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IMPROVING THE EFFICIENCY OF THE SLM-PROCESS BY ADJUSTING THE FOCAL SPOT DIAMETER OF THE LASER BEAM

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Selective laser melting (SLM) is one of the modern methods of additive manufacturing, which allows creating high-density parts with a unique geometry from metal powder. To improve the efficiency of the SLM process, it is desirable to increase the width of the melt pool, as this will increase the distance between the laser passes and a larger volume will be built in a shorter period of time. However, the formation of the outer surface by large tracks will result in its higher roughness, which can significantly reduce the overall reliability of a product. To improve the surface quality, it is necessary to reduce the size of the melt pools, for example, by reducing the diameter of the laser focal spot. The samples were examined produced at different focal spot diameters using the same laser power. Based on the results of the analysis of technological parameters of the process, it was established that to increase the efficiency of SLM-process, printing of the main body of a product can be performed at an increased laser beam focal spot diameter, and to provide a high surface quality, printing of a contour part (shell) should be more performed using a more localized focal spot. According to the redistribution of power along the cross-section of the beam, a change in the configuration of the melt pool, and accordingly the track occurs. It was established that in order to avoid the formation of deep remelting due to a high concentration of energy in the center of the beam, it is necessary to reduce the laser power. 29 Ref., 6 Figures.

Keywords: *selective laser melting, technological factors, quality system, AISI 316L, specific linear energy*

Additive manufacturing (AM) as a method of parts fabrication is becoming increasingly important in recent years [1]. Selective laser melting (SLM) is the process of AM consisting of three main stages: 1 — deposition of a layer of powder with a thickness from 20 to 50 μm on the construction platform; 2 — melting of the powder layer by a laser source based on previously imported data of 3D-CAD models; 3 — lowering of the construction platform and restart at the point 1. The powder is usually applied with a polymer or rubber scraper. SLM allows manufacturing high-density parts with a unique geometry from metal powder. In addition, due to the possibility of reusing unmelted metal powder, SLM is almost waste-free technology [2, 3]. Moreover, only a small amount of further treatment (polishing, sandblasting, heat treatment) of parts manufactured by the additive method is required, so that expensive value-added processes can be minimized [4]. Studies of the last two decades have mainly focused on the influence of different process parameters on its stability and the resulting microstructure and properties of materials [5–7].

The studies of stainless steel by Gu et al. [8] showed that such parameters as laser power and scanning rate affect the porosity and evolution of the microstructure in different ways. Yang et al. [9] experimentally showed that quality of a product primarily depends on scanning rate, laser power and layer thickness. In a statistical study, the relative importance of each process parameter was studied and it was found that scanning rate is the parameter that has the most intensive influence [9]. A low scanning rate provides a complete melting of particles and a dense structure, but the process efficiency is significantly reduced. At very low scanning rates, instability of a melt pool causes a nonuniform melting along each track, which leads to a high surface roughness and a high volumetric porosity due to the effect of ball formation [10, 11]. At high scanning rates, a short-term interaction between the material and the laser beam causes the formation of narrow melt pools, which also leads to an increased surface roughness [11]. In addition, very high scanning rates can provoke an increased porosity, as well as the formation of thermal cracks as a result of high cooling rates [12]. According to the results of [13], at a high laser power density, a larger melt pool with a higher temperature is achieved. A fairly large melt pool leads to a good melt distribution and to a completely dense printing.

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Thus, finding the optimal scanning rate is a compromise between the efficiency and quality of the construction process.

Not only the process parameters have been improved, but also the equipment for the SLM process has undergone significant changes. Modern 3D technologies consider different possibilities of changing technological process of growing parts to increase the efficiency of the equipment preserving a high quality of products. Modern directions of improvement of technological aspects of SLM include an increase in the speed of process by means of a replaceable output chamber, closed control of powder processing, automated powder sieving, multilayer simultaneous printing, two axes of a coating and hoppers with many cavities [14]. Some companies also offer a close cycle powder control system and removable cylinders as new improvements to increase the speed of manufacturing [15–18]. Round platforms prevent powder dispersing and do not require filling or unloading of a powder during the entire fabrication cycle, even during printing at a full capacity [19–21]. This provides a homogeneous process of fabrication, shortens operator time and provides a high level of system security. Some new machines use automatic sieving and powder recycling in order to significantly reduce the time of fabrication. Due to the automation of the sieving process and recirculation of the powder, the time of manual work is reduced, which also increases the efficiency of the process [22, 23].

With an increase in the dimensions of construction a quite large number of technological limitations arises, one of which is a complicated operation of the kinematic system. At a high load on the construction platform, the positioning accuracy of the platform itself should reach several microns, and its horizontality and parallelism relative to the base frame should not exceed a few seconds. The physics of the process and the physical properties of the scanning system do not allow a significant increase in the scanning rate of the laser beam and the specific power with it. As the sizes of the construction platform increase, the fabrication period also increases in direct proportion. To solve this problem, most manufacturers of metal laser printing machines increase the number of scanning systems in combination with an increase in the number of laser radiation sources to 2, 4, 8 and sometimes up to 12 separate systems that scan one working field. On the basis of the analysis of modern 3D printers of world manufacturers, the comparative histogram of the process efficiency was plotted (Figure 1).

The main task in the development of SLM-technology is fabrication of high-quality parts. However, in order to increase the efficiency of the equipment it is necessary to reduce the time spent on fabrication. It

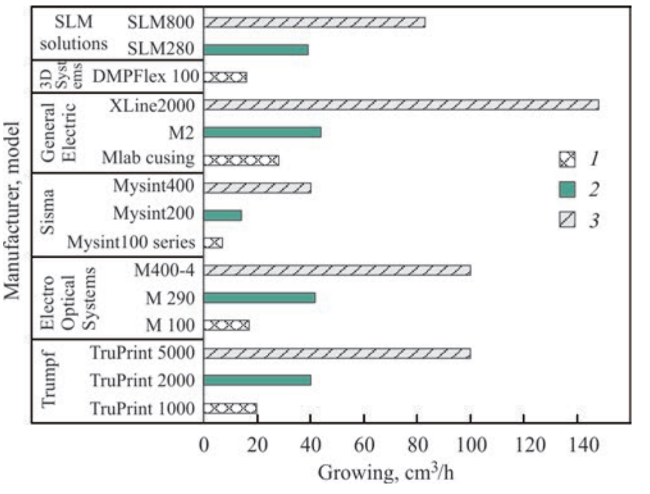

Figure 1. Rate of growing parts in the machines of world manufacturers: small machines (*1*), medium machines (*2*) and heavy machines (*3*)

is necessary to find compromise solutions, or to apply fundamentally new approaches to the formation of individual elements of a part.

One of the ways to improve the quality of a part is to reduce the melt pool, as far as the elements of the structure are refined, which leads to improvement in the set of properties, and significantly reduces the surface roughness of a product. However, with a small size of the melt pool, the fabrication time increases, which leads to a decrease in the efficiency of the SLM-process.

A large melt pool allows increasing the efficiency of manufacturing. However, this will increase the surface roughness of a product, and when the power is higher than the optimal, the conditions for evaporation of the substrate or powder may arise, which will lead to the pore formation and an increase in the total porosity of materials [24].

At the same thickness of the working layer, the time required to fill a certain area of a product layer decreases proportionally with an increase in a pool width, for example: at a pool width of 50 μm, taking into account the overlap of tracks by 30 % to fill the area of 0.1×0.1 mm, it is necessary to perform 28 scanning passes of the laser beam, and at a track width of 200 μm, under the same conditions it is necessary to perform 7 passes, spending 4 times lower time.

A new solution to the problem is the use of different focal diameters to manufacture individual areas of parts.

The aim of the work is to develop technological approaches to increase the efficiency of the SLM-process while providing a high surface quality of products.

Material and procedure of studies. In accordance with modern trends, LLC «Additive laser Technology Ukraine» designed a printing machine ALFA-280 with two scanning systems, each of which can operate at different values of a scanning focal spot. The size of the working chamber of the mentioned

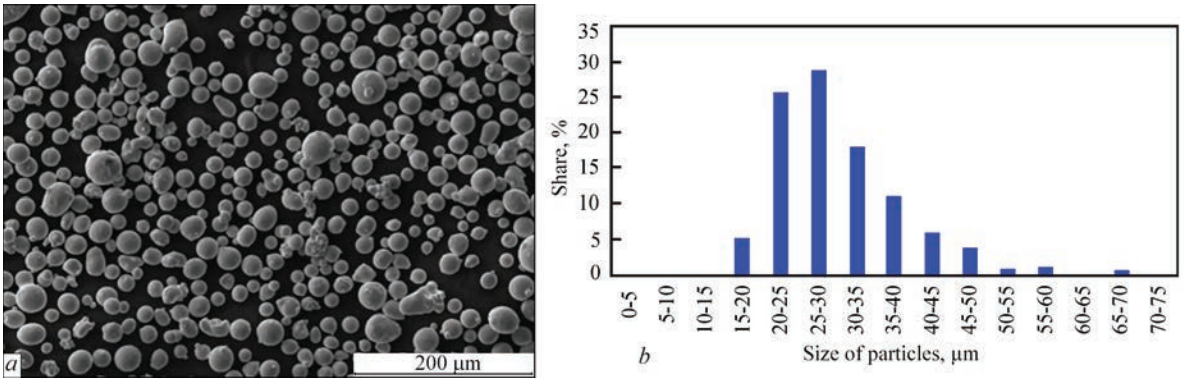

Figure 2. Particles of source material 316L (×200) (*a*) and results of grain-size analysis (*b*)

equipment is 280×280×300 mm that allows referring it to medium machines.

The studies were performed on samples made of powder material. The samples were printed in the Alfa-280 3D printer produced by «ALT Ukraine» LLC [24]. The material used in this study was stainless steel of the austenitic class 316L with a particle size from 10 to 45 µm. The chemical composition of the powder 316L, wt.% is 17.79 Cr; 12.63 Ni; 2.35 Mo; 0.78 Mn; 0.64 Si; 0.016 C.

The source material was examined using a scanning electron microscope REM-106 (Figure 2, *a*) to determine the shape and size of the particles. Figure 2, *b* shows the results of the analysis.

Record of the power distribution along the cross-section of a laser beam with different focal spot diameters was performed in the BeamGage Standard program.

Experimental samples of a cubic shape (10×10××10 mm) were manufactured using different focal spot diameters. During the manufacture of parts the scheme was used shown in Figure 3.

A surface layer (shell) of 1 mm thickness was created using the modes different from those used for the main body of the sample. The mode of shell scanning is the following: focal spot diameter is 75 µm, scanning rate is 1000 mm/s, power is 200 W, distance between scanning passes is 0.13 mm. To form the area of the main body, different construction modes with different focal spot diameters in the range of 100–250 µm with a step of 50 µm were used. Here, a constant scanning rate of 1000 mm/s, power of 350 W and distance between scanning passes of 0.17 mm were used.

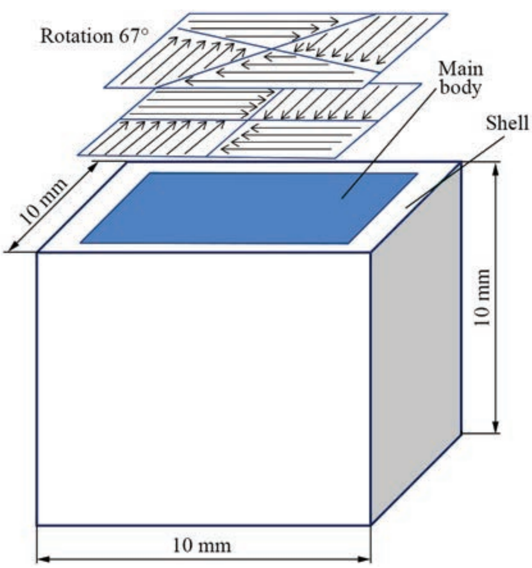

Figure 3. Scheme of strategy of construction of studied samples from AISI 316L alloy

Based on the previous studies of the strategy of construction of the contours of the sample [25], it was found that the order of the beginning of printing the boundaries and the main body does not play a big role in the speed of construction and the quality of manufacturing. Therefore, in this paper, the scheme of construction «main body–boundary of the sample» was chosen.

Results of studies. The melt pool of a one track has an arc configuration. This shape is a consequence of the power distribution along the cross-section of the laser beam according to Gauss. The shape and overlap of the melt pools is seen in the microstructure of a product made by SLM [13, 24–26]. Small dendritic and cellular structures with the size of structural elements of a few micrometers are found within each track [24]. For analytical determination of track parameters, the calculation method according to Rosenthal's formula is common [27].

However, this model includes the calculation of local heating only on a single track. In the conditions of the real process an influence of heat from the neighbouring constructed track is present. Based on this, modeling using the finite element method is performed. A number of scientists applied this method for calculation [28, 29]. This model was created for a two-dimensional coordinate system with a transition T^{i+1} (Figure 4) with a fixed values of a focal spot and working layer thickness.

The calculation was performed on the basis of the differential Fourier method, which is based on the replaced functions $T(x, y)$ of a grid function $T_{i,k}^{j}$ where (I, K is the numbering of nodal two-dimensional grids) under the condition of a uniform grid (step on x is equal to step on y). The temperature distribution in each grid node is determined by the following formula:

$$T_{i,k}^{j} = \frac{T_{i,k}^{j-1} + T_{i-1,k}^{j-1} + T_{i,k+1}^{j-1} + T_{i,k}^{j-1} - 1}{4}. \qquad (1)$$

The temperature field of each moment of time was calculated by means of two templates. The first template displays the starting moment of time. This temperature distribution is described using the boundary conditions of the first kind, i.e. the temperature on the surface of the powder layer is set, which is equal to the ambient temperature. The second template is used to calculate the temperatures at the next moment of time ($J + 1$) based on the formula (1). The results of calculating the temperature distribution for different focal spot diameters of the beam at a constant power of 200 W are shown in Figure 5. It can be seen that at a small diameter of a focal spot, an increase in the power density in the center of the beam leads to heating the powder to a much higher temperature, which can cause a decrease in the metal density of a finished product under the condition of deep penetration. Taken that into account, when reducing the beam diameter, it is necessary to adjust the laser power to provide high quality products.

According to the results of the calculation, it is shown that a decrease in the diameter of a focal spot leads to the redistribution of power along the cross-section of the beam, an increase in the energy concentration in the center of a focal spot, and a growth in the gradient. As the diameter of a focal spot (defocus) increases in the central part of the beam, the energy concentration decreases.

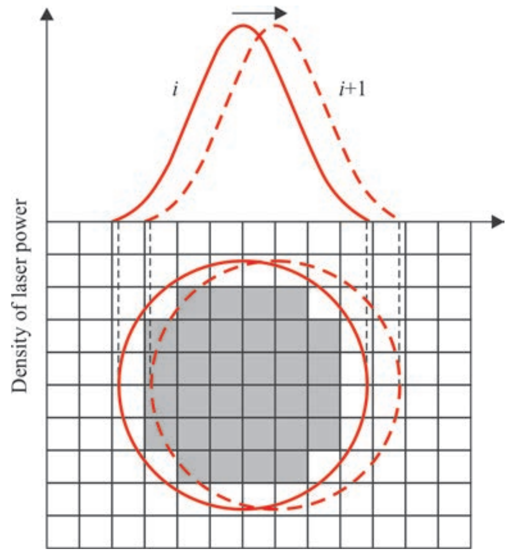

Figure 4. Scheme of model of moving heat source (grid diagram) [28]

Also from the analysis of calculation results it is seen that during construction of the main body of a part with application of larger diameter of a focal spot, tracks of

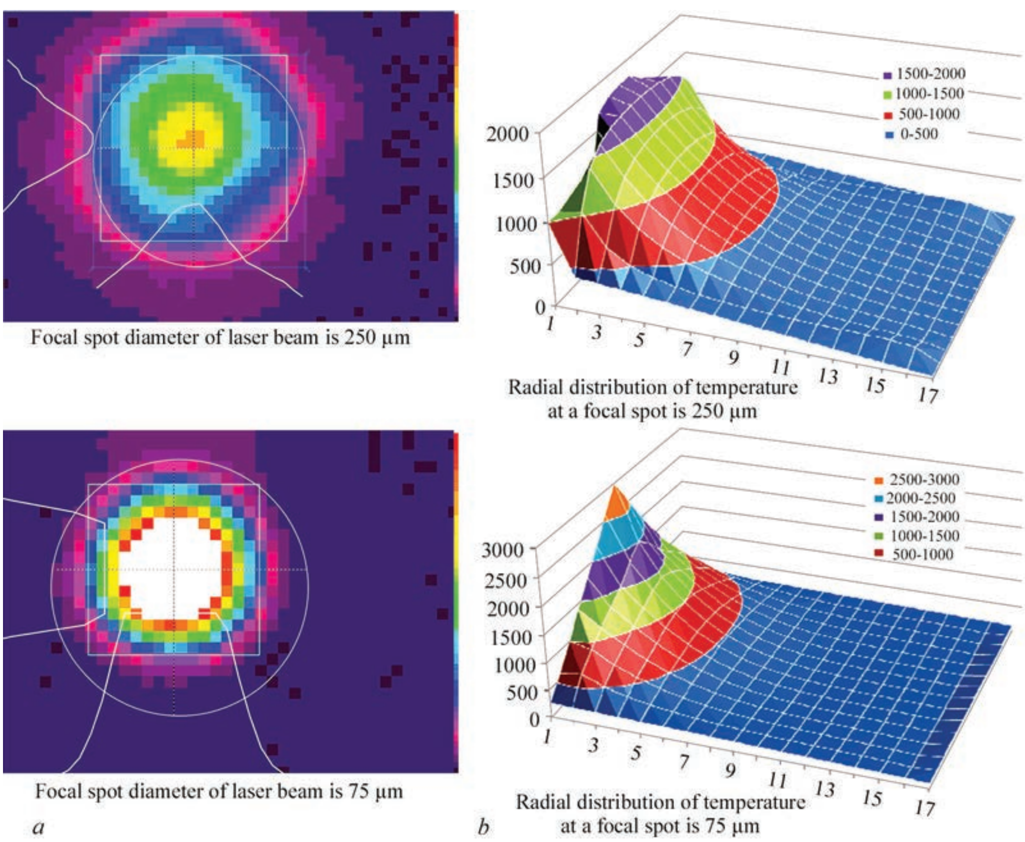

Figure 5. Power distribution along the cross-section of the laser beam with different focal spot diameters (*a*), results of calculation of temperature distribution for different focal spot diameters of the laser beam at a constant power of 200 W and a layer thickness of 40 µm (*b*)

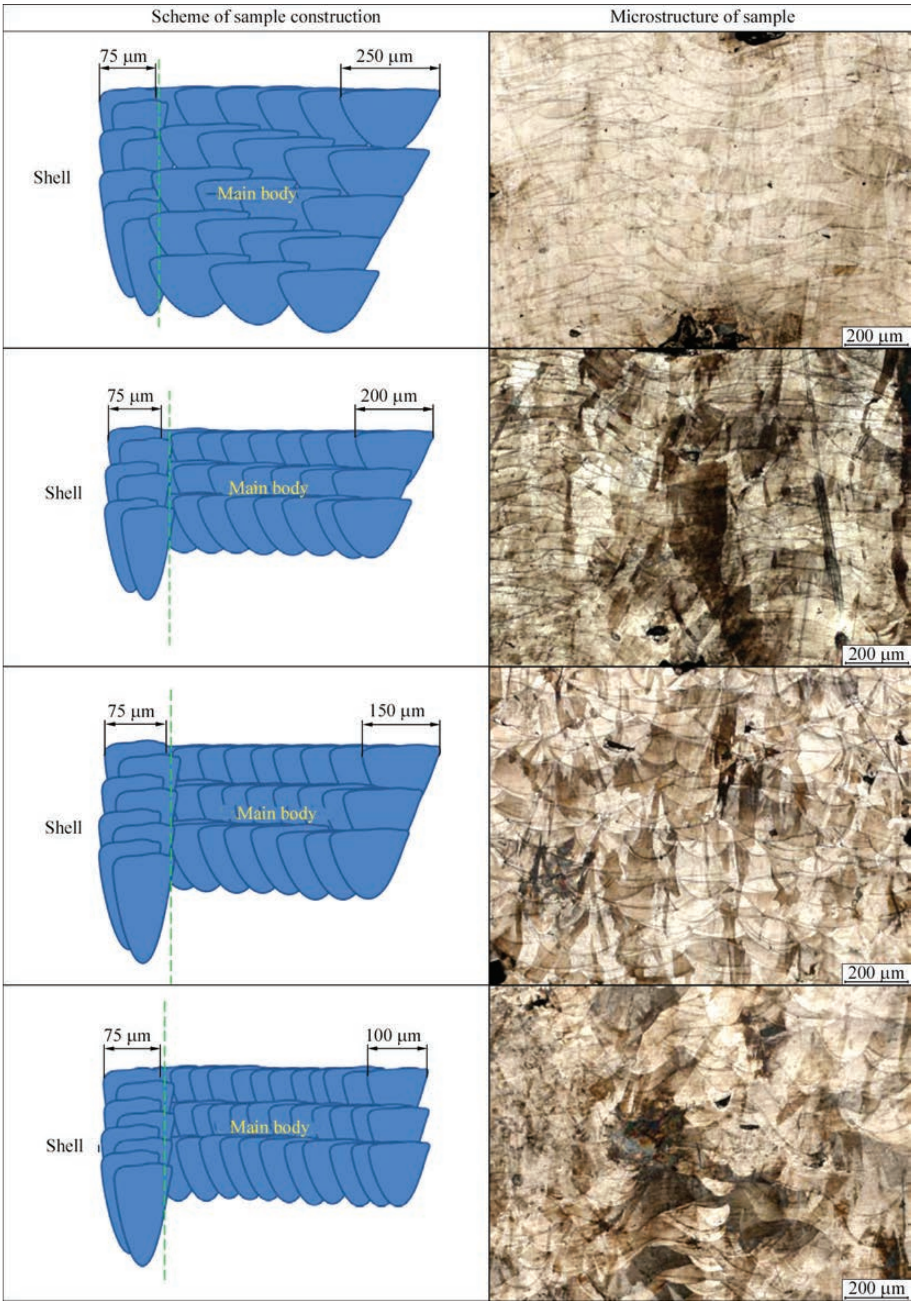

Figure 6. Scheme of formation and microstructure of samples manufactured by SLM-technology with different focal spot diameter of the laser beam

larger width will be formed. Therefore, less time can be spent on construction of a product as a whole.

Figure 6 presents the results of metallographic analysis of test samples and a schematic representation of the scheme of construction of the outer layer (shell) and the main body of the sample.

During the metallographic examination of the samples it was found that it is necessary to adjust the laser power with a change in the focal spot diameter of the laser beam to achieve a high density of metal products manufactured by SLM-technology.

Conclusions

1. The analysis of modern equipment for SLM-process realization was performed. It is shown that for medium and heavy machines one of the directions of

increasing efficiency of the process is an increase in a quantity of sources of laser radiation and separate systems scanning one working field.

2. According to the results of the analysis of technological parameters of the process it was established that to increase the efficiency of the SLM process, printing of the main body of a product can be performed with an increased diameter of a focal spot of the laser beam, and to provide a high surface quality, printing of a contour part (shell) should be performed using a more localized focal beam.

3. It is shown that it is necessary to adjust the power of the laser beam when changing the focal spot diameter of the laser beam to achieve a high density of metal products manufactured by SLM-technology.

1. Frazier, W.E. (2014) Metal additive manufacturing: A review. *J. Mater. Eng. and Performance*, 23(**6**), 1917–1928.
2. Huang, R. et al. (2016) Energy and emissions saving potential of additive manufacturing: The case of lightweight aircraft components. *J. of Cleaner Production*, **135**, 1559–1570.
3. Ford, S., Despeisse, M. (2016) Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. *J. of Cleaner Production*, **137**, 1573–1587.
4. Conner, B.P., Manogharan, G.P., Martof, A.N. et al. (2014) Making sense of 3-D printing; Creating a map of additive manufacturing products and services, *Additive Manufacturing*, **1–4**, 64–74.
5. Liverani, E. et al. (2017) Effect of selective laser melting (SLM) process parameters on microstructure and mechanical properties of 316L austenitic stainless steel. *J. Mater. Proc. Technology*, **249**, 255–263.
6. Yadroitsev, I. et al. (2013) Energy input effect on morphology and microstructure of selective laser melting single track from metallic powder. *J. Materials Proc. Technology*, 213(**4**), 606–613.
7. Yadollahi, A. et al. (2015) Effects of process time interval and heat treatment on the mechanical and microstructural properties of direct laser deposited 316L stainless steel. *Mater. Sci. and Engineering: A.*, **644**, 171–183.
8. Kamath, C. (2016) Data mining and statistical inference in selective laser melting. *Int. J. Adv. Manuf. Technol.*, **86**, 1659–1677.
9. Sames, W.J., List, F., Pannala, S. et al. (2016) The metallurgy and processing science of metal additive manufacturing. *Int. Mater. Rev.*, **61**, 315–360.
10. Kempen, K., Thijs, L., Yasa, E. et al. (2011) Process optimization and microstructural analysis for selective laser melting of AlSi10Mg. *Solid Freeform Fabrication Symposium*, **22**, 484–495.
11. Kamath, C., Eldasher, B., Gallegos, G.F. et al. (2014) Density of additively-manufactured, 316L SS parts using laser powder-bed fusion at powers up to 400 W. *Int. J. Adv. Manuf. Technol.*, **74**, 65–78.
12. Amato, K.N., Gaytan, S.M., Murr, L.E. et al. (2012) Microstructures and mechanical behavior of Inconel 718 fabricated by selective laser melting. *Acta Mater.*, **60**, 2229–2239.
13. Adzhamskyi, S.V., Kononenko, A.A., Podolskyi, R.V. (2020) 2D modeling of nonstationary temperature field of simple track of heat-resistant alloy Inconel 718. In: *Proc. of All-Ukrainian Scientific-Methodical Conf. on Problems of Mathematical Modeling*, 1, 42-45 [in Ukrainian]. https://www.dstu.dp.ua/uni/downloads/material_konf_traven_%202020.pdf.
14. Khorasani, A., Gibson, I., Kozhuthala, J. Veetil, Ghasemi, A.H. (2020). A review of technological improvements in laser-based powder bed fusion of metal printers. *Int. J. Adv. Manuf Technol.*, **108**, 191–209.
15. SLM Solutions (2019) SLM MACHINES. Last modified March 20, 2019, accessed March 21, 2019. https://slmsolutions.com/products/machines
16. Akbari, M., Kovacevic, R. (2019) Closed loop control of melt pool width in robotized laser powder–directed energy deposition process. *Int. J. Adv. Manuf. Technol.*, 1–12.
17. Shrestha, R., Shamsaei, N., Seifi, M., Phan, N. (2019) An investigation into specimen property to part performance relationships for laser beam powder bed fusion additive manufacturing. *Addit. Manuf.*, **29**, 100807.
18. Urhal, P., Weightman, A., Diver, C., Bartolo, P. (2019) Robot assisted additive manufacturing: A review. *Robot Comput. Integr. Manuf.*, **59**, 335–345.
19. SISMA (2019) *LMF «laser metal fusion» technology, last modified March 20, 2019, accessed March 21, 2019.* https://www.sisma.com/en/additive-manufacturing/
20. Jafari, R. et. al. (2019) Recent progress and challenges with 3D printing of patterned hydrophobic and superhydrophobic surfaces. *Int. J. Adv. Manuf. Technol.*, 1–14.
21. Rausch, A.M., Markl, M., Körner, C. (2019) Predictive simulation of process windows for powder bed fusion additive manufacturing: Influence of the powder size distribution. *Comput. Math. Appl.*, 78(**7**), 2351–2359.
22. Renishaw (2019) *Additive manufacturing products, last modified March 20, 2019.* https://www.renishaw.com/en/additive-manufacturing-products%2D%2D17475. Accessed March 21, 2019.
23. Yeung, H., Lane, B., Fox, J. (2019) *Part geometry and conduction based laser power control for powder bed fusion additive manufacturing*. Addit. Manuf. 30:100844.
24. Adjamskyi, S.V., Kononenko, G.A., Podolskyi, R.V. (2020) Influence of technological parameters of SLM-process on porosity of metal products. *The Paton Welding J.*, **10**, 13–18. DOI: https://doi.org/10.37434/as2020.10.03
25. Adjamskyi, S.V., Kononenko, G.A., Podolskyi, R.V. (2020) Simulation of influence of residual stresses and parameters of SLM technology on formation of boundary areas of heat-resistant alloy Inconel 718 products. In: *Proc. of Sci. and Tech. Conf. on Information Technology in Metallurgy and Machine Engineering (17-19 March 2020, Dnepr). Dnepr, 4–6* [in Russian]. DOI: https://doi.org/10.34185/1991-7848.itmm.2020.01.001
26. Adjamskyi, S.V., Kononenko, G.A., Podolskyi, R.V. (2020) Investigation of influence of SLM-process modes on quality in contour area of products. In: *Proc. of Int. Conf. on University Science-2020*, **1**, 157–158. http://eir.pstu.edu/bitstream/handle/123456789/17421/%D0%A3_%D0%BA%D0%B0%D1%8F%20%D0%BD%D0%B0%D1%83% D0%BA%D0%B0_2020_%D0%A2_1.pdf
27. Rosenthal, D. (1941) Mathematical theory of heat distribution during welding and cutting. *Weld J.*, 20(**5**), 220–34.
28. Du, Y., You, X., Qiao, F. et al. (2018) A model for predicting the temperature field during selective laser melting.
29. Promoppatum, P., Shi-Ch Yao, Pistorius, P.C., Rollett, A. (2017) A comprehensive comparison of the analytical and numerical prediction of the thermal history and solidification microstructure of Inconel 718 products made by laser powder-bed fusion. *Engineering*, **3**, 685–694.

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