objects that cannot be made by other means. For example, a part inside a part or very complex cooling systems based on array structures (this cannot be made neither by casting nor by stamping);

● mobility of production and acceleration of data exchange. Additive technologies are based on a computer model of a future product, which can be transferred in a very few minutes to the other end of the world — and immediately start the production;

● high accuracy and repeatability;

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• shortens the cycle of R&D works, providing the creation of complex-shaped parts without the use of equipment;

• allows reducing the weight by creating objects with inner cavities;

• the technology allows working with a wide range of metal powder compositions: stainless and tool steels, aluminum, titanium, nickel, cobalt-chromium, copper alloys and many other.

Additive technologies also have some disadvantages, in particular:

• surface quality of the products, their dimensional accuracy and minimum thickness of the elements are largely depend on the specific method and process parameters;

• need to manufacture supporting structures together with a part with their subsequent removal;

• dependence of structure and properties on the direction of growing, specific technology and equipment;

• limited product dimensions (limited by the working chamber or equipment area).

However, despite these drawbacks, the ease of using additive technologies is confirmed by numerous investigations and applications in real industries.

The method of selective laser melting (SLM) is an innovative technology for the manufacture of complex products by laser melting of metal powder according to mathematical 3D-models. This process successfully replaces traditional production methods, since the physical and mechanical properties of products built using SLM technology are often superior to the properties of products manufactured with the use of traditional technologies, so this technology with the use of powder is one of the most popular and successful.

In selective laser melting, metal powder bonding is achieved by melting and solidifying of a small volume of material in a track using one or more powerful lasers. In other words, the laser beam scans the powder layer and melts the powder particles under the beam, creating a small pool of molten metal and a thin track of solidified metal behind. By repeating single tracks with a clearly distinct overlapping (distance between the tracks), a layer of cross-section is created. By repeating this layer-by-layer deposition, the entire part is built. The installation and the whole process are controlled by a computer, on which the loaded mathematical model goes through several stages of preparation with the creation of supporting structures, trajectories, and procedures of beam scanning for each generated model layer, adjustment of a technological process for operation with a one or another selected material, etc. The process of products building occurs in the chamber of SLM machine, filled with an inert gas — argon or nitrogen, depending on the type of powder from which the building occurs, with its laminar flow. An admissible oxygen content is less than 0.15 %. The almost complete absence of oxygen avoids oxidation of a consumable, which enables printing with such materials as aluminum and titanium.

Depending on the geometry, the layers are divided into zones, where each one is assigned a separate identifier, according to which the movement trajectories are built and the laser beam parameters are set. These identifiers can be divided into three main groups: down-skin, in-skin and up-skin (Figure 1, *a*). At the same time, in each group its own subgroups are created: hatches, border and fill border as is shown in Figure 1, *b*.

The laser beam is moved using a system of mirrors on a quick-response drive. However, one of the problems in the technical aspect of the process is providing the stability of the laser beam spot diameter. The spot diameter is defined as a diameter in the beam waist, which is 86.5 % of the total power and corresponds to a beam diameter of $1/e^2$ in the working plane for Gaussian beams. It depends on the light source (laser wavelength and the quality of the conjugated laser beam), as well as on the aperture and focal length of the scanning system. As a result, a curvilinear focal surface is formed, the radius of which corresponds to the focal length of the system. There are basically two different approaches to solving this problem: the use of corrective F-Theta lenses and the control of laser movement along the *z* axis.

From the point of view of materials science, the problem of SLM technology is providing the required microstructure of a synthesized material and reducing

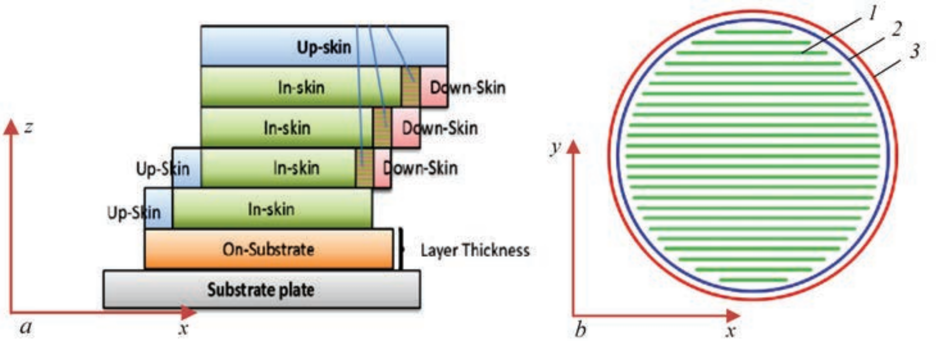

Figure 1. Formation of layers in the direction of growing a part (*a*), subgroups of tracks (*b*): *1* — hatches; *2* — border; *3* — fill border

the porosity of the produced material, which is typical for this technology. The values of porosity depend on the material used, parameters of the fusion mode, quality of the source powder, etc. The values of porosity for aluminum alloys can reach 4–5 %, for titanium alloys — up to 2 %, for steels and nickel alloys — less than 0.2 %. The products manufactured by selective laser melting, may contain defects. These are mainly pores and microcracks.

There are two types of pores: pores of a round shape and pores of irregular shape (lack of fusion) [1]. Round pores are formed for the following main causes: atmospheric gases absorbed by the molten pool, and gas mixed with the powder, which fails to be released from the molten pool before solidification. Bubbles of gas in a liquid have a spherical shape, which is maintained after solidification of the metal [2, 3]. Another cause is the capture of gas inside the powder particles during gas spraying [4]. However, the main defect is an irregular pore, which is formed because of the unstable shape of the molten pool or as a result of insufficient penetration of the powder layer. As a result, in places where the particles did not melt completely, or the fusion of the molten powder particles with the previously treated layer did not occur, flat pores are formed that are located perpendicular to the growing direction [2, 5–7]. The pores of the second type have a significantly greater effect on mechanical properties of the material due to their larger size, as well as their flat shape [3, 5]. To reduce the porosity in critical final products, hot isostatic pressing is used, which in many cases, provides a significant improvement in the quality of products after SLM [8].

A high power and localization of the heating source and a high speed of its movement contribute to the formation of large thermal gradients in the metal after building using the SLM method. Although these thermal gradients directly affect the formed microstructure of the metal, they also contribute to the formation of high thermal stresses, which can be sufficiently high and lead to buckling of products, as well as a change in their mechanical properties. Residual stresses, as a rule, are not directly taken into account, but considered as a hidden parameter, and sometimes they are not taken into account at all.

These defects have a significant effect on mechanical properties, such as ductility during tensile tests, fracture toughness and fatigue strength. To manufacture high-quality products, it is necessary to select manufacturing parameters in such a way as to minimize the resulting discontinuities in the metal. The structure and properties of a final product manufactured by selective laser melting depend on a large number of technological parameters. At present, up to 120 different factors are identified, affecting the quality and operational characteristics of the produced objects [9, 10]. A variety of influencing factors shows the complexity of physical processes occurring during SLM and the need in a scientifically-grounded choice of optimal values of the main technological parameters. Among the most important of them, laser radiation power, speed of scanning laser beam along the powder surface, thickness of a poured powder layer, distance between the melted tracks, diameter of the laser focal spot, melting strategy, i.e., the trajectory of the laser beam movement and also the chemical composition, structure and dispersion of the initial powder can be mentioned.

Porosity is considered as one of the main problems of objects manufactured by the SLM method. However, providing the constancy of geometric characteristics of each separate track, such as width, height, diameter and its good adhesion with the previous layer, which is determined by the penetration depth, it is possible to manufacture objects with the porosity of less than 1 %.

A track with a constant geometric shape, without breaks along the entire length and with penetration into the substrate is called stable. To manufacture objects with minimal porosity, crystallization of stable tracks is required.

At the first stage, the influence of the following parameters was studied: laser power and its movement speed on the size and shape of single tracks. This set of variable parameters was selected because of their direct contribution to the volume energy density and due to the possibility of their simultaneous variation in the manufacture of a set of specimens. In this case, the intervals of varying the parameters were the following for the laser power — 50–400 W at an increment of 30 W, for laser speed 450–1000 mm/s at an increment of 50 mm/s. The thickness of the applied powder layer was 50 μm.

The appearance and geometric parameters of single tracks obtained during the experiment were analyzed. At a low power, the powder did not fuse with the substrate. At a high speed of scanning, the effect of the formation of balls or lumps was observed. At a high power, the melt boils and the pressure of its vapor causes distortion of sintered tracks. The microstructure of the cross-section of single tracks was investigated. According to the results of the experiment, the modes were established that provide the formation of a molten pool of optimal geometry: the depth of the melting zone should exceed the layer thickness by about one and a half to two times, the ratio of the depth to the width of the track should be at a level from 1 to 1.5:

P = 110 W, V = 450–500 mm/s;

P = 140 W, V = 600–700 mm/s;

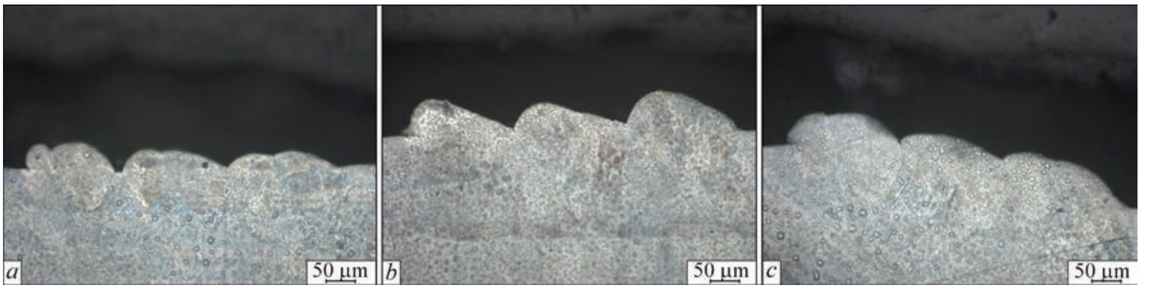

Figure 2. Microstructure of single layer at a laser power of 140 W and scanning speed: *a* — 1000 mm/s (E = 28 J/mm^3); *b* — 950 mm/s (E = 31 J/mm^3); *c* — 850 mm/s (E = 33 J/mm^3)

Figure 3. Microstructure of single layer at a laser power of 200 W and scanning speed: *a* — 800 mm/s (E = 50 J/mm^3); *b* — 750 mm/s (E = 53 J/mm^3); *c* — 700 mm/s (E = 57 J/mm^3)

P = 170 W, V = 600–700 mm/s;
P = 200 W, V = 650–800 mm/s;
P = 230 W, V = 800–950 mm/s.

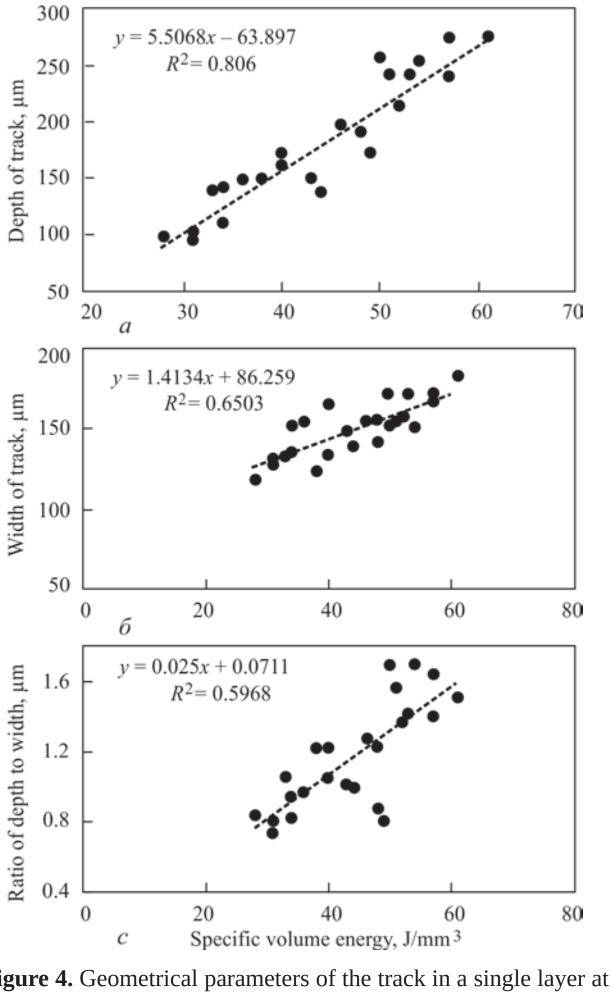

Figure 4. Geometrical parameters of the track in a single layer at different levels of specific volume energy

In the literature, to evaluate the energy input of the heating source, the volume energy density is used since it allows taking into account the contribution of the basic technological parameters of selective laser melting and their effect on the fused material [11, 12]. To calculate the volume energy density, the following equation was used:

$$E = P/(Vdt), \qquad (1)$$

where E is the energy density, J/mm^3; P is the laser power, W; V is the laser scanning speed, mm/s; d is the layer thickness, mm; t is the distance between laser passes, mm.

The energy density should be such as to provide a complete remelting of the powder and its fusion with the substrate. However, as is seen from the presented data, the specific volume energy of the mentioned modes during calculation for the interval between the tracks of 0.1 mm and a layer thickness of 50 μm varies in a wide range: from 44 to 61 J/mm^3. In addition, when creating a single layer, overlapping of neighboring tracks occurs, as a result of which the molten pool of the created track receives additional thermal influence from the cooling metal of the previous track, which will affect its geometry, properties and structure formation. In the experiment, the modes with a specific volume energy were calculated, which is by 30 % less than the optimal for single tracks.

The aim of the experiment is to specify the modes that provide a stable high-quality printing of a single layer and volume specimens to observe the optimality of the geometry of the pools of tracks in single layers and the minimum porosity in volume specimens.

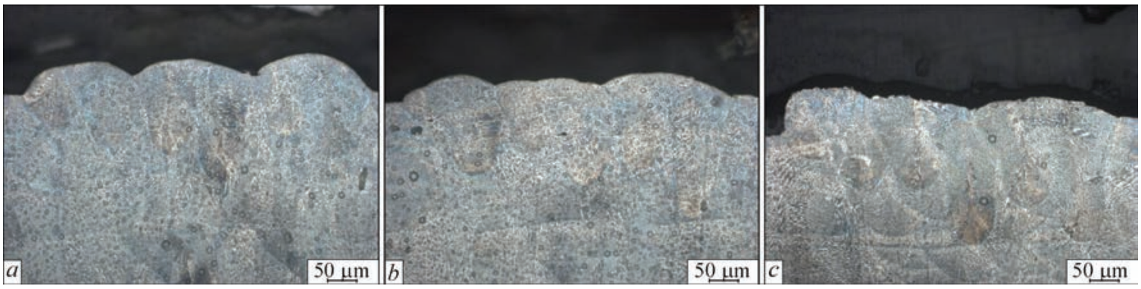

Figure 5. Microstructure of single layer at a laser power of 170 W and scanning speed: *a* — 900 mm/s (E = 38 J/mm^3); *b* — 850 mm/s (E = 40 J/mm^3); *c* — 700 mm/s (E = 48 J/mm^3)

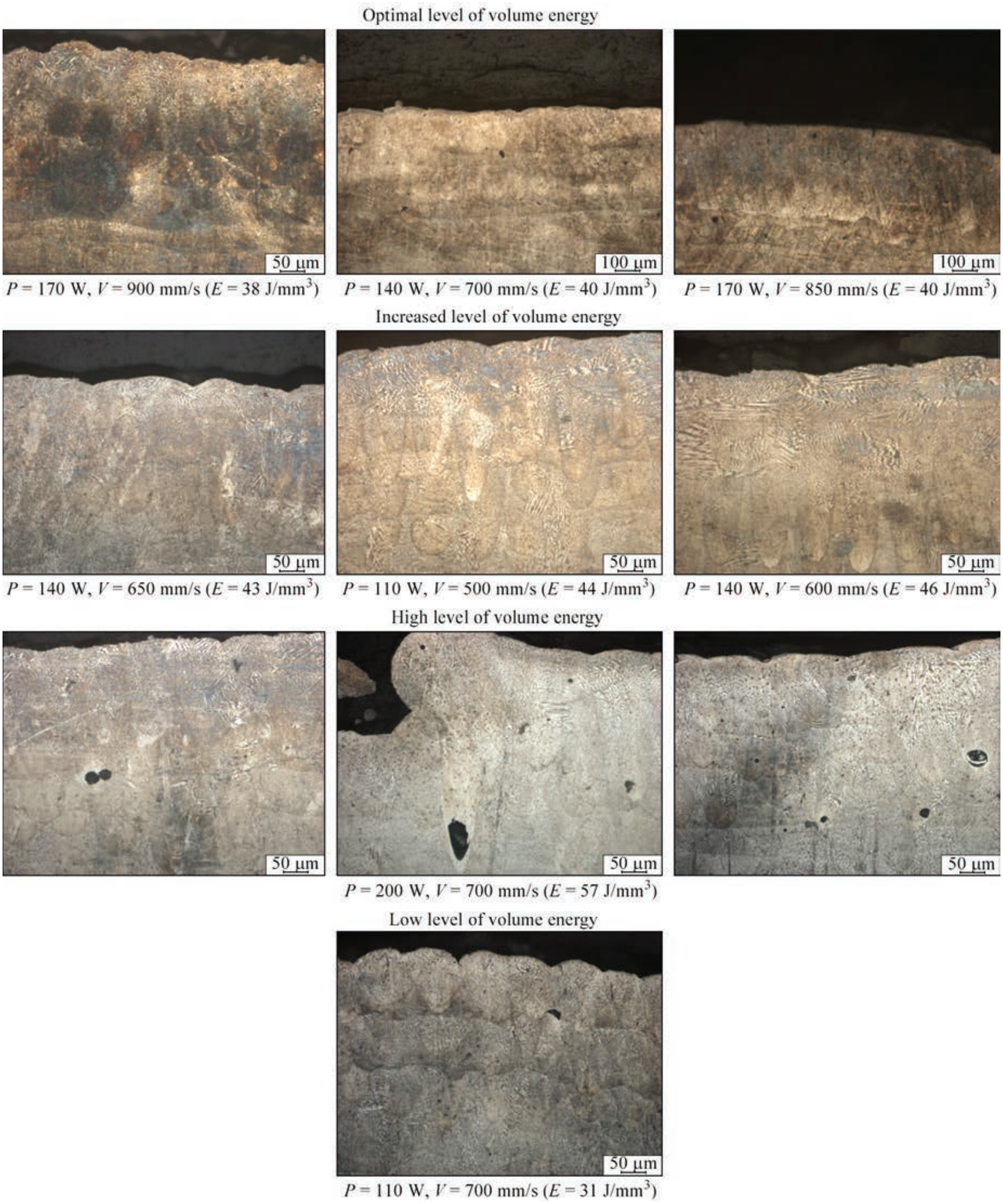

Figure 6. Microstructure of volume specimens manufactured at different levels of volume laser power

In the experiment, single layers were created from six single tracks printed with an interval of 0.1 along the zig-zag trajectory. Single layers, manufactured from calculated modes with a energy reduced relative to optimal ones for single tracks had an unstable shape. This was especially clear for the first track. With an increase in the specific volume energy, the outer tracks had a stable shape. In the cross-section of the specimens microstructural examinations were carried out. In Figures it can be seen that, at the level of energy being 28–33 J/mm^3, the amount of power turned out to be insufficient for a high-quality overlapping of neighboring tracks (Figure 2), and at the level of specific energy being higher than 48–50 J/mm^3, the penetration depth of neighboring tracks became nonuniform (Figure 3).

After crystallization of the track, there are areas depleted of powder next to it. Therefore, when melting the neighboring track, a smaller amount of powder was used which led to a decrease in its height. In addition, the absorption and reflection coefficients of laser radiation in the powder and remelted material are significantly different, which had an additional effect on physics of the process.

In this work, the average depth and width of the track in a single layer were determined. Figure 4 shows the results of the investigation. The functional dependence of the track depth on the specific volume energy with a sufficient level of the approximation validity coefficient was established. An equation was obtained, with the help of which the optimal level of energy required to provide penetration to the value of not more than two layers was determined. It amounted to 39 J/mm^3.

For this energy level, the average ratio of depth to width of the tracks is at the optimum level. Figure 5 shows the microstructure of single layers with an optimal energy level, the overlap of adjacent tracks and their penetration depth are uniform.

When analyzing volume specimens, manufactured according to the same modes as single layers, the conclusion about the optimal level of specific volume energy of 38–40 J/mm^3 is confirmed. It was shown that at a higher energy level, deep penetration conditions are realized, and at a lower volume energy, guaranteed overlapping of adjacent tracks is not provided (Figure 6).

However, our previous investigations for single tracks found that the intensity of the scanning speed effect on their geometric parameters is significantly higher than the laser power. And the same level of volume energy can be achieved by a different combination of laser power and scanning speed. Further investigations will be devoted to establishing a preferred method of achieving an optimal level of energy input.

Conclusions

● As a result of investigations, the optimal values of scanning speed and laser power for the alloy Inconel 718 were determined from the point of view of producing a stable single track under the condition of forming a melt pool with a depth of up to two layers.

● The optimal process conditions for the Inconel 718 alloy were specified to produce single layers with the geometry of the tracks corresponding to the set conditions: the average depth of the tracks to two layers, the average ratio of depth to the width of the track is up to 1.5.

● The dependence of the average depth of the track of a single layer on the specific volume energy and the optimal level of this characteristic were established.

● The results on the optimal level of specific volume energy obtained during the investigation of single layers on volume specimens were confirmed: with the implementation of optimal conditions, specimens of maximum density were produced.

1. Thijs, L., Verhaeghe, F., Craeghs, T. et al. (2010) A study of the micro-structural evolution during selective laser melting of Ti–6Al–4V. *Acta Mater.*, 58(**9**), 3303–3312.
2. Simonelli, M., Tse, Y.Y., Tuck, C. (2014) Effect of the build orientation on the mechanical properties and fracture modes of SLM Ti–6Al–4V. *Materials Sci. and Eng. A*, **616**, 1–11.
3. Frazier, W.E. (2014) Metal additive manufacturing: A review. *J. of Materials Eng. and Performance*, 23(**6**), 1917–1928.
4. Parimi, L.L., Clark, R.G.A.D., Attallah, M.M. (2014) Microstructural and texture development in direct laser fabricated IN718. *Mater. Charact.*, **89**, 102–111.
5. Wu, M.W., Lai, P.H., Chen, J.K. (2016) Anisotropy in the impact toughness of selective laser melted Ti–6Al–4V alloy. *Materials Sci. and Eng. A*, **650**, 295–299.
6. Chlebus, E. et al. (2011) Microstructure and mechanical behaviour of Ti–6Al–7Nb alloy produced by selective laser melting. *Materials Characterization*, 62(**5**), 488–495.
7. Vilaro, T., Colin, C., Bartout, J.D. As-fabricated and heat-treated microstructures of the Ti–6Al–4V alloy processed by selective laser melting. *Metallurgical and Materials Transact. A*, 42(**10**), 3190–3199.
8. Qiu, C., Adkins, N.J.E., Attallah, M.M. (2013) Microstructure and tensile properties of selectively laser-melted and of HIPed laser-melted Ti–6Al–4V. *Materials Sci. and Eng. A*, **578**, 230–239.
9. Santos, E.C. et al. (2006) Rapid manufacturing of metal components by laser forming. *Int. J. of Machine Tools & Manufacture*, **46**, 1459–1468.
10. Zakiev, S. et al. (2006) Modelling of the thermal processes that occur during laser sintering of reacting powder compositions. *Appl. Phys. A*, **84**, 123–129.
11. Meier, H., Haberland, C. (2008) Experimental studies on selective laser melting of metallic parts. *Materialwissenschaft und Werkstofftechnik*, 39(**9**), 665–670. DOI: 10.1002/mawe.200800327.
12. Islam, M., Purtonen, T., Piili, H. (2013) Temperature profile and imaging analysis of laser additive. *Physics Procedia*, **41**, 828–835.

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