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ADDITIVE MANUFACTURING OF STRUCTURAL ELEMENTS ON A THIN-WALLED BASE: CHALLENGES AND DIFFICULTIES (REVIEW)

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ABSTRACT

In the work a literature review of materials was conducted, devoted to different areas of studying selective laser melting (SLM) and selective laser sintering (SLS) technologies in order to analyze the processes associated with selective laser deposition occurring during SLM and SLS, as well as the impact of technological measures on the final structure, mechanical and service characteristics of a manufactured part in the additive manufacturing of structural elements on a thin-walled base. The main tasks of research works analyzed in the review were studies focused on the features of structural element formation on a thin-walled base by means of SLM and SLS technologies: modeling of additive manufacturing processes; aspects of planning experiments and manufacturing processes; studying the course of SLM and SLS processes in the given conditions; need in pre- or post-treatment of material; as well as analysis of the final microstructure and characteristics of samples manufactured using these technologies. Based on the results of literature review, problems were identified and the prospects of using SLM and SLS processes were considered during formation of structural elements on a thin-walled base. A number of aspects were defined, to which it is necessary to pay attention during these studies of SLM and SLS processes when working with a thin-walled base.

KEYWORDS: selective laser melting (SLM), additive manufacturing, selective laser sintering (SLS), thin-walled products

INTRODUCTION

Thin-walled parts are a category of parts, where thickness is much smaller than their dimensions (and does not exceed 3–5 mm). Thin-walled parts can include different types of products, the main characteristic of which is absence of rigidity and high final thinness factor, which is determined as their height, divided by their thickness. As regards the product varieties by their characteristics, these parts can be classified into two groups: monolithic blocks and skin panels. Such parts are widely applied in aviation industry (Figure 1), engine building, as well as in other industries [1, 2].

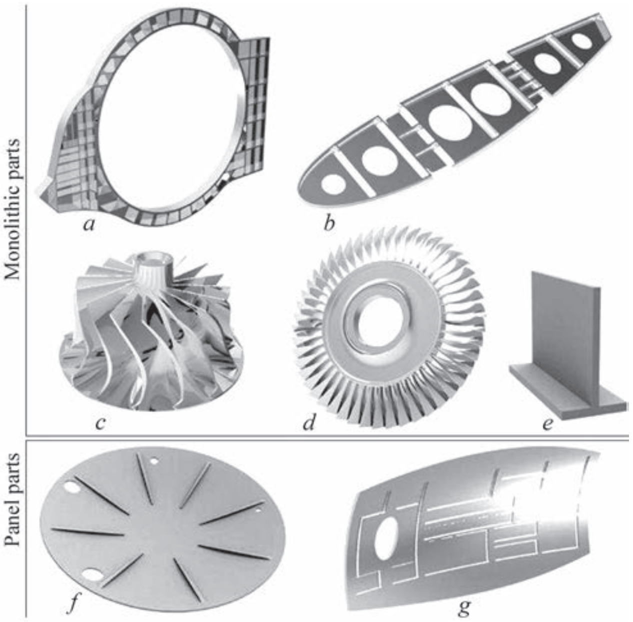

Figure 1. Examples of thin-walled parts in aviation industry: *a* — frame; *b* — stiffener ; *c, d* — components of jet engine turbines; *e* — ribs; *f* — partitions; *g* — fuselage skin components [1]

These and other parts often require fabrication of structural elements, which can be manufactured using many technologies, including laser cladding [1, 3].

Laser cladding is a procedure for manufacture of structural elements by creating material layers on the product surface as a result of melting of this material powder by the laser beam [4, 5]. This process allows deposition of layers of up to 100–500 μm thickness, using 2–4 mm laser beam (of up to 5 kW power) [6, 7] and feeding metal powder or wire by different methods (Figure 2) [5].

Over the last decades, however, such additive manufacturing technologies as selective laser sintering and selective laser melting have been more and more often used for manufacturing structural elements on thin-walled parts for reasons, related to the characteristics of materials produced by these methods [8–10].

Selective laser sintering (SLS) is an additive manufacturing technology, which is used for making products of a complex shape and structure from powder materials and optional polymer additives (Figure 3). This process consists in a sequential layer-by-layer sintering (or par-

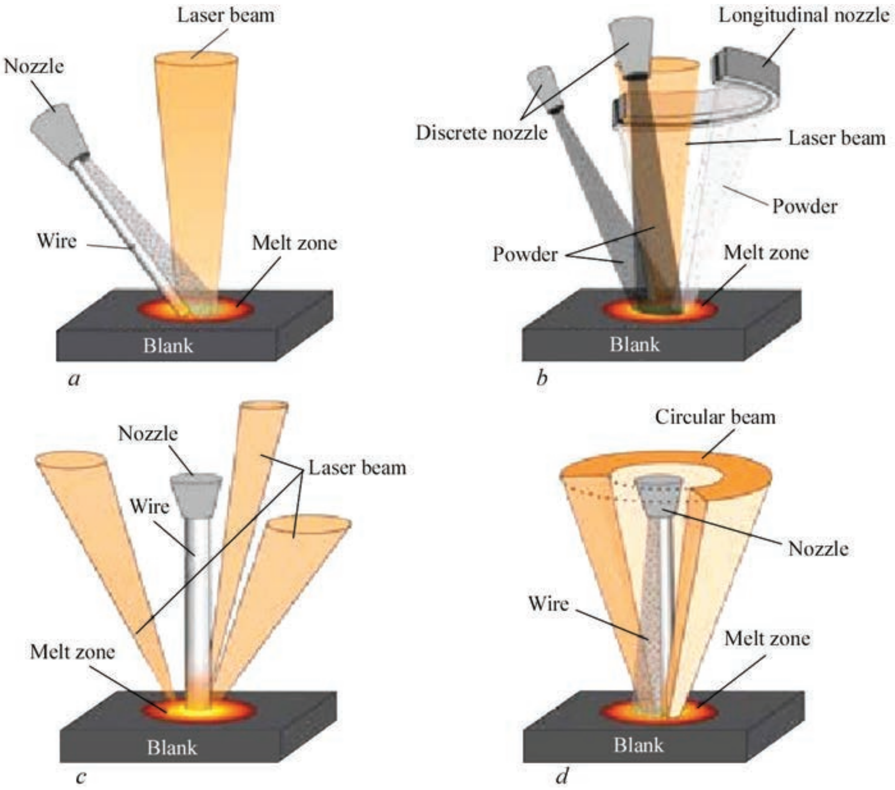

Figure 2. Schemes of material feed for laser deposition: *a* — lateral; *b* — coaxial with feeding from two angles; *c* — axial, with laser beams coming from the sides; *d* — axial with circular laser beam [5]

tial melting) of material in a pre-laid powder material, using laser radiation or the electron beam [11]. This technology allows deposition of layers of metallic, plastic or ceramic material 20–150 μm thick by a laser or electron beam of up to 300 μm diameter [12, 13].

Advantages of SLS technology application are as follows:

- wide range of possible materials;
- sufficient accuracy of the finished part;
- possibility of making parts of a more complex geometry.

The disadvantages of SLS technology are high porosity of the manufactured part surfaces and nonuniform value of internal density of the part material [5, 11, 13].

Selective Laser Melting (SLM) is one of the modern additive manufacturing technologies, which is used for making products of a complex shape and structure from powder materials. This process consists in a sequential layer-by-layer melting of pre-laid powder material in a special protective chamber using powerful laser radiation (Figure 4) [13, 14]. This technology allows deposition of up to 20–200 μm layers by a laser beam of 100 W to 2–3 kW.

The advantages of SLM technology application are the basis for serious prospects — increase of production efficiency in many industries, as:

- the process ensures high accuracy (up to 0.4 mm) and repeatability;

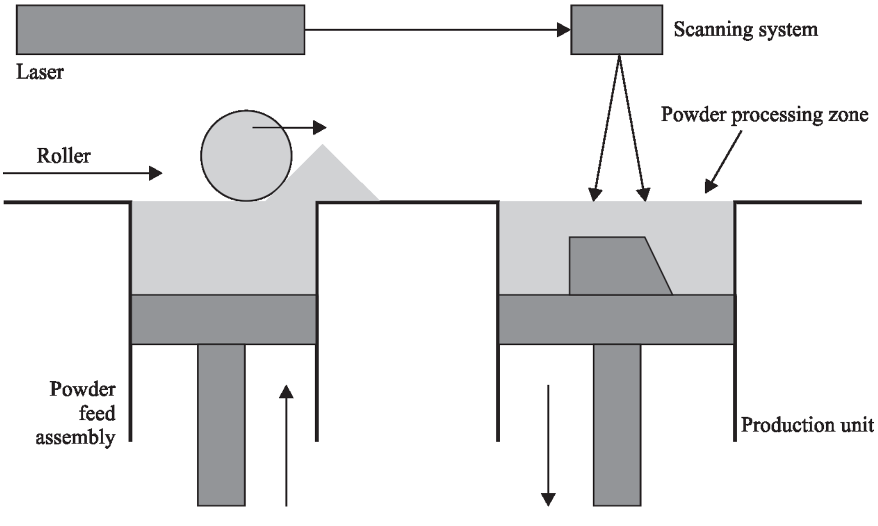

Figure 3. Schematic of the unit for SLS process [12]

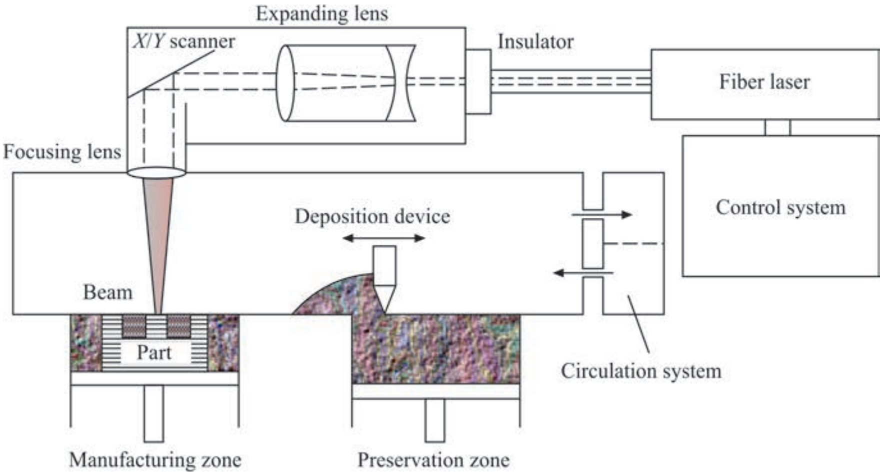

Figure 4. Schematic of the unit used for SLM [5]

- mechanical characteristics of products printed in this type of 3D-printer are comparable with castings [15];
- it solves complex technological tasks, associated with manufacturing products of a complex geometry;
- it allows reducing the weight due to construction of objects with inner cavities; and
- it allows material saving in production.

Despite the numerous advantages, the main disadvantages of SLM process, compared to deposition-based methods of part manufacturing, is a comparatively low productivity and impossibility to produce large-sized parts [5, 13, 14].

The main difference between the SLS and SLM processes consists in that SLS sinters the powder material at a temperature equal to approximately 85 % of deposited material T_m, while SLM joins the powder material by classical laser melting.

When working with thin-walled products, the problem arose of deposition of structural components on a thin-walled blank. Under these conditions laser cladding application involves a very high risk of deformations and blank melting-through [4, 7]. Manufacturing of thin-walled elements, as well as elements on a thin-walled base, remains to be one of the rapidly advancing directions of development of additive manufacturing technologies. Here, application of additive manufacturing technologies opens up new possibilities for deposition process control [9, 11, 14], as well as achieving better properties of the deposited material [14, 15].

For this reason, it was determined to be necessary to conduct analysis of the works devoted to studying the technologies of laser additive manufacturing, in order to take into account the experience of process improvement, which is used during fulfillment of this task. Special attention is given to analysis of the studies, related to products on thin-walled base, as parts of such a configuration are some of the most complex items for application of additive manufacturing processes. In view of this issue, as well as other features inherent to SLM and SLS processes [16–18], the problem arises of studying the components of these processes. For this purpose, a number of studies were reviewed in this paper, which are devoted to SLM and SLS manufacturing of parts on a thin-walled base. The objective of this work is establishing the relevant directions of studying different scientific components of SLM and SLS process, as well as analysis of the influence of technological measures on the final structure of the finished part, and its mechanical and service characteristics, in order to determine important aspects of SLM and SLS processes in manufacture of parts with a thin-walled base.

ANALYSIS OF THE INFLUENCE OF EXPERIMENT PLANNING ON ADDITIVE TECHNOLOGY PROCESSES

When studying the additive manufacturing processes sufficient attention is given to the components of experiment planning and preliminary mathematical preparation: studying the additive manufacturing processes in the mathematical dimension, as well as preliminary modeling of the process.

Mathematical modeling is an integral part of the experiment, as it allows quickly establishing the most promising variants of processing modes, and other factors, which markedly enhances the process productivity. There exist several variants of mathematical modeling; the most widely used is the finite element method. In practical studies of the finite element method two approaches are distinguished: a procedure focused on studying the influence of a separate quantity on the process, and is aimed at obtaining an optimal result for an individual task, which was described in works [19, 20]; as well as a procedure based on application of rows of planeless numbers, which was described in the work by Mukherjee, et al. [21]. This procedure is based on Marangoni, Peclet and Fourier numbers and values of planeless energy input, and it assumes that use of groups of values simplifies the

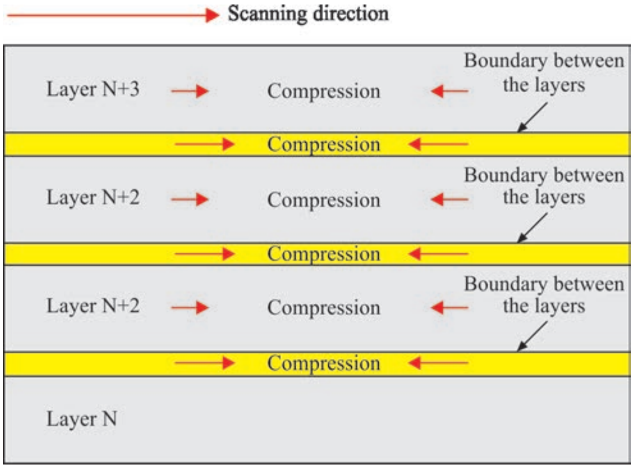

Figure 5. Abstract scheme of loads inducing deformations in additive manufacturing of thin-walled parts or elements on their surface [22]

general process of modeling the complex processes of additive manufacturing, may lead to a more profound analysis of the dynamics of behaviour of such processes, and it also allows establishing more profound principles of interdependence between the values of variables in these processes [21].

The next relevant problem of studying the processes of additive manufacturing on a thin-walled base is modeling the stresses generated when working with thin-walled elements. The process of thin-walled element manufacturing using SLM is considered in the paper by Yang et al. [22]. The results of this work point to considerable internal stresses, arising in the first deposited layers of powder material, the magnitude of which is believed to be sufficient for deformation of this surface during operation (Figure 5).

It should be noted that there is such a risk also for the pre-specified existing thin-walled part, onto which a layer will be deposited during selective laser deposition. Reduction of internal stresses can be achieved by many methods: from controlling the laser radiation energy characteristics, reported in the works by Li et al. [23] and Abele et al. [24], controlling the powder feed rate (paper by Liu et al. [25]), up to subsequent complex heat treatment of the part, which was described in the paper by Niu et al. [26].

Here, however, we should not forget about the discrepancies between the mathematical model values and the actual experimental data. Complex manifestations of the discrepancies between the results of modeling the additive manufacturing processes and the experimental results are given a lot of attention in works [19–21]. This discrepancy often is dynamic. Figure 6 gives an example in which it was reported [21] that even at confirmation of the majority of mathematical calculations by experimental data, there exist problems of accurate calculation of the melt zone during computation of the first deposited layers of the powder material.

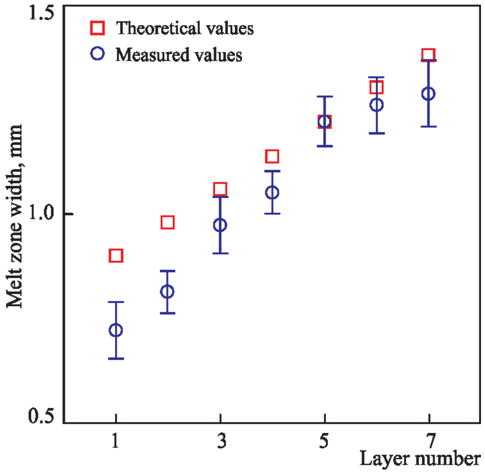

Figure 6. Comparison of calculated and experimentally measured width of the melt zone for 7 deposited layers of powder material [21]

The next important element of experiment planning is selection of the scan pattern, as it was determined that this component has a strong influence on additive manufacturing processes [5, 13]. So, in the work by AlMangour et al. [27] analysis of a number of patterns was performed, which gives argumentation as to the advantages of scan patterns where each layer differs from the previous one. In this study [27], as well as in the works by Zhao et al. [28] and Bambach et al. [29] the scanning strategy was found to influence the continuity of grain growth through the adjacent layers and grain growing inside the melt path. As a result, several schemes were considered (Figure 7):

- linear, where the process of material deposition is conducted by identical monotonic movements;
- parallel, where the deposited material paths run parallel to each other as to orientation, but not the deposition direction (see Figure 7, *a*);
- radial where material is deposited from the center to the edges or vice versa (see Figure 7, *c*);
- mixed, which combines several schemes simultaneously (see Figure 7, *b*).

The mechanism of interaction of the deposited material layers is worth mentioning separately. In works [28, 29] it was proved that the change of the angle of powder material deposition path between the layers has a positive influence on the material mechanical properties. However, in the paper by AlMangour et al. [27] it was found that the change of the angle of the path ("path rotation") of powder material deposi-

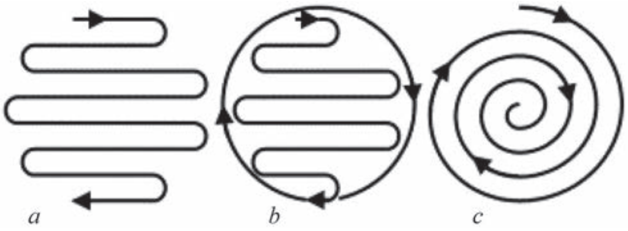

Figure 7. Scan patterns considered in the work by Bambach et al. [29]: *a* — parallel scheme; *b* — mixed scheme; *c* — radial scheme

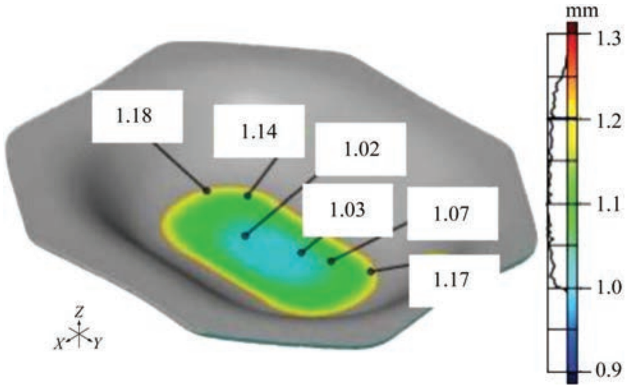

Figure 8. 3D scheme of thin-walled base deformation after selective laser melting of an element. Accuracy of ±0.15 mm [30]

tion may lead to changes of various parameters of the deposited material. Therefore, the change of the path angle during transition to a new layer of the material is not a universally positive principle 27, 29].

ANALYSIS OF THE COURSE OF ADDITIVE MANUFACTURING PROCESSES WHEN WORKING WITH THIN-WALLED BASES

When deepening the knowledge of additive manufacturing processes while working on a thin-walled base, a lot of attention is given to studying the influence of variables on progress of SLM and SLS processes, as well as deeper understanding of the course of these processes proper under the specified conditions. The paper by Ahuja et al. [30] describes powder material deposition on a thin-walled base in the form of a stamped part 1.5 mm thick. A structural assembly from Ti–6Al–4V alloy in the form of 10×5 mm cylinder was manufactured using SLM-280HL printer with laser radiation power of 400, 700 and 1000 W and up to 10 m/s scanning speed. In paper [30] special attention is also paid to size (25–45 μm particle size), and phase composition of powder material and its compatibility with thin-walled base material. The need for correct fastening and cooling of the part is also described here, as in the presence of air behind the thin-walled base it undergoes deformations under the impact of laser radiation. The magnitude of possible deformations detected in paper [30], was visualized (Figure 8).

The need for cooling the thin-walled part during processing is also mentioned in the paper by Heilemann et al. [31]. To avoid deformation, the authors used a 4 mm copper substrate. Also emphasized is the need to control the energy component with separation of the processes of deposition of the first layers of powder material and next layers, highlighting the great difference between the nature of different stages of this process [32–34].

ANALYSIS OF THE PROPERTIES OF PARTS WITH MATERIALS DEPOSITED ON THEM BY SLM OR SLS PROCESSES

It is important to pay attention to the transition zone, as well as mechanical properties of the assemblies produced by additive manufacturing on a thin-walled base. In earlier mentioned works [18, 29–31], this question was seen from different angles, as the mechanical properties of the parts can be influenced by many components of additive manufacturing process: both energy and thermophysical ones. The microstructure of this zone of such elements should be considered separately, as the transition zone between the base and the deposited powder material is one of the critical areas. So, for instance, in the work by Ahuja et al. [30] formation of microcracks in the transition zone was studied. To prevent their formation, it was proposed to perform deposition with a fillet radius of 0.5 mm (Figure 9).

It should be noted, however, that correct fastening of the part affects not only the base, but also the deposited materials. So, in works [30, 35] it was noted that the evenness of material distribution directly influences the deposited material dilution and the microstructure, forming weakened zones. In the paper by Schaub et al. [55] it was determined that the strength of the bond between the sheet metal and the deposited element can be improved, preventing oxidation and reducing the temperature gradient between the upper surface of the sheet metal and the first layers of the portion molten by the laser beam. Also mentioned here was pre- and postheat treatment, which agrees with the experiments conducted by Niu et al. [26]. In this study [26], as well as in the works by Lesyk et al. [9, 36] the presence of partially melted metal powder on the side surfaces of the deposited material layers was reported. Minimizing

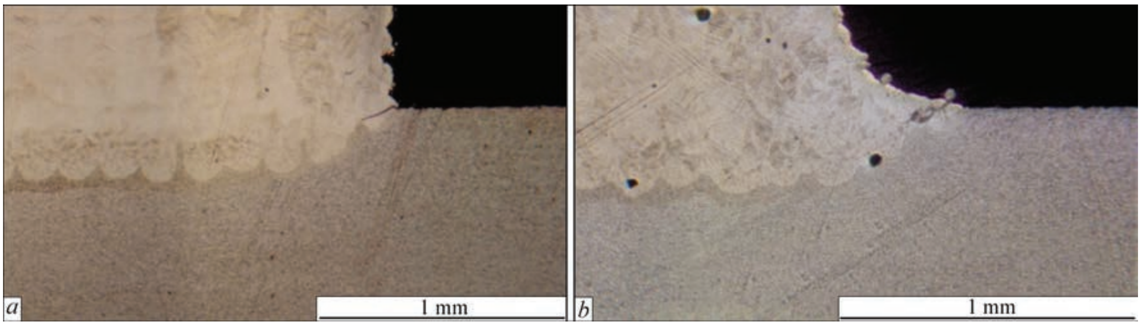

Figure 9. Transition zone structure [30]: *a* — without a fillet radius one can see cracking on the transition zone edges; *b* — with a fillet radius of 1.0 mm in the first layers of deposited material cracking is absent

of the amount of such formations is another reason for conducting the heat treatment.

ANALYSIS OF THE RESULTS OF THE CONSIDERED STUDIES. SPECIFICS OF APPLICATION OF ADDITIVE TECHNOLOGIES AT DEPOSITION OF ELEMENTS ON A THIN-WALLED BASE

Based on the results of the conducted analysis, we can note that the considered studies use a more comprehensive view of additive manufacturing processes, associated with element deposition on a thin-walled base. A difference in the approaches to modeling and consideration of the technologies is noticeable. For instance, most of the works, considering the questions of modeling of additive manufacturing processes use the finite element method, but the difference in the approaches to the variables slowly changes towards complex consideration of rows of parameters [5, 20, 21]. One can also see an additional focus on differentiation of the process of deposition of the first layers of powder material on the thin-walled base and deposition of additional layers, because of the importance of the influence of laser radiation on the thin-walled base and the transition layers. In this respect, the importance of correct fastening and cooling of the part should be noted, as there is a general understanding that this is important not only for a uniform formation of the deposited material [18, 29, 30], but also for prevention of thermal deformations of the thin-walled base [30]. There is, however, a reverse side: reduction of temperature gradient due to postheat treatment of the thin-walled base provides an increase of the strength of “base–deposited element” transition zone [35]. It is also important to single out the problem of deformations, which may develop through internal stresses, generated in the molten powder material [18], and which require additional heat treatment of the parts. It should be further noted that the “base–deposited element” transition should proceed with minimal temperature gradient — it minimizes the risk of lowering of the product strength characteristics [25, 26]. Together with the questions to phase composition, these problems add up to a complex issue of the priority of the characteristics, desirable for fulfillment of particular tasks.

CONCLUSIONS

Analysis of investigations of additive manufacturing of elements on a thin-walled base allowed establishing certain regularities, which are worth using for development of the process of selective laser deposition, namely:

- need for correct planning of the experiment, as well as the technological process, that is selection of scan pattern; processing modes, as well as modeling of “thin-walled base–deposited material” transition zone to form the smoothest and strongest transition zone;
- need to control the technology during the entire process, ensuring even distribution of the metal powder and cooling of the thin-walled base;
- need to ensure cooling of the thin-walled base to prevent thermal deformations, as well as use of heat treatment for leveling the internal stresses, developing in the upper layers of the molten material.

REFERENCES

1. Del Sol, I., Rivero, A., Lacalle, L., Gámez, A. (2012) Thin-wall machining of light alloys: A review of models and industrial approaches. *Materials*, **12**. DOI: https://10.3390/ma12122012.
2. Singh R., Gupta A., Tripathi O. et al. (2020) *Powder bed fusion process in additive manufacturing:* An overview. Materials today: Proceedings. DOI: https://doi.org/10.1016/j.matpr.2020.02.635
3. Mazumder, J. (2017) *1 — Laser-aided direct metal deposition of metals and alloys*. Ed. by M. Brandt. *Woodhead Publishing*, 21–53. DOI: https://doi.org/10.1016/B978-0-08-100433-3.00001-4
4. Yushchenko, K.A., Borysov, Yu.S., Kuznetsov, V.D., Korzh, V.M. (2007) *Surface Engineering*: Manual. Kyiv, Naukova Dumka [in Ukrainian]. ISBN 978-966-00-0655-3
5. Li Yuan, Songlin Ding, Cuie Wen. (2019) Additive manufacturing technology for porous metal implant applications and triple minimal surface structures: A review. *Bioactive Materials*, **4**, 56–70. DOI: https://doi.org/10.1016/j.bioactmat.2018.12.003
6. Kritskiy, D., Pohudina, O., Kovalevskyi, M. et al. (2022) Powder mixtures analysis for laser cladding using OpenCV Library. In: Integrated Computer Technologies in Mechanical Engineering — 2021. Eds by, M. Nechyporuk, V. Pavlikov, D. Kritskiy. *Lecture Notes in Networks and Systems*, **367**. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-94259-5_72
7. Duriagina, Z., Kulyk, V., Kovbasiuk, T. et al. (2021) Synthesis of functional surface layers on stainless steels by laser alloying. *Metals*, **11**, 434. DOI: https://doi.org/10.3390/met11030434
8. Korzhyk, V., Khaskin, V., Voitenko, O. et al. (2017). Welding technology in additive manufacturing processes of 3D objects. *Mat. Sci. Forum*, **906**, 121–130. DOI: https://doi.org/10.4028/www.scientific.net/msf.906.121
9. Lesyk, D.A., Martinez, S., Pedash, O.O. et al. (2022) Nickel superalloy turbine blade parts printed by laser powder bed fusion: Thermo-mechanical post-processing for enhanced surface integrity and precipitation strengthening. *J. of Mat. Eng. and Perform.*, **31**, 6283–6299. DOI: https://doi.org/10.1007/s11665-022-06710-x
10. Peleshenko, S., Korzhyk, V., Voitenko, O. et al. (2017) Analysis of the current state of additive welding technologies for manufacturing volume metallic products (Review). *Eastern-European J. of Enterprise Technologies*, **3/1**, 42–52. DOI https://10.15587/1729-4061.2017.99666.
11. Kumar, S. (2014) 10.05 – Selective laser sintering/melting. Eds by Saleem Hashmi, Gilmar Ferreira Batalha, Chester J. Van Tyne, Bekir Yilbas. *Comprehensive Materials Processing, Elsevier*, 93–134. DOI: https://doi.org/10.1016/B978-0-08-096532-1.01003-7
12. Serin, G., Kahya, M, Unver, H. et al. (2018) A review of additive manufacturing technologies. In: *The 17th Inter. Conf. on Machine Design and Production (Bursa, Turkey, January 2018).*
13. Najmon, J.C., Sajjad Raeisi, Tovar, A. (2019) 2 — Review of additive manufacturing technologies and applications in the aerospace industry. Eds by F. Froes, R. Boyer. *Additive Manufacturing for the Aerospace Industry, Elsevier*, 7–31. DOI: https://doi.org/10.1016/B978-0-12-814062-8.00002-9.
14. Del Sol, I., Rivero, A., Lacalle, L., Gámez, A. (2019) Thin-wall machining of light alloys: A review of models and in-

dustrial approaches. *Materials*, **12**, 2012. DOI: https://doi.org/10.3390/ma12122012.
15. Adjamsky, S.V., Sazanishvili, Z.V., Tkachov, Y.V. et al. (2021) Influence of the time interval between the deposition of layers by the SLM technology on the structure and properties of Inconel 718 alloy. *Mater. Sci.*, **57**, 9–16. DOI: https://doi.org/10.1007/s11003-021-00508-3
16. Sun, Z., Tan, X., Tor, S. Chua, C. (2018) Simultaneously enhanced strength and ductility for 3D-printed stainless steel 316L by selective laser melting. *NPG Asia Materials*, 10(**4**), 127–136.
17. Wang, Y., Voisin, T., McKeown, J. et al. (2017) Additively manufactured hierarchical stainless steels with high strength and ductility. *Nature Materials*, 17(**1**), 63–71.
18. Yang, W., Tang, Y. (1998) Design optimization of cutting parameters for turning operations based on the Taguchi method. *J. Materials Proc. Technology*, 84(**1–3**), 122–129.
19. Gibson, D. Rosen, B. Stucker (2015) *Additive manufacturing technologies: 3D printing, rapid prototyping and direct digital manufacturing Ch.10.* Springer, New York.
20. Pulin, Nie, Ojo, O.A., Zhuguo, Li (2014) Numerical modeling of microstructure evolution during laser additive manufacturing of a nickel-based superalloy. *Acta Materialia*, **77**, 85–95. DOI: https://doi.org/10.1016/j.actamat.2014.05.039
21. Mukherjee, T., Manvatkar, V., De, A., DebRoy, T. (2017) Dimensionless numbers in additive manufacturing. *J. Appl. Phys.*, **121**, 064904. DOI: https://doi.org/10.1063/1.4976006
22. Yang, T., Xie, D., Yue, W. et al. (2019) Distortion of thin-walled structure fabricated by selective laser melting based on assumption of constraining force-induced distortion. *Metals*., 9(**12**), 1281. DOI: https://doi.org/10.3390/met9121281
23. Zhonghua, Li, Renjun, Xu, Zhengwen, Zhang, Ibrahim, Kucukkoc (2018) The influence of scan length on fabricating thin-walled components in selective laser melting. *Inter. J. of Machine Tools and Manufacture*, 126(1–12). DOI: https://doi.org/10.1016/j.ijmachtools.2017.11.012
24. Eberhard Abele, Hanns A. Stoffregen, Kniepkamp, M. et al. (2015) Selective laser melting for manufacturing of thin-walled porous elements. *J. Materials Proc. Technology*, **215**, 114–122. DOI: https://doi.org/10.1016/j.jmatprotec.2014.07.017
25. Jichang, Liu, Lijun, Li (2005) Effects of powder concentration distribution on fabrication of thin-wall parts in coaxial laser cladding. *Optics & Laser Technology*, 37(**4**), 287–292. DOI: https://doi.org/10.1016/j.optlastec.2004.04.009
26. Xu Niu, Ruixian Qin, Yunzhuo Lu, Bingzhi Chen (2021) Energy absorption behaviors of laser additive manufactured aluminium alloy thin-walled tube tailored by heat treatment. *Materials Transact.*, 62(**2**), 278–283.
27. AlMangour, B., Grzesiak, D., Yang, J. (2017) Scanning strategies for texture and anisotropy tailoring during selective laser melting of TiC/316L stainless steel nanocomposites. *J. of Alloys and Compounds*, **728**, 424–435.
28. Zhao, C., Bai, Y., Zhang, Y. et al. (2021) Influence of scanning strategy and building direction on microstructure and corrosion behaviour of selective laser melted 316L stainless steel. *Materials & Design*, **209**, 109999.
29. Bambach, M, Sviridov, A, Weisheit, A, Schleifenbaum, JH. (2017) Case studies on local reinforcement of sheet metal components by laser additive manufacturing. *Metals*., 7(**4**), 113. DOI: https://doi.org/10.3390/met7040113
30. Bhrigu Ahuja, Adam Schaub, Michael Karg et al. (2015) High power laser beam melting of Ti–6Al–4V on formed sheet metal to achieve hybrid structures. In: *Proc. Of SPIE 9353, Laser 3D Manufacturing II, 93530X (16 March 2015)*. DOI: https://doi.org/10.1117/12.2082919
31. Heilemann, M., Beckmann, J., Konigorski, D., Emmelmann, C. (2018) Laser metal deposition of bionic aluminum supports: reduction of the energy input for additive manufacturing of a fuselage. *Procedia CIRP*, **74**, 136–139. DOI: https://doi.org/10.1016/j.procir.2018.08.063.
32. Vekilov, S.Sh., Lipovskyi, V.I., Marchan, R.A., Bondarenko, O.Ie. (2021) Specifics of using of technology in SLM manufacture for LRE components. *J. of Rocket-Space Technology*, **29**, 112–123. DOI: https://doi.org/10.15421/452112
33. Kelly, S.M., Kampe, S.L. Microstructural evolution in laser-deposited multilayer Ti–6Al–4V builds, Pt I. (2004) Microstructural Characterization. *Metallurgical and Materials Transact.*, **35A**, June 1861.
34. Heilemann, M., Möller, M., Emmelmann, C. et al. (2017) Laser metal deposition of Ti–6Al–4V structures: Analysis of the build height dependent microstructure and mechanical properties. In: *MS&T 2017*.
35. Schaub, A., Ahuja, B., Karg, M. et al. (2014) Fabrication and characterization of laser beam melted Ti–6Al–4V geometries on sheet metal. In: *DDMC 2014 Fraunhofer Direct Digital Manufacturing Conf., Berlin, Germany*.
36. Lesyk, D., Martinez, S., Dzhemelinkyi, V., Lamikiz, A. (2020) Additive manufacturing of the superalloy turbine blades by selective laser melting: Surface quality. Microstructure and porosity. New Technologies, Development and Application III. NT 2020. Eds by I. Karabegović. *Lecture Notes in Networks and Systems*, **128**. Springer, Cham. DOI: https://doi.org/10.1007/978-3-030-46817-0_30

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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