This paper reports the technology and equipment designed for manufacturing parts and components with predefined properties by 3D printing methods. Underlying the technology is the use of a beam of high-power electrons to smelt metal powder in a vacuum chamber with the formation of successive layers that repeat the contours of the digital model of the article.

The object of research is the process of surfacing articles from the Ti_6Al_4Vtitanium alloy powder. The purpose is to determine the optimal surfacing modes based on identifying the effect of process parameters on the quality indicators of articles.

The result of the study is the analyzed influence of technological parameters on the properties of articles. The optimum energy density of the beam of 44.5 J/mm^3 has been determined. Based on the research results, 25 experimental samples were printed. Three beam speed modes were used: 270, 540, and 780 mm/s. For each mode, the dynamic focusing current varied from –1.2 to 1.27 A in increments of about 0.3 A.

The articles were carefully examined. A method of raster electron microscopy was used to study the morphology of the samples' surfaces in several zones, namely in the central zone and along the contour; the roughness parameters of the surface micro relief, as well as the presence of defects (pores, non-melting, micro irregularities, inclusions), were established. It has been found that the articles are characterized mainly by a homogeneous micro relief of the profile. The structure of surfaces, formed in different zones depending on technological modes, differs in its morphology. Surfacing modes have been established that have the practical application: beam speed, 780 mm/s; power, 675 W; dynamic focus current, from –1.2 to 0 A. This provides for the minimal parameters of the surface micro relief and the absence of defects such as shrinkage pores, non-melting, as well as a minimum number of inclusions

Keywords: electron beam surfacing, Ti_6Al_4V, technological parameters, raster microscopy, surface roughness

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DETERMINING THE INFLUENCE OF TECHNOLOGICAL PARAMETERS OF THE ELECTRON-BEAM SURFACING PROCESS ON QUALITY INDICATORS

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1. Introduction

Innovative technologies of layer-by-layer manufacturing of articles by the rapid prototyping method open up new opportunities for fabricating parts of the predefined shape with predicted properties.

The process of making articles using this method involving an electronic beam is relatively new but has already shown great prospects for the manufacture of a wide range of industrial and medical articles. Underlying it is the operation of layer-by-layer smelting of metals in a vacuum with an electron beam. This approach is characterized by the rapid transition to the production of three-dimensional articles directly from the computer-aided design system providing for the possibility of using a wide range of metals and alloys, including refractory and chemically active ones.

For the world, it is time to devise additive technologies for growing articles by electron beam surfacing. It is a relevant task to design equipment and to develop software for the implementation of additive production, focused on its implementation in the aerospace industry and turbine engineering enterprises, as well as for the needs of the biomedical industry.

Manufacturers of additive equipment supply turnkey technology, that is, technological equipment, the range of materials, and modes of their processing. This provides for only some of the possible characteristics of the strength and quality properties of the resulting articles, which does not allow the full introduction of additive technology methods into the industry. Technological modes are often unknown because they are hidden in software that does not give the production flexibility in terms of the possible replacement of raw materials and technological equipment with analogs [1].

Therefore, important now are those studies that address the search for technological modes that would ensure the construction of articles with the required properties and from the raw materials needed by a manufacturer.

At the same time, it is also important to tackle the issue related to fabricating high-quality articles in terms of their defect-free structure in the absence of non-melting, pores, inclusions, etc., including the formation of surfaces with homogeneous relief.

2. Literature review and problem statement

Determining the technological parameters of surfacing by additive electron beam technology is a necessary component for making articles with the desired properties [1].

Paper [2] reports the results of studying the influence of modes of electron beam surfacing on the roughness of surfaces of articles made of Ti_6Al_4V. It is shown that the beam current and speed function are the most important processing parameters for the directional scanning strategy. However, there remained unresolved issues related to the influence of focusing the electron beam (shifting focus) on the formation of the surface of articles.

In [3], the results showed that the shift in focus had the main effect on the roughness of the surface of articles, to a greater extent than the current and speed of the beam. In addition, the cited paper notes that the shift in focus greatly affected the density of articles, more than other parameters. However, there are unresolved issues related to the influence of technological parameters on the formation of structures of the surface of articles.

In work [4], an attempt was made systematically, using methods of mathematical analysis, to understand the influence of technological parameters on the formation of the surface of articles. However, the cited work has no practical application since there are no methods for determining surfacing modes.

Study [5] states that the surface quality of an article depends on the speed function and focus shift. The surfaced surface of an article should look even and smooth to get completely dense parts. However, there are no methods for determining technological parameters and surfacing modes in the cited study.

Paper [6] argues that optimized parameters of the process of electron beam surfacing of articles made from the Ti_6Al_4V titanium alloy lead to the manufacture of parts with similar, if not better, mechanical properties than articles made of wrought-on metal.

Thus, further optimization of the parameters of the process of electron beam surfacing is of primary importance for achieving a better quality of the surface of articles [7].

Paper [4] states that there is a limited number of studies at present on the impact of technological regimes on the condition of the surface of articles. That gives grounds to assert that it is advisable to investigate the process of electron beam surfacing and determine the optimal technological parameters.

3. The aim and objectives of the study

The purpose of this work is to determine the optimal technological modes of electron beam surfacing based on the identification of the influence of the main parameters of the process on the quality indicators of articles. This will make it possible to apply the results obtained for the manufacture of metal articles by the additive method.

To accomplish the aim, the following tasks have been set:

– to analyze the technological parameters of surfacing;

– to determine the technological modes of printing;

– to fabricate experimental samples;

– to investigate the impact of printing parameters on the structure of article surfaces and the presence of defects.

4. The study materials and methods

4. 1. Experimental equipment

Specialists from the Institute of Electric Welding named after E. O. Paton conducted research in the field of technology and equipment development for the additive production of metal parts. For the research, a prototype of additive equipment was built on the basis of a small-sized installation for electron beam welding such, the type of SV-212M [8].

Together with Materialise, a company from Belgium, the software and hardware platform to control the equipment was designed, which includes a controller and a software package for implementing additive production [9].

The general view of the equipment is shown in Fig. 1.

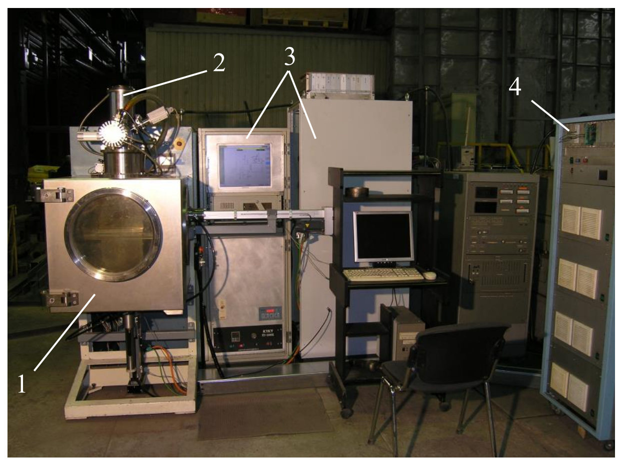


Fig. 1. Equipment for electron beam 3D printing: 1 — vacuum chamber; 2 — electron beam gun; 3 — control cabinets; 4 — high-voltage source

The installation is composed of a small vacuum chamber 1 with mechanisms for moving the platform, as well as mechanisms for supplying and distributing metal powder. The installation includes an electron beam gun 2 and a high-voltage power supply 4. The electron beam gun is placed in a vacuum chamber. The vacuum system provides for pressure in the chamber up to 10^{-4} Torr. The elements of the equipment control system are in cabinets 3, which host an industrial computer, a monitor, a controller, electric drives, the high-voltage source and vacuum system control units. High-voltage source 4 makes it possible to receive an adjustable voltage of up to 60 kV and the current of a beam of electrons of up to 100 mA.

The process of electron beam surfacing occurs in the vacuum chamber 1 (Fig. 2).

Metal powder in bulk is fed to table 9 from hoppers 3. Rail 4 moves along table 9 and forms on the surface of pallet 7 a layer of powder of the required thickness. In the initial position, the platform is located on top of mine 8. The focused beam of electrons, formed by electron beam gun 2, melts the surface of the powder along a predefined trajectory. Thus, according to the algorithm, article 6 is made. Next, platform 7 is lowered so that the next layer of powder is applied. The process is repeated. The article is grown layer by layer.

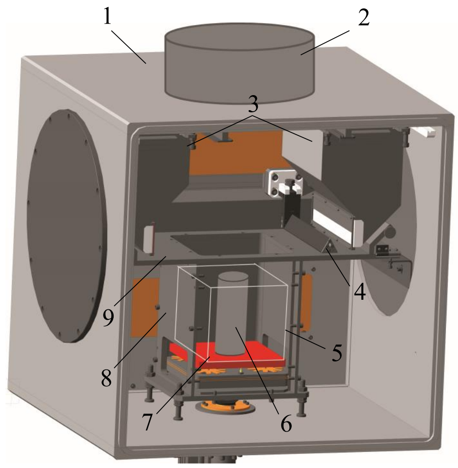


Fig. 2.Schematic of a vacuum chamber in the installation for additive production: 1 — vacuum chamber; 2 — beam gun; 3 — bunkers; 4 — rail; 5 — powder; 6 — article; 7 — platform; 8 — mine; 9 — table

After construction and cooling, the part can be removed from the equipment.

Then one cleans the article from melted powder 5, polishes and finishes the surface of the parts. It is also possible to further process them to the desired standard. That requires the use of other machines and tools [10].

The fabricated prototype of additive electron beam equipment, experimental articles were printed for further tests.

To print samples, we used the Ti_6Al_4V ELI titanium alloy powder produced by the Chinese company Sino-Euro Materials Technologies of Xi'an Co., Ltd. The powder obtained by plasma melting and centrifugal spraying (PREP technology) was applied. Powder granules have a spherical shape with minimal defects (Fig. 3).

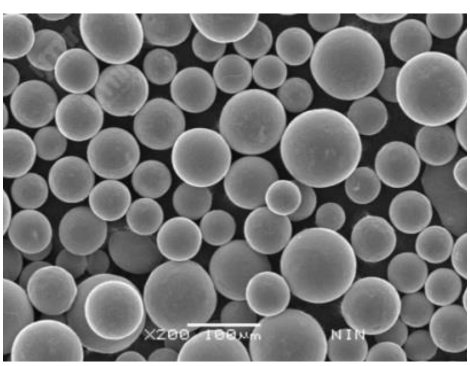


Fig. 3. Ti_6Al_4V ELI powder

Technological characteristics and chemical composition of Ti_6Al_4VELI powder are given in Table 1, 2 [11].

PREP powder is the best for electron beam additive production [12].

Table 1

Technological characteristics of Ti_6Al_4V ELI powder

Fraction, μm		45–106
Distribution by factions (PSD), μm	D10	53–58
	D50	85–90
	D90	125–130
Fluidity, s/50 g		20–25
Density, g/cm^3		2.5–2.7
Oxygen content, ppm		500–1800

Table 2

Ti_6Al_4V ELI powder chemical composition

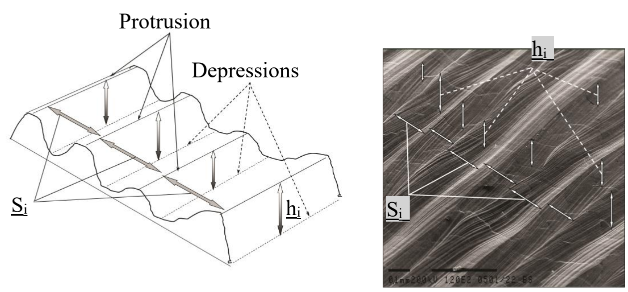
Composition of alloying elements. wt % of share				Impurity content. wt % of share		
Al	V	Fe	Ti	C	N	H
5.5–6.75	3.5–4.5	≤0.3	Balance	≤0.08	≤0.05	≤0.015

4. 3. The research methods

Each experimental sample was tested. We investigated the influence of printing parameters on the formation of the surface of an article.

At the first stage of testing, the roughness of the surface of the samples was investigated. To do this (Fig. 4), the parameters of the height of the micro irregularities in a relief h_i were determined (the distance between the line of depressions and protrusions at the surface of an article), which are formed under the influence of the electron beam, as well as the S_i parameter – the step of irregularities of the protrusions between the vertices.

Our study of the surface structure of the samples was carried out using analytical raster electron microscopy (REM, microscope SEM-515, Philips, the Netherlands).



a *b*

Fig. 4. Image of the micro relief of the test surface: *a* — diagram; *b* — structure

For each article, the structure was shot in the central zone and along the contour at different magnifications, including the inclination of the sample to measure the h_i parameter. The presence of defects was investigated: pores, non-melting, inclusions. We described the structures and measured the surface roughness parameters in the studied zones. The influence of technological regimes on the formation of defects was determined.

5. Results of studying the technological parameters of surfacing and their impact on the quality indicators of articles

5. 1. Analysis of technological parameters of surfacing

In the process of electron beam surfacing, there are many parameters that can be directly or indirectly changed. This assumes that some parameters are set when setting up the equipment while some change automatically during printing. The main technological parameters include beam current, its focusing, speed of movement, scanning strategy, the thickness of the powder layer [13].

The speed of movement of the beam has a reverse effect on the amount of energy injected per unit of material volume (energy density), so the speed significantly affects the microstructural properties of an article. In addition, an important effect on the energy density is exerted by the scanning strategy – the scanning step and the diameter of the beam, which depends on the focus. The relationship between these parameters is given in (1) [14]:

$$E=\frac{P}{S\times l\times h}, \quad (1)$$

where E is the energy density, J/mm^3; P is the power of the electron beam, W; S is the beam movement speed, mm/s; l is the trajectory shift step, mm; h is the thickness of the surfacing layer, mm.

The power of the electron beam is determined from the equation:

$$P=U\times I, \quad (2)$$

where P is the power of the electron beam, W; U is the accelerating voltage of the electron beam gun, kV; I is the current of an electron beam, mA.

The current of the beam has a direct connection with the injected energy (1), (2) and can reach a maximum of 100 mA. The relation between the beam current and scanning speed is very important for surfacing due to their significant impact on the elimination of defects and for determining the grain composition of the structure [15].

The focus of the electron beam depends on the current in the coils of the static and dynamic focusing of the beam gun. When building an article, the current in the coil of static focusing is not variable, a dynamic focus coil is used to correct the focus. Focus shifting occurs depending on the current of focus and its direction, which significantly affects the geometry of molten tracks.

The focus shift is schematically shown in Fig. 5.

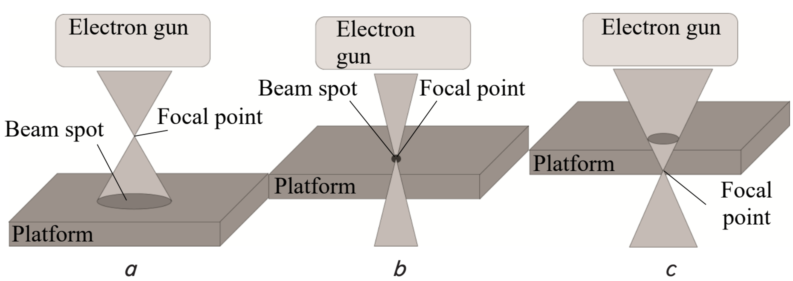


Fig. 5. Schematic illustration of focus shift:
a – a focal point above the platform; *b* – a focal point on the platform; *c* – a focal point under the platform

The size of abeam spot is influenced by the position of the focal point. It can be higher than the platform (*a*), on the platform (*b*), or below the platform (*c*), and mostly depends on the current of dynamic focusing. The current can take a negative or positive value and vary from –2.0 to 2.0 A.

A schematic illustration of the displacement of the trajectory is shown in Fig. 6.

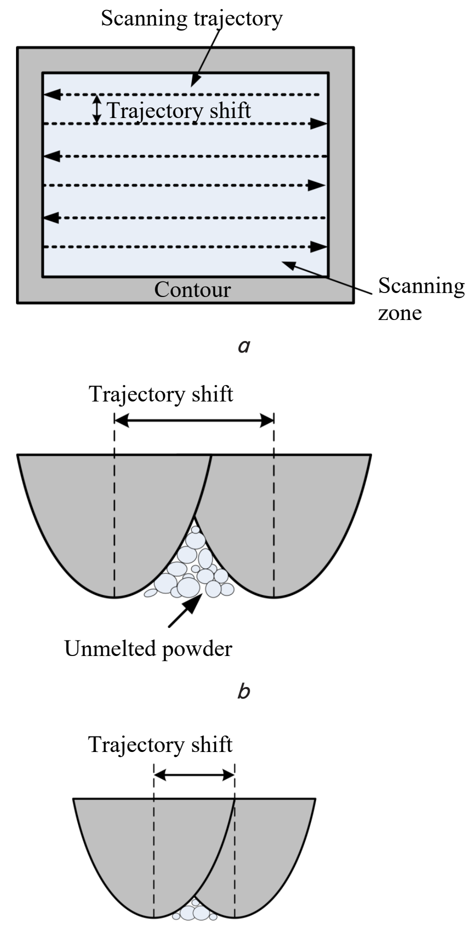


Fig. 6. Schematic illustration:
a – displacement of the trajectory; *b* – overlapping areas with less displacement of the trajectory; *c* – overlay area with greater trajectory shift

The displacement of the trajectory determines the distance between the two adjacent runs of the beam scan (Fig. 6, *a*). Optimizing this parameter is one of the approaches to reducing the number of pores. By reducing to some extent the magnitude of the trajectory shift, it is possible to improve the overlap between the two adjacent runs, which reduces the risk of the presence of unmelted powder in the article. On the contrary, for a greater parameter of shifting the trajectory, the risk of unmelted powder appearing in the lower part of the overlapping area may be high (Fig. 6, *b, c*) [16].

The choice of the trajectory of movement of the electron beam during surfacing is called a scanning strategy, which can be used as a tool to optimize the structure of an article [17]. Various scanning strategies may be applied (Fig. 7), which include unidirectional, double-directional (snake), and spot melting.

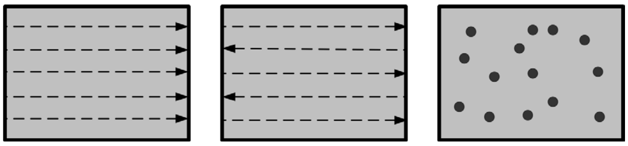


Fig. 7. Scanning strategies: *a* — unidirectional; *b* — two-directional (snake); *c* — spot melting

In the case of a single- or bidirectional strategy, rotation of the scanning direction is usually used at a predetermined angle between each layer. In addition, for a specific scanning strategy, beam speed and current must be optimized.

5. 2.Determining the technological printing modes

An important stage of research is to determine the technological parameters of printing. To do this, one needs to get the modes of the electron beam: power, speed of movement, current focusing. One also needs to define technological parameters such as the thickness of the surfacing layer, the scanning strategy, the diameter of the beam, the step of shifting the print trajectory.

The thickness of the surfacing layer was set to 0.1 mm, which is equal to the maximum size of the granules of the Ti_6Al_4V ELI powder. Granulometric composition is given in Table 1.

The diameter of the beam of electrons is 0.25 mm for the focus current of the radial gun of 570 mA. The focus current was established experimentally, by influencing the electron beam on the copper target. A focus that corresponds to the smallest diameter of the beam spot on the platform where the article is grown has been found. A method of scanning tungsten wire was used to determine the effective diameter of the beam of electrons.

The shift step of the trajectory was 0.2 mm, which ensures its sufficient overlap when moving the electron beam.

Next, one needs to determine the parameters of the speed of movement of the beam and its power.

Since these parameters depend on the properties of raw materials (Ti_6Al_4V ELI powder), a series of experiments on surfacing articles according to various technological modes were carried out. The photographs of the obtained samples are shown in Fig. 8.

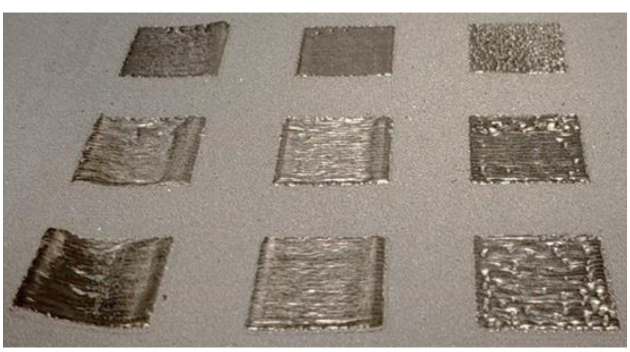


Fig. 8. Experimental samples

As a result of the experiments, we obtained articles with the required surface structure (Fig. 9) and we established optimal surfacing modes (Table 3), which correspond to the low (240 mm/s), medium (540 mm/s), and high (780 mm/s) speed of movement of the beam.

Fig. 9. Article samples: *a* — sample No. 1; *b* — sample No. 2; *c* — sample No. 3

Table 3

Technological modes of sample printing

Sample No.	Beam parameter	
	Speed, mm/s	Power, W
1	240	270
2	540	495
3	780	675

Based on the results of the experiment, the optimal ratio between the speed of movement of the beam and its power (Fig. 10) was calculated, the speed function was built. According to this function, Ti_6Al_4V ELI powder produces high-quality articles.

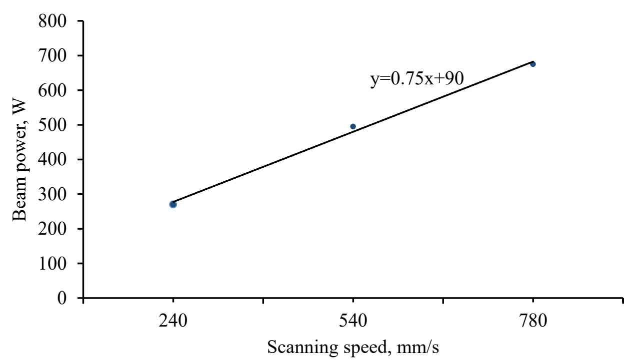


Fig. 10. Speed function for the powder Ti_6Al_4V ELI

The ratio between the power and speed of movement of the beam is determined from the equation:

$$P = 0.75 \times S + 90, \qquad (3)$$

where P is the power of the electron beam, W; S is the speed of movement, mm/s.

Based on (1), we calculated the energy density, which must be introduced per unit of material volume for the formation of the surfacing layer.

The optimal value of the energy density required for the construction of an article (sample No. 2, Fig. 8) made from the powder Ti_6Al_4V ELI in accordance with Table 3 is:

$$E = \frac{495\,\text{W}}{540\,\frac{\text{mm}}{\text{s}} \times 0.2\,\text{mm} \times 0.1\,\text{mm}} = 45.8\,\frac{\text{J}}{\text{mm}^3}, \qquad (4)$$

where 495 W is the beam power; 540 mm/s – the speed of its movement; 0.2 mm – the step of displacement of the trajectory; 0.1 mm is the thickness of the powder layer.

The estimated value of the energy density for other surfacing modes is given in Table 4.

Table 4

Energy density for the Ti_6Al_4V ELI powder

No. of entry	Beam power, W	Displacement speed, mm/s	Trajectory shift, mm	Layer thickness, mm	Energy density, J/mm^3
1	240	270	0.2	0.1	44.4
2	495	540	0.2	0.1	45.8
3	675	780	0.2	0.1	43.3
Total value					44.5

The average value of energy density (Table 4), necessary for the formation of articles made from the powder Ti_6Al_4V ELI, is:

$$E = 44.5\,\frac{\text{J}}{\text{mm}^3}. \quad (5)$$

Printing parameters such as the energy density, beam speed, its power are the basis for further calculations of technological modes of the surfacing of articles.

5. 3.Fabrication of prototypes

25 experimental samples were printed from the powder of Ti_6Al_4V ELI titanium alloy for further tests (Fig. 11).

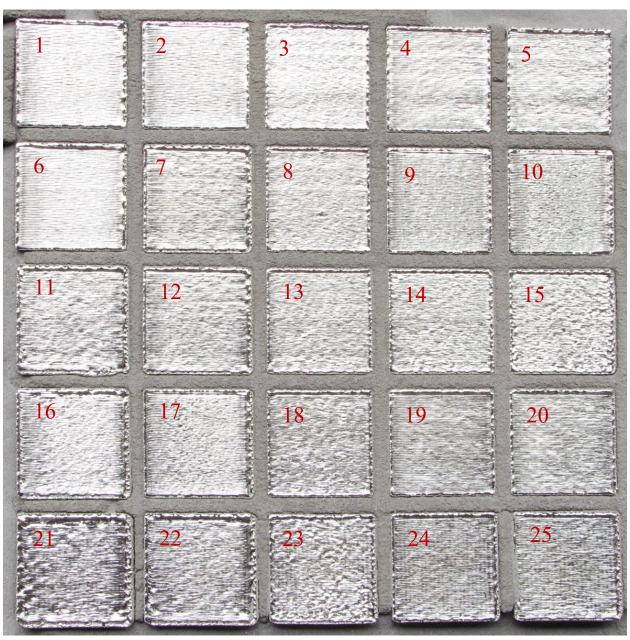


Fig. 11. Experimental samples

The articles have a rectangular shape of 24×24 mm and a height of 10 mm, of which 5 mm are technological supports and 5 mm are the body of an article.

Printing parameters are given in Table 5.

The following technological parameters were used for printing: energy density, 44.5 J/mm^3; a shift step of the beam trajectory, 0.2 mm; the thickness of the powder layer, 0.1 mm; scanning strategy is bidirectional with a direction rotation at 90° for each layer.

Table 5

Technological modes of surfacing samples

Sample No.	Beam parameter		Dynamic focus current, A
	Speed, mm/s	Power, W	
1	780	675	–0.9
2	780	675	–0.61
3	240	270	–0.9
4	540	495	–0.31
5	540	495	–0.61
6	780	675	–1.2
7	540	495	1.27
8	240	270	–0.61
9	780	675	–0.31
10	780	675	0.33
11	540	495	0.96
12	540	495	0.65
13	240	270	–0.31
14	240	270	0.33
15	240	270	0.65
16	780	675	0.65
17	780	675	0
18	240	270	–1.2
19	540	495	–0.9
20	540	495	–1.2
21	780	675	1.27
22	780	675	0.96
23	240	270	0
24	540	495	0
25	540	495	0.33

Using (1), we determined the speed of movement of the beam and its power.

5. 4. Investigating the impact of printing parameters on the structure of article surfaces and the presence of defects

We investigate the samples of articles printed using three technological modes of printing (Table 3). For each article, a variable parameter was the dynamic focus current (*Idf*), which changed from –1.2 A to 1.27 A (Table 5). The characteristic microstructures of the surface of the samples for a third printing mode (Table 3) are shown in Fig. 12.

For articles printed with an electronic beam speed of 780 mm/s and a power of 675 W (Nos. 1, 2, 6, 9, 10, 16, 17, 21, 22, Table 5), the following has been established. In the zones of the contour of samples in comparison with the central zone of articles (Fig. 12, *a–f*), except for the modes at *Idf*: 0.65 and 1.27 A (Fig. 12, *g–i*), there is an increase in the S_i parameter.

The same trend persists for the parameter of the height of the micro irregularities of the relief (h_i). The maximum S_i values in the central zone of the samples are characteristic of articles obtained at the dynamic focus current *Idf*: 0.33; 0.65; 1.27 A (Fig. 12, *g*; Fig. 13, *a*). The smallest S_i values in the central zone are observed for the following *Idf* modes: –1.2 (Fig. 12, *a*); –0.9; –0.61; –0.31; 0 (Fig. 12, *d*) and 0.96 A. At the same time, the minimum height of the micro relief (h_i) is provided at *Idf*: –1.2; –0.9; –0.61; 0 A (Fig. 12, *d–g*; Fig. 13, *b*).

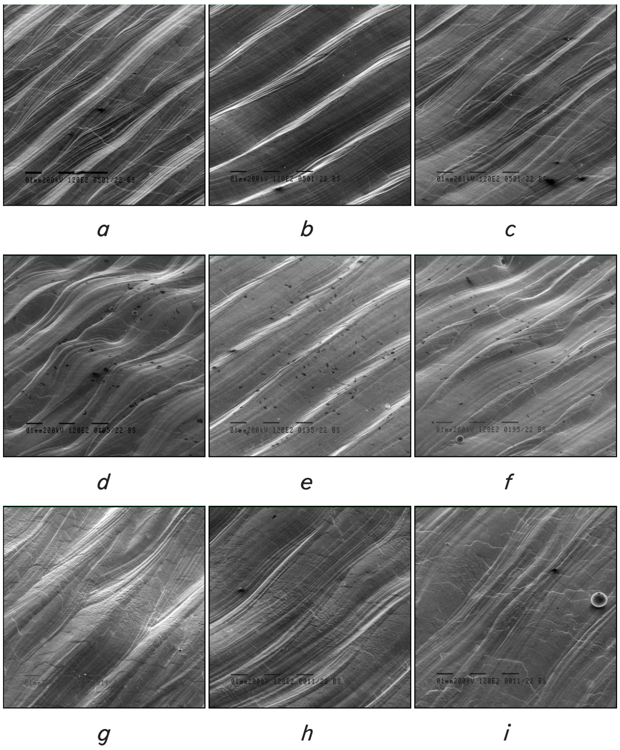


Fig. 12. Surface relief (×120) in different article zones at a beam speed of 780 mm/s and a power of 675 W depending on the dynamic focus current (*Idf*): *a* – in the central zone at *Idf*=–1,2 A (sample No. 6); *b* – in the contour zone on one side at *Idf*=–1.2 A (sample No. 6); *c* – in the contour zone on the other side at *Idf*=–1.2 A (sample No. 6); *d* – in the central zone at *Idf*=0 A (sample No. 17); *e* – in the contour zone on one side at *Idf*=0 A (sample No. 17); *f* – in the contour zone on the other side at *Idf*=0 A (sample No. 17); *g* – in the central zone at *Idf*=1.27 A (sample No. 21); *h* – in the contour zone on one side at *Idf*=1.27 A (sample No. 21); *i* – in the contour zone on the other side at *Idf*=1.27 A (sample No. 21)

In addition, the surfaces of articles are characterized by the presence of such defects as micro irregularities, shrinkage pores, non-melting (in the contour area), and melted areas (on the border of the contour of the samples). The absence of shrinkage pores and non-melting is characteristic of samples obtained by the following *Idf* modes: –0.61; –0.31 A. Single pores are observed in the central zone of articles obtained under the following *Idf* modes: –1.2;–0.9 A. The largest, but not significant, number of shrinkage pores is observed in samples obtained under the following *Idf* modes: 0.65; 0.96; 1.27 A.

Similar studies were conducted for all samples of printed articles (Table 5).

Analysis of experimental studies into the microstructure of surfaces by REM method, as well as the statistical results of measurements of parameters of micro irregularities of the surface of the profile of the studied samples made it possible to generalize our results. It is established that the articles are characterized mainly by a homogeneous micro relief of the surface profile.

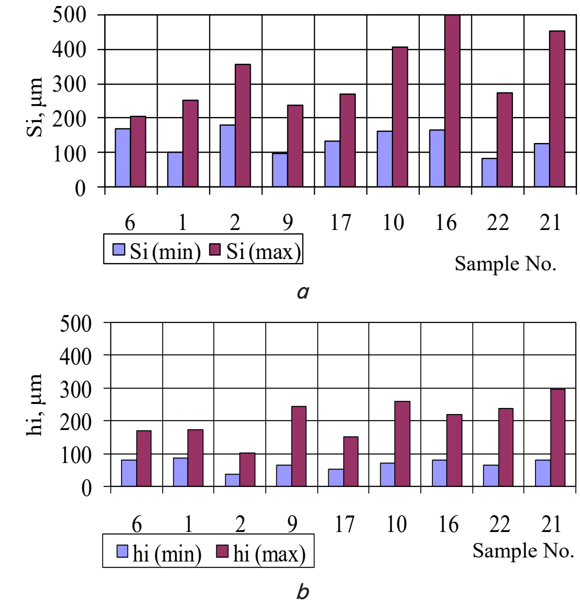


Fig. 13. Parameters of the surface micro relief in the central zone of the samples at a beam speed of 780 mm/s and a power of 675 W: *a* – the step of irregularities of the protrusion between the vertices (S_i); *b* – the height of micro irregularities relief (h_i)

The articles printed with an electron beam speed of 780 mm/s and a power of 675 W are characterized by a homogeneous micro relief of the surface profile and single defects in the form of shrinkage pores and small non-melting sites (in the contour area). The minimum parameters of micro relief surfaces (h_i and S_i) are provided at the following *Idf*: –1.2; –0.9; –0.61; 0 A (Fig. 13). The absence of shrinkage pores and non-melting is ensured under the modes: 0.61; –0.31 A; single pores are observed in samples obtained under the following *Idf* modes: –1.2; –0.9 A.

The minimum parameters of the micro relief of surfaces (h_i and S_i) of the articles printed with an electron beam speed of 540 mm/s and a power of 495 W are provided at *Idf*: –0.61; –0.31; 0; 0.33; 0.65 A (Fig. 14).

The articles are also characterized by a homogeneous micro relief of the surface profile in the presence of inclusions, minor micro irregularities of an undulating nature, and small areas with non-melting sites (in the contour zone). Single pores are observed in the samples obtained under the following *Idf* modes: 0; 1.27 A.

The articles obtained with an electron beam speed of 240 mm/s and a power of 270 W are characterized by both a homogeneous micro relief of the surface profile with single defects and the presence of heterogeneous relief. On the surface of articles with heterogeneous relief, there is a large number of shrinkage pores and non-melting sites.

The minimum indicators of the height parameters of the micro irregularities of the relief *hi* at approximately the same S_i values are characteristic of the following *Idf* modes: –1.2 A; –0.9 A; –0.31 A; 0.33 A (Fig. 15).

The absence of shrinkage pores and non-melting is ensured by the following *Idf* modes: –0.61 A; –0.31 A. The maximum number of defects such as significant micro irregularities (h_i up to 700 μm), large pores, accumulations of inclusions, massive non-melting in the contour zone and in the central zone, are observed under the mode of *Idf*=0 A.

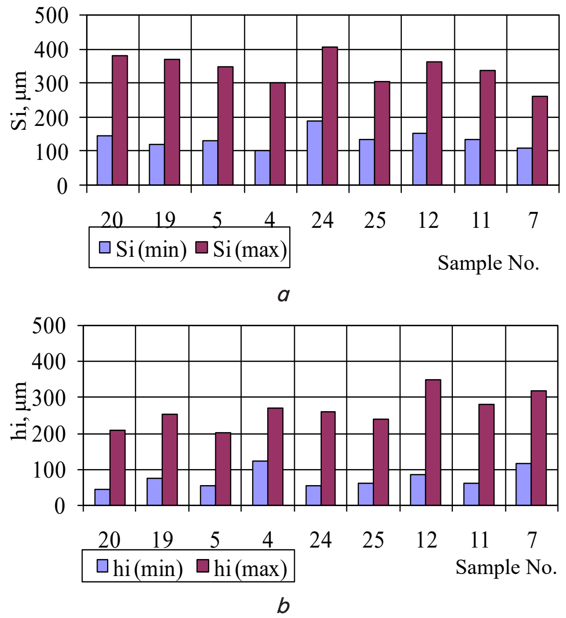


Fig. 14. Surface relief parameters in the central zone of the samples at a beam speed of 540 mm/s and a power of 495 W: *a* – the step of irregularities of the protrusion between the vertices (S_i); *b* – the height of micro irregularities relief (h_i)

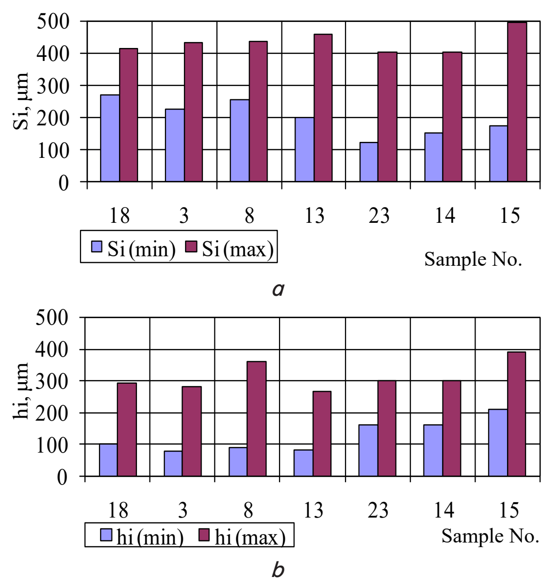


Fig. 15. Surface relief parameters in the central zone of samples at a beam speed of 240 mm/s and a power of 270 W: *a* – the step of irregularities of the protrusion between the vertices (S_i); *b* – the height of micro irregularities relief (h_i)

6. Discussion of results of studying the impact of technological parameters of surfacing on the quality indicators of articles

The result of our studies has proven that the main parameters of the technological process of electron beam surfacing such as the beam power, the speed of its movement, the dynamic focusing current exert a significant impact on the micro relief of article surfaces and the formation of defects. This is due to the peculiarities of the melting processes of metal powder and the properties of molten metal. Our studies have established the optimal energy density of the electron beam for the powder of titanium alloy Ti_6Al_4V ELI, which is 44.5 J/mm^3. This parameter should be universal when using Ti_6Al_4V ELI alloy powders with granules ranging in size from 45 to 106 μm.

According to the results of research (1), the influence of the speed of movement of the electron beam on other parameters of the technological process has been determined. This parameter is important because it affects the total time of article construction.

In addition, the studies found a connection between the speed of the electron beam and its power, which is determined by the speed function. Increasing the speed of movement of the beam requires an increase in power and vice versa.

An important factor influencing the formation of articles is the dynamic focus current, the change in which leads to a shift in focus, and significantly affects the micro relief of surfaces.

Our studies into the influence of printing parameters in electron beam layered surfacing on the structure of surfaces of articles have shown that all the surfaces under study acquire roughness. The roughness of the surfaces of the samples differs in the parameters of the micro irregularities of the relief.

When using the printing mode with a beam speed of 240 mm/s and a power of 270 W, a micro relief with h_i (min/max)=78 parameters is formed on the surface of the articles, with *Si* (min/max)=121...271/403...500 μm (Fig. 15). Under a printing mode with a beam speed of 540 mm/s and a power of 495 W, the micro relief parameters are reduced to h_i (min/max)=54...123/240...350 μm and S_i (min/max)=102...146/262...407 μm (Fig. 14). And in the case of using the print mode at a beam speed of 780 mm/s and a power of 675 W, the surface of articles is characterized by roughness with minimal parameters h_i (min/max)=36...85/100...298 μm at S_i (min/max)= =82...180/205...500 μm (Fig. 13). In the case of an increase in the speed of movement of the beam, the formation of a defect-free structure is observed, namely the absence of large shrinkage pores and inclusions. At a beam speed of 240 mm/s, a heterogeneous relief with a large number of shrinkage pores is formed on the surface of the articles.

However, for each of the three modes of the speed of movement of the beam, the roughness of the surfaces of articles also has different parameters. In this case, the effect of focusing the electron beam appears. Shifting the focus (Fig. 5), and, accordingly, changing the size of the radial spot have a significant impact on the parameters of the roughness of the surfaces of articles and the quality of articles (obtaining a defect-free structure).

Thus, for a printing mode with a beam speed of 240 mm/s and a power of 270 W, the maximum values of the step of irregularities of the surface profile at the tops (S_i) in the central zone of the samples are characteristic of articles obtained at the dynamic focus current *Idf*: 0.31; 0.65 A (Fig. 15, *a*). The maximum height of the micro relief (*hi*) is observed at *Idf*: 0.61; 0.65 A (Fig. 15, *b*). The maximum number of defects such as significant micro irregularities (*hi* up to 700 μm), large pores, accumulations of inclusions, massive non-melting sites in the contour zone and in the central zone, are observed under the mode *Idf*=0 A: 0.9; 0.31; 0.33 A (Fig. 15, *b*).

Under a printing mode with a beam speed of 540 mm/s and a power of 495 W, the smallest distances between the surface tops are observed under the following *Idf* modes: 0.61; 0.31; 0.33; 0.65; 0.96, 1, 27 A (Fig. 14, *a*). The minimum height of the micro relief (*hi*) is provided at –1.2; –0.9; –0.61; –0.31; 0; 0.33; 0.65 A (Fig. 13, *b*).

When using the printing mode at a beam speed of 780 mm/s and a power of 675 W, the smallest distances between the tops of the surface relief are observed under the following *Idf* modes: 1.2; 0.9; 0.61; 0.31; 0; 0.96 A (Fig. 13, *a*). The minimum height of the micro relief (h_i) is provided at *Idf*: 1,2; 0.9; 0.61; 0 A (Fig. 13, *b*).

It should be noted that the research was carried out under some restrictions. Technological parameters such as the speed of the electron beam and its power were obtained experimentally. This method is complex, takes a lot of time and effort to conduct a series of experiments. In the future, it is necessary to develop the theoretical foundations of surfacing processes, which would provide the possibility for determining technological parameters by the estimation method.

Also promising is to perform computer modeling of additive processes while predicting the properties of articles.

Thus, based on the results of our research, it has been established how the printing parameters for electron beam layered surfacing affect the structure of the surfaces of articles. The next stage of research could be to study the structure of the articles obtained by examining the cross-section of samples and comparing the structural parameters depending on the beam speed and power.

7. Conclusions

1. We have analyzed the technological parameters of surfacing. It was noted that the main parameters of printing such as the power of the electron beam, the speed of movement, the shift step of the trajectory, the thickness of the surfacing layer determine the energy density of the electron beam (1). The optimum energy density value for the Ti_6Al_4V titanium alloy powder is 44.5 J/mm^3. We have also derived ratio (3) between the speed of the electron beam and its power, which makes it possible in the process of preparing articles for printing to determine the power of the beam according to its speed. The total time of article construction depends on the speed of the beam.

2. The technological modes for printing articles made of the Ti_6Al_4V ELI titanium alloy powder were established. The printing parameters are: the thickness of the powder layer is 0.1 mm, the shift step of the electron beam trajectory is 0.2 mm, the scanning strategy is two-directional with a direction rotation of 90° for each layer. The power of the electron beam is 240 W for its movement speed of 270 mm/s, 495 W for 540 mm/s, 675 W for 780 mm/s.

3. Based on the additive technology, 25 experimental samples, 24×24 mm in size and 10 mm high, were made, of which 5 mm are technological supports and 5 mm are the body of the article. The printing settings are individual for each sample. In our studies, three modes of electron beam speed were applied: 270, 540, and 780 mm/s.

4. Laboratory studies of the surface structure of samples using analytical raster electron microscopy were carried out. It has been shown that the articles are characterized mainly by a homogeneous micro relief of the surface profile. The modes of electron beam layer surfacing have been established (beam speed, 780 mm/s; power, 675 W; *Idf*=–1.2; –0.9; –0.61; 0 A), which provide the minimal parameters of micro relief surfaces (*hi* up to 200 μm; S_i up to 300 μm) and no defects.

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