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PROBLEMS AND PROSPECTS OF STUDYING THE PROCESSES OF SELECTIVE LASER MELTING OF MATERIALS FOR AEROSPACE ENGINEERING (REVIEW)

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ABSTRACT

In this work, a literary review of the materials devoted to different directions of research of SLM technology was made, in order to determine the relevant directions of research of different scientific components of the process of selective laser melting (SLM), as well as technological measures affecting the final structure, mechanical and service characteristics of a manufactured part. The directions of scientific works considered in this review were: research and deepening knowledge on the influence of the energy component of SLM process; possibilities of SLM process modification by the control of laser defocusing amount; study of modes and methods of SLM processing, as well as final microstructure of the specimens; study of corrosion resistance of products, manufactured using SLM. Based on the results of the literary analysis, the problems and prospects of studying SLM processes for materials of aerospace industry are shown, the need in creating a systematic comprehensive approach to the study of the components of SLM process, as well as deepening knowledge about the technological capabilities of its application is substantiated.

KEYWORDS: selective laser melting (SLM), additive manufacturing, powder metallurgy, control of focal spot size, scanning strategy, aerospace industry metals

INTRODUCTION

Selective laser melting (SLM) is one of the modern technologies of additive manufacturing, used in manufacture of products of a complex shape and structure from metal powders. This process consists in successive layer-by-layer melting of powder material by powerful laser radiation. Selective laser melting allows creating unique products of a complex profile without the use of machining or complex expensive fixtures, in particular, due to the possibility of controlling the physico-mechanical properties of products.

SLM technologies have the ability to solve complex problems of aerospace, power, oil and gas and other mechanical engineering industries, as well as of metal processing, medicine and jewelry. However, despite the numerous advantages, the main disadvantage of SLM, compared to methods of manufacturing various parts and structures based on the deposition process, is a relatively low productivity of this technology. Increase of laser beam diameter improves SLM build-up rate, but leads to loss of precision. At the same time, it is necessary to understand that in order to produce a fully solid piece without defects (pores or other stress raisers), the metal powder particles should be completely melted. In this case, it is rational to use sufficiently high laser power. It should be noted, however, that at selection of excess power, the process may go into a less stable form, resulting in appearance of such defects as “balling effect” and excess local concentration of internal stresses that may cause deformation of the part or initiation of internal microcracks [1, 2].

These and other issues [3–5] raise the problem of studying the SLM-process components. For this purpose a number of works were reviewed, which are related to SLM processing of some of the most common aerospace materials, namely AISI 316L steel, as well as Inconel 625 and 718 alloys. All these materials are extensively applied in the aerospace industry due to their corrosion resistance and high working temperatures.

The objective of this work is determination of relevant direction of studying different scientific components of SLM process, as well as technological measures, affecting the final structure of the manufactured part and its mechanical and service characteristics.

ANALYSIS OF DIFFERENT DIRECTIONS OF STUDYING THE SLM PROCESS COMPONENTS

The issue of studying the selective laser melting process is complex. It requires analysis of various factors, which would take into account all the mechanical and physical properties of the manufactured structures and parts. Information and analytical studies showed that different methods are used to solve this complex of problems. These methods are concentrated on optimization of one or two characteristics, influencing the running of the process of analysis of different ways of studying the SLM process components. The scientific works discussed in this study are focused on SLM process optimization by the following methods:

- investigations and deepening of the knowledge on the influence of energy components of SLM process on its result;
- possibilities of modification of SLM process by controlling the laser defocusing amount;
- determination of the modes and methods of SLM processing, as well as final microstructure of the specimens. Studying the corrosion resistance of SLM products.

INVESTIGATIONS OF ENERGY COMPONENT OF SLM PROCESS

Earlier investigations [1–6] of the energy component of SLM process showed that laser power and energy density are important factors, influencing the quality of parts manufactured by this technology. The methods developed in works [3–5] would be beneficial for studying this process parameters. These methods involve orthogonal array design and analysis of HAZ dimensions. Thus, application of the normalized processing map, developed in the work by Thomas [6], which brings to the fore the use of dimensionless parameters of the process energy component for calculations, leads to the conclusion that the most significant factor is the normalized laser power q^*, influencing a large number of process variables. The same model emphasizes the importance of the magnitude of normalized equivalent energy density (E_0^*) as a key parameter influencing the properties of the manufactured parts [6–11].

In the study by Jiang [12], a normalized dimensionless technology map of SLM process was accepted for experiment planning. The effectiveness of its application was demonstrated by papers [2, 7, 9, 10]. This work analyzed the influence of normalized equivalent power density E_0^* and dimensionless laser density q^* on SLM process to study the developing defects, shape of the melt pool, as well as primary interdendritic spacing for the microstructure of parts built from 315L steel by SLM method.

Dimensionless laser power q^* is found from the following equation:

$$q^* = Aq/[R\lambda(T_m - T_0)], \tag{1}$$

where A is the surface absorption factor; q is the laser power (W); R is the laser beam radius (m); λ is the heat conductivity ($\mathrm{W \cdot m^{-1}\ K^{-1}}$); T_m is the melting temperature (K); T_0 in the melting temperature of the initial (or powder) material (K).

Equivalent power density E_0^* can be represented by the following equation (2):

$$E_0^* = q^*/(v^* l^* h^*) = [Aq/2vlh]\ [1/pC_p(T_m - T_0)], \tag{2}$$

where q^* is the dimensionless power density (1); v^* is the dimensionless speed of laser scanning; l^* is the dimensionless height of the deposited layer; h^* is the dimensionless distance between the axes of scan passes (3):

$$v^* = vR/a,\ l^* = 2l/R,\ h^* = h/R, \tag{3}$$

here, v is the laser scanning speed (m/s); α is the heat conductivity coefficient in the melting point ($\mathrm{m^2 \cdot s^{-1}}$); l, h is the layer thickness (μm) and distance between the scan pass axes (μm).

The dendrite microstructure obtained during the experiment through calculations by this model, reflects a combined influence of the process parameters and features of material phase composition on its final state in the HAZ. The study revealed that the low values of E_0^* parameter can lead to increase of the cooling rate, resulting in a structure with smaller interdendritic spacing. It was experimentally derived in the work that when manufacturing a part which must withstand considerable tensile stresses, the process parameters should be selected so as to ensure relatively low E_0^* values. In works [1, 11] it was proved that the shape of the melt pool, as well as the size of the HAZ are controlled by laser power. The specimen studied in the work by Sun et al. [1] had a melt pool of a narrow deep shape, demonstrating better mechanical properties compared to a specimen with a wide and shallow shape of the weld pool. The narrow deep pool is formed at a combination of the high value of dimensionless parameter of laser power, q^* and sufficiently high value of normalized equivalent power density E_0^*. However, the scientific work by Ma et al. [11] revealed that such a combination increases the instability of the melt pool, causing *keyhole* defects. It is pointed out that for each technical assignment there exist optimal values of q^* and E_0^* parameters. Here, the results of work [12] emphasize that at application of SLM technology without subsequent heat treatment to relieve the residual stresses, high complex characteristics of strength and ductility of the produced part can be achieved with the use of a rather low value of E_0^* parameter. Influence of process parameters on the microstructure of stainless steel 316L was also studied in the work by Kurzynowski et al. [13]. However, reaching similar conclusions, he noted that the SLM process is highly localized and rapid that made it complicated to achieve a deeper understanding of the mechanism of formation of various morphologies of the material, as well as microstructures of the manufactured part surfaces. So far just a few investigations were devoted to this problem, in the majority of which experimental results were studied using local X-ray visualization [13, 14].

An alternative method of studying the structure of parts produced by SLM process is computational modeling and predictive modeling. This method is becoming ever wider accepted in modern research on this subject. So, the work by Tang et al. [15] demonstrated a 3D model developed for simulation of formation of traces of 316L stainless steel melt during SLM process. Here it was proved that surface tension and recoil pressure were exactly the two key factors in formation of the macrostructure of single-pass deposited specimen of both spherical and irregular shapes.

Work [16] is a study of the features of the surface of Inconel 718 specimens, produced by SLM at different laser power and scanning speeds, while correlating the combinations of these values with the known principles of molten powder behaviour. Both experimental and model approaches were applied for investigation of surface morphology and solidification microstructure of Inconel 718 alloy, using a mezoscale 3D model of the height function of lattice-Boltzmann method (HF-LBM) [17, 18]. It was found that it is exactly the surface tension, and not the recoil pressure, as previously thought [18], that sucked the molten powder into the melt pool during SLM. As regards the low level of applied energy, the powder melt merges with unmolten particles before penetrating into the melt pool, which was determined to be the main cause for formation of surface fluctuations in the melt pool and further formation of closed surface pores. Deng et al. [19] noted that when the laser input energy exceeds the limit, the “balling effect” will be manifested in the melt pool.

In his dissertation Kempen et al. [20] came to the conclusion that the first step for enhancement of SLM process capabilities is précising the scanning path of single-line tracks with different combinations of laser power and scanning speed for a preset laser beam diameter and layer thickness. After that he stated the need to perform structure analysis in the melt pool, in order to select an optimal parameter series for further construction of a 3D-model of the manufactured part. The next step mainly includes determination of optimal scanning strategy and hatch spacing between the adjacent tracks. So, for instance, Wang et al. [21], as well as Yadroitsev et al. [22], studied the correlation of heat input and material morphology obtained after single-line scanning, namely in these works the influence of linear energy density Θ — a ratio of laser power P and scanning speed v — on the final structure of SLM part was investigated. On the whole, these studies confirm the theories given in works [14, 16, 20], but question the use of experimental single-pass specimens, as a mulitpass procedure is envisaged in practical manufacturing of the parts.

POSSIBILITIES OF SLM PROCESS MODIFICATION BY CONTROLLING LASER DEFOCUSING AMOUNT

In his study Promopattum et al. [23] reported that application of high laser power and small beam diameter does not lead to a stable SLM process, as concentration of a large amount of energy in a small point may lead to evaporation of the processed material and keyhole formation. After experimental tests he came to the conclusion that at a constant scanning speed increase of the laser spot diameter allows application of high-power lasers without overheating of the processed material. It, however, complicates maintaining the specified level of accuracy and surface roughness.

This problem can be prevented using the shell-core strategy, which envisages a set of high performance working parameters for the part core and high-precision operating modes for the surface layers of the manufactured part [24]. This procedure combines the high speed, geometrical precision and low surface roughness. The set of the main parameters of the operating modes in such a case usually includes increase of the defocusing amount that leads to increase of the melt pool size and greater thickness of the processed layer. Here, the need to maintain the minimal required power to conduct an SLM process operation is pointed out.

In work [25] the melt pool morphology was analyzed, taking into account SLM parameters, including laser power, scanning speed and defocusing distance. The bulk energy density, normalized enthalpy and an analytical approach using Rozenthal equation were applied to correlate the melt pool morphology and heat input. This equation was derived for classical fusion welding methods. However, due to the closeness of these processes to those occurring at SLM, Metelkova et al. [25] decided to apply the design parameters derived from this calculation equation with its condi-

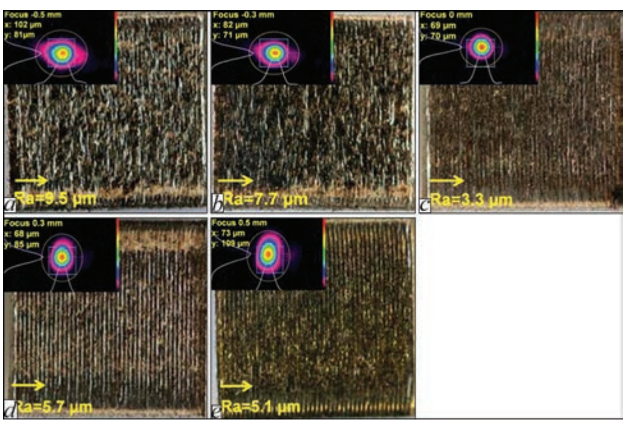

Figure 1. Macroscopic top view of SLM specimens produced with different defocusing amount, mm: *a* — –0.5; *b* — –0.3; *c* — 0; *d* — 0.3; *e* — 0.5 [25]

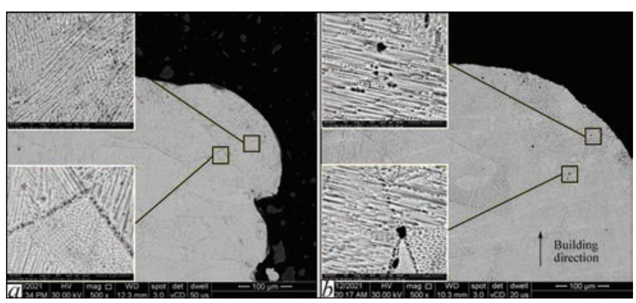

Figure 2. Porosity at negative (*a*) and positive (*b*) defocusing amount [27]

tions for computation of SLM processes. During work performance, the suitability of normalized enthalpy as a design parameter for prediction of the melt pool depth was emphasized, and the usability of Rozenthal equation for pool width prediction was proved. This investigation shows that realization of the proper defocusing amount may lead to a significant increase of potential productivity of the laser unit. However, one can note that the increase in productivity is achieved due to partial increase in roughness (Figure 1).

In work [26] the influence of negative (–0.5 mm, –0.3 mm) and positive (0.3 mm, 0.5 mm) values of defocusing distance in part manufacturing by SLM was conducted (Figure 2), to assess the influence of the defocusing amount on the melt zone width, height and depth, surface roughness, its density and tensile strength of parts.

One can see from the results of work [27] that the defocusing distance has a great influence on surface quality. Application of negative defocusing distances provides a melting mode in Inconel 625, where the melt pool is of a small depth and spherical shape. And contrarily, use of positive distances generates a keyhole melting mode, where the melt pool depth is greater than its half-width.

However, McLouth et al. [28] noted in his research results that despite the similarity of different processes of additive manufacturing, the influence of the defocusing amount on porosity and microstructure cannot be generalized for the processes for even one alloy type, as this value is influenced by a large number of parameters.

STUDYING SLM-PROCESSING MODES AND METHODS, FINAL SPECIMEN MICROSTRUCTURE AND CORROSION RESISTANCE OF SLM PRODUCTS

When trying to get a deeper insight into SLM, significant attention is attracted to studying the factors affecting the material corrosion resistance. Resistance of a heat-treated specimen of 316L steel, where the melt pool temperature reached a subcritical value of 950 °C, was better than that of the specimen, where temperature reached 1100 °C [27]. Another work [29] showed that residual compressive stresses, caused by SLM processes, can improve the growth of the passive film, and reduce the driving force of repassivation, leading to a slight improvement of point corrosion resistance of 316L steel. Pores detected in SLM specimens, compared to those made by traditional technologies, were described as such which promoted cracking and pitting which probably formed in extremely aggressive media [30]. Other defects, forming during SLM, namely defects of melt pool boundaries, nonequilibrium microstructure and nonuniform distri-

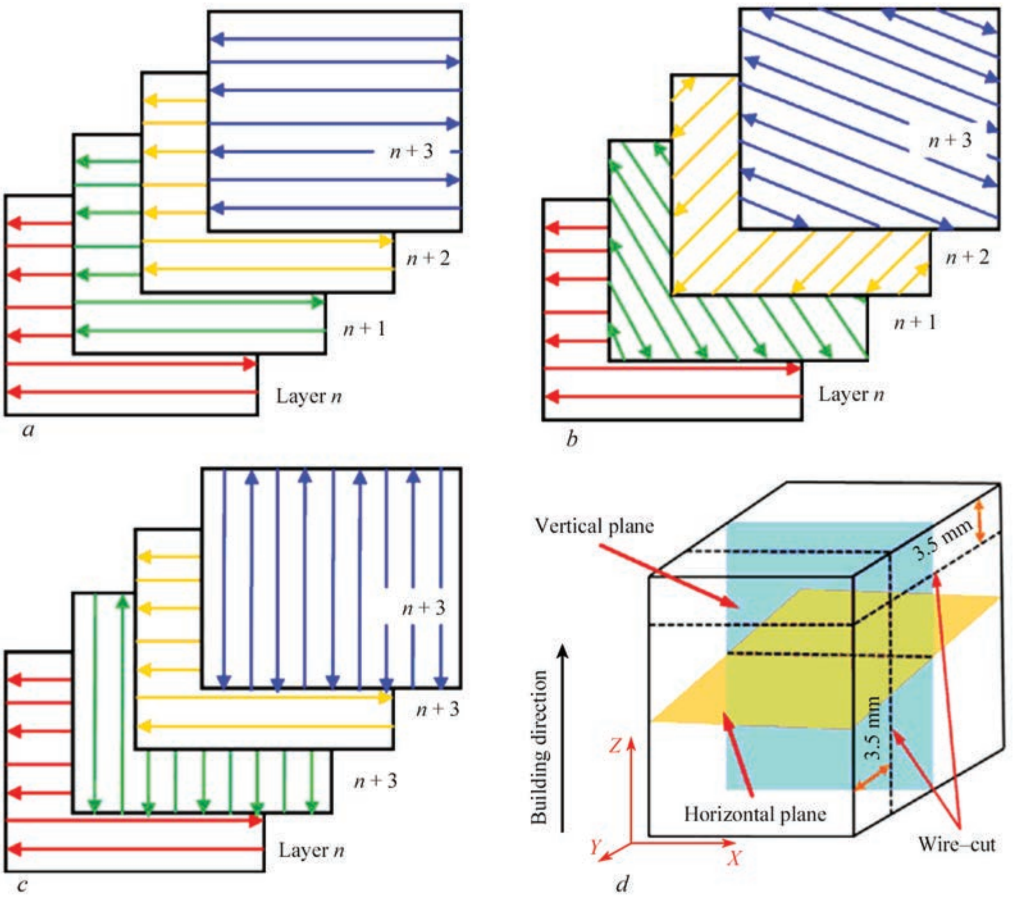

Figure 3. Scanning strategies used in [33]: *a* — without rotation; *b* — with rotation by 67.5°; *c* — with rotation by 90°; *d* — indication of vertical and horizontal planes

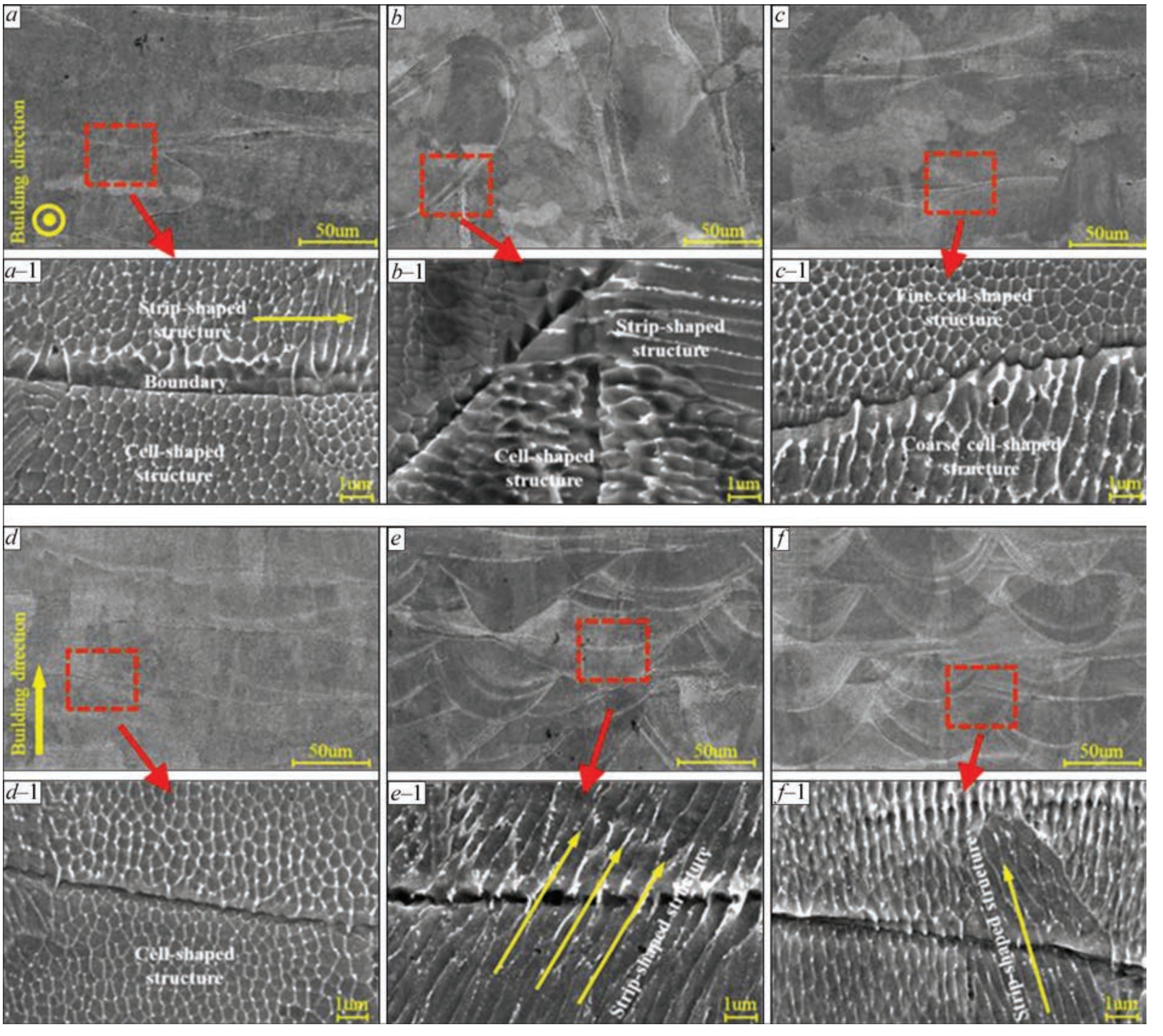

Figure 4. SEM micrograph of specimens: *a*, *d* — *XY* and *XZ* planes with strategic rotation angle of 0°; *b*, *e* — *XY* and *XZ* planes with strategic rotation angle of 67.5°; *c*, *f* — *XY* and *XZ* planes with strategic rotation angle of 90° [34]

bution of the solute, can also lead to deterioration of corrosion resistance [31, 32]. Thus, homogeneous microstructure and thicker surface film which may form after recrystallization heat treatment, can effectively improve the corrosion resistance of SLM specimens.

Laser scanning strategy and directions of building the grains and their bonds also have a strong influence on the microstructure and mechanical properties of final parts manufactured by SLM. Such a search for optimal scanning strategy (Figure 3) can be also used in SLM manufacture of parts with higher mechanical properties [33]. Moreover, at application of scanning strategy with rotation in each next pass, a porous structure was found on the upper surface of the manufactured part, and a columnar (dendritic) structure was present on its side surface. Their formation directly affects the mechanical properties of the part.

In work [34] use of various scanning techniques was studied during SLM of test specimens made from 316L steel, in order to determine the optimum scanning strategy at application of this material. Microstructure analysis using EBSD and SEM-microscopy (Figure 4) shows that the scanning strategy influences the continuity of grain growth through the adjacent layers and grain growth inside the melt track. Electrochemical testing pointed to an obvious difference in the corrosion resistance normal and in parallel to the scanning direction and with different techniques. Point corrosion is the main form of corrosion in 316L stainless steel, and it arises predominantly on the melt pool boundaries.

There is a large number of experimental research on the microstructures and mechanical properties of specimens produced from Inconel 718 by SLM. However, there are just a few studies of the influence of laser radiation parameters on the microstructure and mechanical properties of such parts [35]. Strossner et al. [36] proved that the microstructures of SLM specimens of Inconel 718 were very fine and oriented along the building direction. Yi et al. [37] found formation of a bright area in the form of a crescent on the lower edge of the melt pool of parts produced from Inconel 718 alloy. This area consisted of thinner

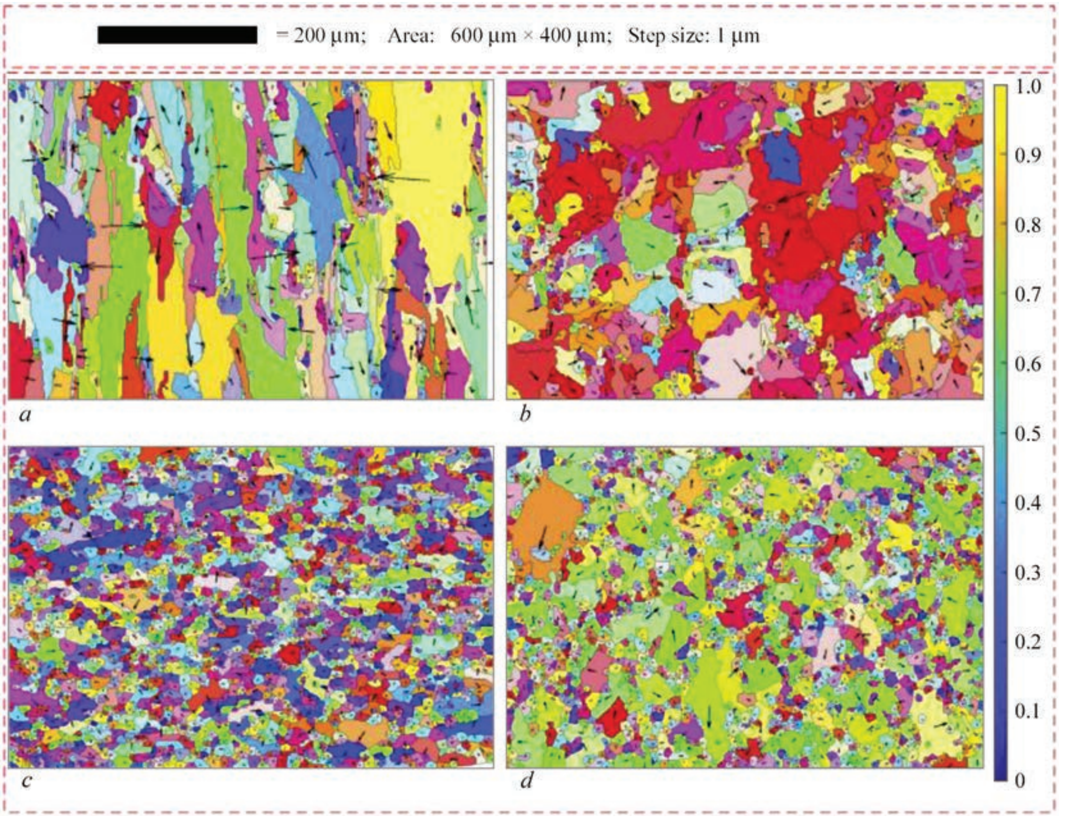

Figure 5. Grain microstructure in deformed (*b*, *d*) and undeformed (*a*, *c*) specimens of Inconel 718 alloy, produced by forging (*c*, *d*) and selective laser melting (*a*, *b*) technologies [42]

columnar dendrites of the same orientation as on the melt pool surface. Wan et al. [38] studied the influence of scanning strategy on the microstructure and texture of SLM Inconel 718, establishing a number of dependencies, pointing to a direct influence of scanning strategy on mechanical properties of the produced parts. Popovich et al. [39] proved the ability of additive manufacturing to produce individual microstructures with specified mechanical properties. In addition to these studies, many researchers focused on investigation of the influence of further treatment to achieve a comprehensive improvement of the part mechanical characteristics. Amato et al. [40] noted that the microstructure of a portion of an SLM part demonstrates columnar grains, irrespective of whether it was parallel or normal to the building direction, and studied the microhardness (Vickers) of rolled material produced by HIP and of annealed material.

Investigations of the structure of high-strength Inconel 718 alloy produced by SLM, was described in [41]. The influence of density of laser input energy (E, J/mm^3) on the density, phase composition, microstructure, homogeneity and mechanical properties of SLM specimens was analyzed in detail. Proceeding from experimental data of this study, it was noted that the surface morphology and density of SLM specimens were controlled by the power density value. The authors believe that it is possible to control also the dendrite structure in the same way by controlling the power density value, as increase of power density reduced the thickness of dendrites in experimental specimens.

Results of work [42] (Figure 5) showed that SLM Inconel 718 alloy demonstrates a slight coarsening of grain boundaries in the metal structure, as well as weakening of manifestation of its texture that differs from the phenomena of grain boundary coarsening and slight enhancement of the texture of cast Inconel 718 alloy. The SLM specimen has lower residual compressive stresses, compared to the wrought alloy, while the values of tool wear, surface roughness and microhardness are higher then those in a micromilled part.

Most of the current works on corrosion resistance report that SLM parts from 316L steel demonstrate better corrosion resistance, compared to parts from 316L steel with the structure produced at material forging. The results, however, cam be relatively fragmented [43-45]. In work [46] the corrosion behaviour of steels 316L(WS — forged structure), 316L(SLM) and 316L(SLM-1050 — annealing at 1050 °C for 15 min and quenching in water) was analyzed, allowing for their microstructure, residual stresses and physico-chemical properties of passively formed films. This work is a rather profound study of corrosion behaviour of these materials, taking into account the alloying additives and impurities (Figure 6).

CRITICISM OF WORKS

The works, in which the influence of energy component of SLM processes on its results was studied,

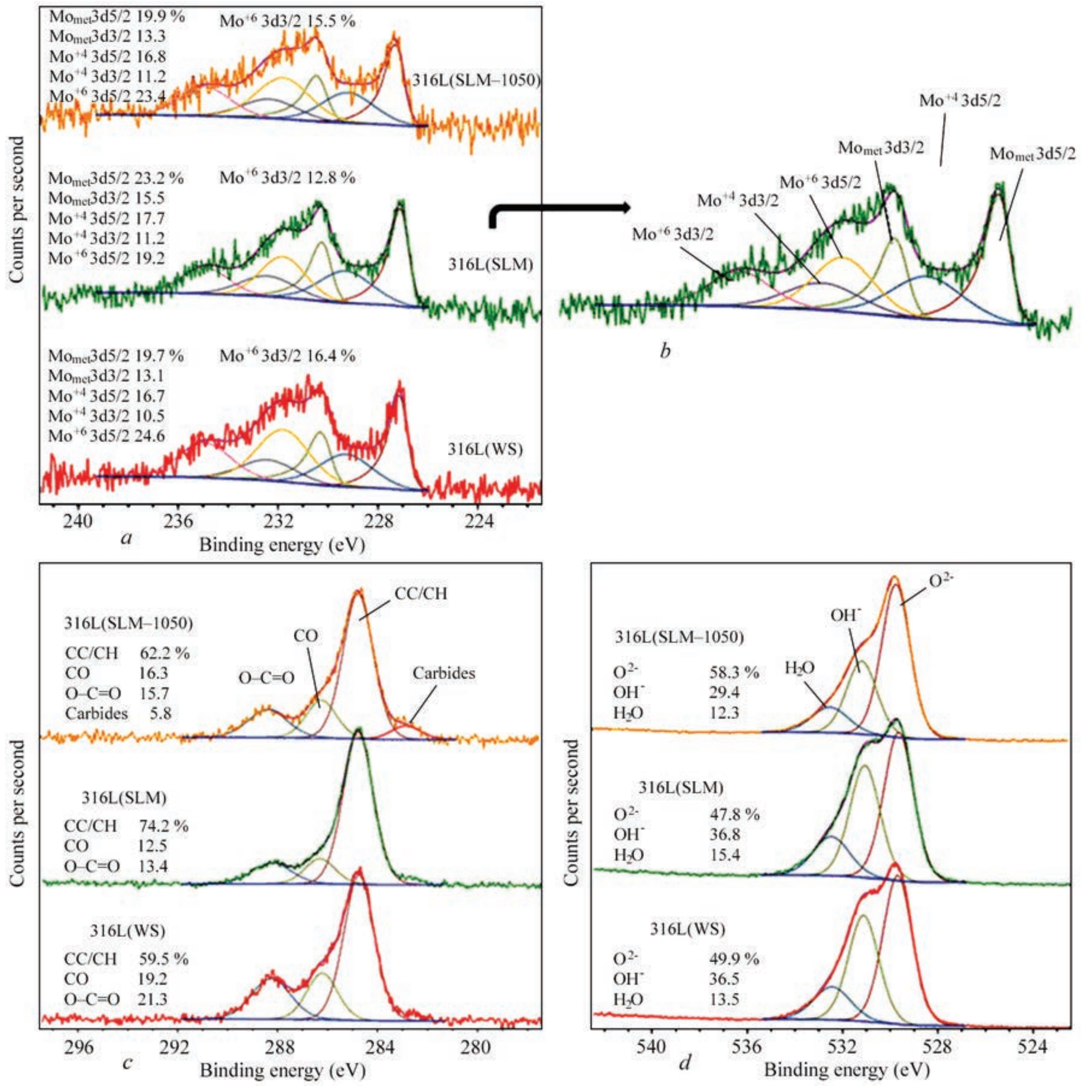

Figure 6. XPS-spectroscopy results of varieties of 316L steel after surface treatment: *a*, *b* — molybdenum levels; *c* — carbide levels; *d* — oxide levels [46]

considered individual cases of SLM process analysis for performance of certain tasks. Attempts to create a general model to study the influence of variables of SLM process energy component were noted. So, results of modeling the structure of upper layers of the processed surface in work [16] were compared with those of the experiment. Despite the fact that these results were in good agreement, this model did not become widely accepted, because of a lack of assessment of its capabilities under different conditions. Here, this model was not taken to such a condition that would allow its application for general computation of SLM processes. This, in its turn, leads to cardinally different works being the base for studying similar processes in work [12].

The works in which the possibilities of SLM process optimization by controlling the amount of laser radiation defocusing were analyzed, provided a rather profound study of both their advantages and disadvantages, related to such an application of SLM process. However, because of a relatively small number of works considering these possibilities, the general assessments of the effectiveness of this work are empirical, and not been brought to a holistic theory confirmed by general regularities.

The considered studies of the methods of improving the adaptability-to-manufacture of SLM specimen microstructure, focused on two directions, namely control of the process of microstructure formation by finding the optimum path of scanning and powder feed, as well as removal of undesirable admixtures in the structure of SLM specimen. The works, focusing on finding a more effective path of scanning and powder feed, demonstrated rather big problems with this component, as the movement pattern of the head of laser technological complex (LTC) has an important role in this process, both as to the microstructure and further characteristics of the part. So, a large number of parts studied in [36] were found to have point corrosion and pitting, which adversely affect the part performance. Although other works indicate that in certain cases the SLM parts demonstrate better corrosion resistance than do parts with a forged metal structure, the question of general resistance of SLM parts remains quite relevant.

Analysis of investigations of SLM-manufacturing of parts from a number of widely accepted metals revealed that there are numerous experimental studies, which analyze the final microstructure and mechanical properties of SLM parts. On the other hand, in the opinion of the author, there are not enough studies focused on determination of the influence of laser radiation parameters on the final microstructure and mechanical properties of the parts. Certain regularity was noted: control over SLM process is considered in the form of special processing modes, individual for each technical assignment. However, the obtained research data is insufficient to formulate the regularities of the influence of individual laser radiation characteristics on the microstructure in SLM parts.

CONCLUSIONS

PROBLEMS OF DEEPENING THE KNOWLEDGE ON SLM PROCESS

The main problem of further optimization of SLM process is absence of general regularities of the influence of SLM parameters on structure formation, geometry and level of mechanical characteristics of the produced specimens, which could be taken into account at development of the respective procedure of controlling the technological process parameters. It would allow increasing the quality and level of service and functional properties of the produced specimens and developing technological recommendations on product manufacturing for different industries, allowing for the respective service requirements. A literature review of the state of research into the processes of SLM manufacturing was conducted to verify this thesis.

Therefore, it is considered rational to emphasize the need to create a systematized comprehensive approach to optimization of SLM process. Obtained using this approach regularities of the influence of laser radiation characteristics on the microstructure and mechanical properties of SLM parts, can be used to develop a complex of technological measures for SLM manufacturing processes. Introduction of this complex of SLM technological measures, in the opinion of the author, will allow solving a large variety of tasks, posed by different industries at manufacturing a wide range of products.

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