UDC 621.791.92
DOI: 10.15587/1729-4061.2024.297773

DETERMINING THE INFLUENCE OF TECHNOLOGICAL PARAMETERS OF ELECTRON BEAM SURFACING PROCESS ON THE MICROSTRUCTURE AND MICROHARDNESS OF Ti-6Al-4V ALLOY

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This paper reports the devised technology and equipment for manufacturing parts and assemblies with pre-defined properties by 3D printing methods. Underlying the technology is the application of a high-power electron beam to fuse metal powder in a vacuum chamber with the formation of successive layers that repeat the contours of the digital model of the product.

The object of research is the process of surfacing products made of Ti6Al4V titanium alloy powder. The influence of technological parameters (speed and power of the electron beam) on the formation of the structure of the deposited metal and its mechanical properties was investigated.

3 samples printed under 3 modes were studied: beam speed, 270, 540, and 780 mm/s; power, 240, 495, and 675 W, respectively. The beam energy density was 44.5 J/mm³; the trajectory displacement step was 0.2 mm; the dynamic focusing current Idf was –0.31 A; and the powder layer thickness was 0.1 mm.

The samples were examined by conventional methods. The structures were studied using an optical microscope, images were recorded with a camera. The Vickers hardness was measured with a microhardness meter in the direction from the technological supports to the surface of the sample, as well as along the surface of the product, and in the layers of the middle part of the sample.

It was established that the articles had a dense cast structure of surfaced metal. On all samples, large crystallites with a uniform lamellar-acicular structure of α′-phase with a small amount of β-phase are formed along the height, mostly without defects with uniform microhardness both along the height and along the surface.

It was determined that the surfacing mode at beam speed, 240 mm/s; power, 270 W is the most rational for practical use. Under this mode, a stronger structure is formed when it is crushed, reducing the width of the crystallites by 1.55 and 1.17 times compared to other modes

Keywords: electron beam surfacing, titanium alloy, Ti-6Al-4V, technological parameters, metallographic studies

Received date 05.12.2023
Accepted date 07.02.2024
Published date 12.02.2024

How to Cite: *Matviichuk, V., Nesterenkov, V., Berdnikova, O. (2024). Determining the influence of technological parameters of electron beam surfacing process on the microstructure and microhardness of Ti-6Al-4V alloy. Eastern-European Journal of Enterprise Technologies, 1 (12 (127)), 6–12. doi: https://doi.org/10.15587/1729-4061.2024.297773*

1. Introduction

Innovative technologies of layer-by-layer production of articles by the method of rapid prototyping open up new opportunities for the production of parts of a given shape with predictable properties. The process of making articles by this method using an electron beam is relatively new but it has successfully opened up great prospects for the production of a wide range of industrial and medical products. The basis is the operation of layer-by-layer fusion of metals in a vacuum with an electron beam. This approach is distinguished by the rapid transition to the production of three-dimensional articles directly from the automated design system with the possibility of using a wide range of metals and alloys, including refractory and chemically active ones [1].

The titanium alloy Ti-6Al-4V is of significant interest for the aerospace and biomedical industries, which is characterized by high mechanical characteristics, wear and corrosion resistance, and mechanical and biological compatibility with bone tissue. Further improvement of Ti-6Al-4V alloy articles by searching for optimal technological modes of their printing should be considered relevant. This will provide an opportunity to obtain the maximum mechanical properties of products taking into account the optimal technological parameters of printing [2].

2. Literature review and problem statement

Determining the technological parameters of surfacing using additive electron beam technology is a necessary component of obtaining articles with the required properties [2].

In [2], the influence of the technological parameters of surfacing on the shaping of products from the Ti-6Al-4V alloy was determined but the mechanical properties were not investigated.

In work [3], the authors investigated the properties of articles made of Ti-6Al-4V, obtained at the maximum load of the working chamber of the additive equipment. A comprehensive comparative analysis of printed samples was carried out for a critical assessment of the quality and performance of articles both in the finished state and after mechanical surface treatment. But the influence of technological parameters on the quality of samples was not investigated.

In [4], the microstructures and mechanical properties of Ti-6Al-4V alloy samples obtained by electron beam technology were investigated but the problem of the connection of properties with technological modes of printing was not solved.

In [5], microstructures and microhardness of an industrial product made of Ti-6Al-4V were studied. But the influence of technological parameters on the properties of the product was not investigated.

The influence of the electron beam scanning strategy on the structure and microhardness of Ti-6Al-4V articles was investigated in [6]. The influence of other printing parameters was not investigated.

Work [7] reports results of studying the influence of technological parameters on the microstructure and mechanical properties of the Ti-6Al-4V alloy. The authors changed the main parameters of the surfacing process: the speed and power of the electron beam, its focusing and the step of the trajectory displacement. It is shown that the variation of the displacement step of the electron beam trajectory from 0.16 mm to 0.28 mm has the greatest effect on the mechanical properties of articles. But the questions related to the effect of the speed and power of the electron beam on the properties of products, with unchanged values of other parameters of the technological process, remained unresolved.

The effect of electron beam speed on the structure and mechanical properties of Ti-6Al-4V alloy articles was investigated in [8]. It is noted that speed has a noticeable effect on the peculiarities of the formation of the structure of products. But the studies were carried out on equipment where the technological parameters are closed by the manufacturer and are represented in the form of typical speed functions. This makes it impossible to apply research results for wide use since the interrelationship of technological parameters is unknown.

The speed and power of the electron beam are the main parameters of the additive process, which primarily affect the quality indicators of articles. The study of the influence of these parameters on the formation of the metal structure and its mechanical properties is necessary for making products with predictable properties.

3. The aim and objectives of the study

The purpose of our research is to find rational technological modes of printing from the Ti-6Al-4V alloy, which will make it possible to manufacture articles with the necessary strength properties by the additive method.

To achieve the goal, the following tasks were set:

– to obtain test samples according to various printing technological parameters;

– to investigate their microstructure;

– to determine the microhardness of the samples;

– to find printing modes that enable the formation of the best structural state.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of research is the additive process of manufacturing articles from Ti-6Al-4V titanium alloy powder by the electron beam surfacing method. The hypothesis of the study assumed that the technological parameters such as speed and power of the electron beam have a predominant influence on the formation of the structure and strength properties of products. This influence must be investigated, and rational technological parameters of surfacing must be determined. To this end, it is planned to determine the microstructure and microhardness of experimental samples. Other technological parameters such as the energy density of the beam, its focusing, the displacement step of the printing trajectory remain unchanged. This will make it possible to determine the influence of only the speed and power of the electron beam on the properties of articles. The integrated influence and interaction of all parameters of the additive process is a complex phenomenon that requires additional and gradual research.

4. 2. Materials and equipment

Samples for our study were printed from Ti-6Al-4V ELI titanium alloy powder produced by Sino-Euro Materials Technologies of Xi’an Co., Ltd (China), which is manufactured by the method of plasma melting and centrifugal spraying (PREP technology). Powder granules have a regular spherical shape with sizes from 45 to 106 microns. The chemical composition of raw materials is given in Table 1 [9].

Table 1

Chemical composition of Ti-6Al-4V ELI powder

Composition of alloying elements, mass % of shares				Composition of impurities, mass % of shares		
Al	V	Fe	Ti	C	N	H
5.5–6.75	3.5–4.5	≤0.3	Balance	≤0.08	≤0.05	≤0.015

For research, 25 samples (Fig. 1) measuring 24×24 mm with a height of 10 mm were printed, where 5 mm are technological supports and 5 mm are the body of the product (Fig. 2). The samples were made by the method of layer-by-layer electron-beam deposition on experimental additive equipment designed at the Institute of Electric Welding named after E. O. Paton (Ukraine) [1].

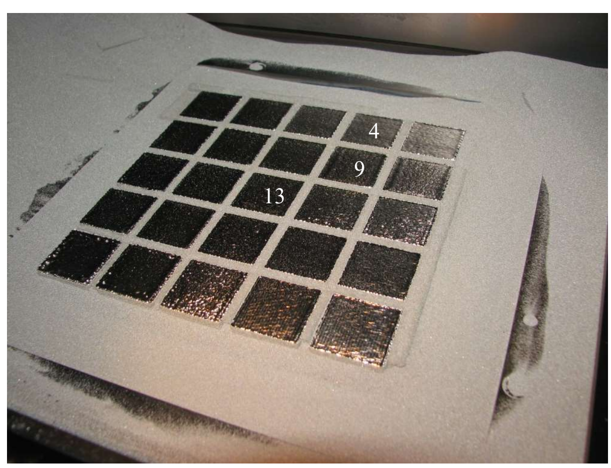


Fig. 1. Experimental samples

The surfacing process took place in the vacuum chamber 1 of the electron beam equipment (Fig. 3). The accelerating voltage of electron beam gun 2 was 60 kV. Preheating of the powder layer to a temperature of 730 °C was carried out by a raster beam with a power of 1700 W at a scanning speed of 14.6 m/s (an 8-pass rastering scheme was used). The working pressure in the vacuum chamber during surfacing was 10^{-4} Torr. Preliminary sintering of the powder layer was carried out in a helium environment with a pressure of $5\cdot10^{-2}$ Torr.

The equipment of the vacuum chamber of the additive equipment is shown in Fig. 4.

The vacuum chamber 1 of the equipment (Fig. 4) consists of shaft 2 where there is platform 3 with pallet 10, on which the product is grown. In hoppers 4, there is metal powder, which is fed in bulk to table 5. Rail 6 moves along table 5 and distributes the metal powder on the surface of pallet 10. Rail 6 is fixed on guides 7. Actuator 8 with the electric motor 9 moves the rail in the horizontal plane.

Platform 3 with pallet 10 are in shaft 2 and are moved along the vertical axis with the help of spindle 11, which is fixed on rail 12, mounted on brackets 13. The electric motor 14 controls the movement.

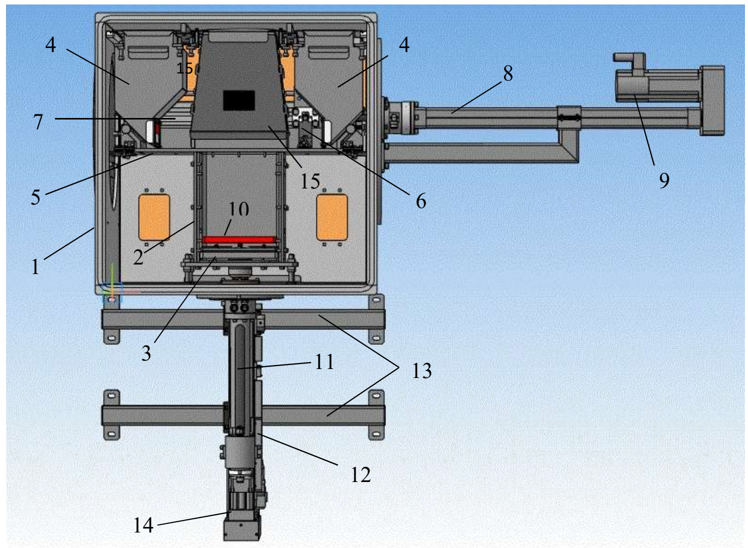


Fig. 4. Vacuum chamber equipment: 1 – vacuum chamber; 2 – shaft; 3 – platform; 4 – bunker; 5 – table; 6 – rail; 7 – guides; 8 – actuator; 9 – electric motor; 10 – pallet; 11 – spindle; 12 – rail; 13 – bracket; 14 – electric motor; 15 – reflector

Reflector 15 protects the vacuum chamber from the high temperature created on the surface of the layer where the product is formed.

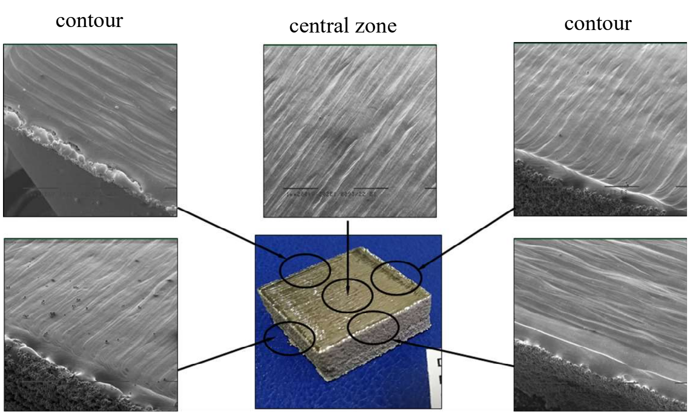


Fig. 2. Macrostructure of a typical test sample

4. 3. Research methods

Microstructure studies were performed using conventional methods. Cross-sections of the samples were made on an EDM machine, which were sanded with sandpaper and polished with a diamond suspension. The surfaces were etched with an aqueous solution of 15 % HNO_3 and 5 % HF. The structures were examined using a Neophot-32 optical microscope. The image was recorded with an Olympus camera. Vickers hardness was measured on a microhardness meter M-400 LEKO under loads of 1.0 kg (HV10) with a step of 500 μm in the direction from the technological supports to the surface of the sample, as well as along the surface of the product and in the layers of the middle part of the sample at a distance of 2.5 mm from foundation.

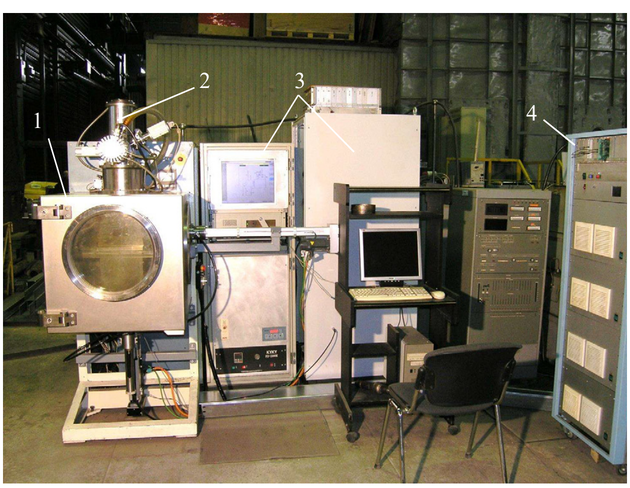


Fig. 3. Equipment for electron beam 3D printing: 1 – vacuum chamber; 2 – electron beam gun; 3 – control cabinets; 4 – high-voltage source

5. Results of investigating experimental samples

5. 1. Obtaining experimental samples according to various printing technological parameters

The following technological parameters were used to print the test samples:

– the thickness of the powder layer is 0.1 mm;
– electron beam energy density is 44.5 J/mm^3;
– dynamic focusing current Idf: –0.31 A;
– trajectory displacement step – 0.2 mm;
– the scanning strategy is bidirectional with layer-by-layer direction rotation by 90°.

Variable printing parameters are given in Table 2.

Samples No. 4, No. 9, and No. 13 were studied (Fig. 1). For each of the samples, the speed of the electron beam and its power were changed. The influence of the parameters of the electron beam on the structure of articles was studied at a constant value of the energy density of the beam, its focus, and the displacement step of the trajectory.

Table 2

Technological parameters of printing

Beam parameters	Sample		
	No. 13	No. 4	No. 9
Power, W	240	495	675
Displacement speed, mm/s	270	540	780

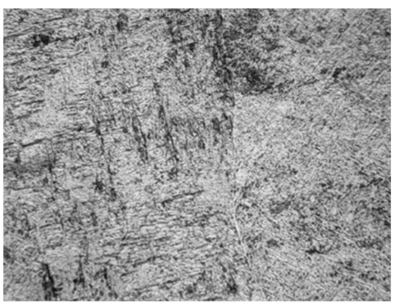
5. 2. Study of microstructure and determination of microhardness of samples

Analysis of cross sections of the samples determines obtaining a dense cast structure of the surfaced metal.

Studies of the microstructure with a magnification of ×500 have established that the samples are characterized by a structure that consists mainly of a lamellar-acicular α-phase (Fig. 5).

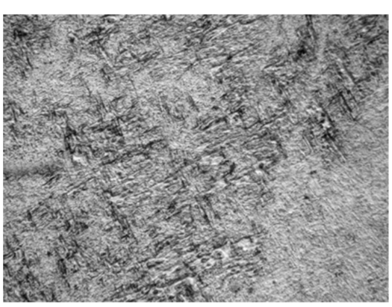
According to [10], the structure contains a small amount of the β-phase, which lies in the form of thin layers between needle-like secretions of the α'-phase.

Metallographic studies of sample No. 13 established that the structure consists of crystallites with different degrees of etching, the width of the crystallites is from 80 to 500 μm (Fig. 6, *a*).



a

b



c

Fig. 5. Microstructure of samples (×500): *a* — No. 13 (270 mm/s; 240 W); *b* — No. 4 (540 mm/s; 495 W); *c* — No. 9 (780 mm/s; 675 W)

The structure is uniform over the entire height of the sample. Small inclusions up to 30 μm in size and single pores from 20 to 40 μm in size are observed.

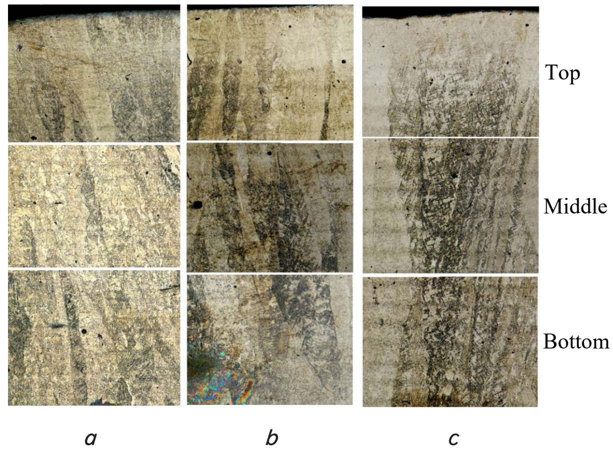


Fig. 6. Microstructure of samples (×100): *a* — No. 13 (270 mm/s; 240 W); *b* — No. 4 (540 mm/s; 495 W); *c* — No. 9 (780 mm/s; 675 W)

Metallographic studies of sample No. 4 established that the structure consists of large crystallites with different degrees of etching. The width of the crystallites ranges from 80 to 600 μm (Fig. 6, *b*).

A homogeneous plate-needle structure is formed along the entire height of the sample. Small inclusions up to 30 μm in size and single pores from 20 to 70 μm in size are observed.

Studies of sample No. 9 have established that its structure consists of large crystallites with varying degrees of etching, the length of which can be compared to the height of the sample. The width of the crystallites ranges from 100 to 800 μm (Fig. 6, *c*). A homogeneous lamellar-needle structure is formed along the entire height. Small inclusions ranging in size from 10 to 50 μm are observed, most characteristic of the zone near the surface of the product.

5. 3. Determination of microhardness of samples

Changes in hardness (*HV*) in the cross-section of sample No. 13 along the entire height of the sample from the base to the surface (vertically) are shown in Fig. 7. Changes in hardness along the surface (horizontally) are shown in Fig. 8, in the layers of the middle part of the sample at a distance of about 2.5 mm from the base – in Fig. 9.

Based on the height of sample No. 13, the hardness has an uneven distribution, gradients from 350 to 400 MPa are observed (Fig. 7).

On the surface of the sample, the level of microhardness is mostly uniform (Fig. 8) with an increase (on average by 6 %) from the general level of hardness over the entire height of the sample. There are small gradients around 300 MPa with hardness from HV=3780 to HV=4070 MPa.

Measurements of a chain of indenter impressions in a row in several local layers of the middle part of the sample at a distance of 2.5 mm from the base show that the level of microhardness in local layers is not uniform (HV=3530...3950 MPa), gradients up to 420 MPa are observed (Fig. 9).

Therefore, the study of sample No. 13 established that the structure in the cross-section of the section along its height is uniform, mostly without defects (several pores are present) with slight gradients of hardness along the height and along the surface.

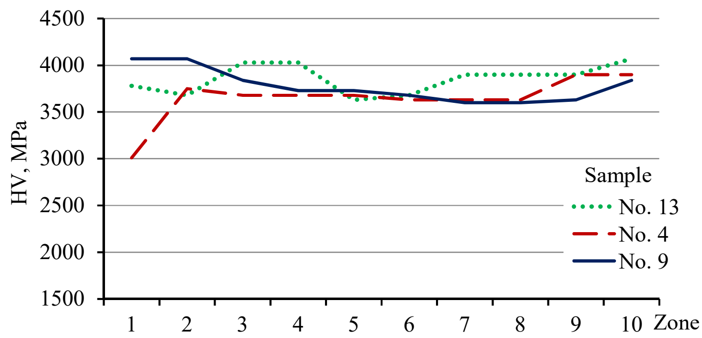


Fig. 7. Variations in microhardness (*HV*) in the section cross-section

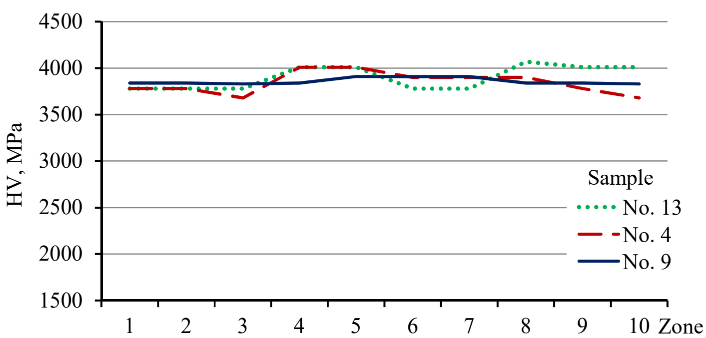


Fig. 8. Variations in microhardness (*HV*) along the surface of the section

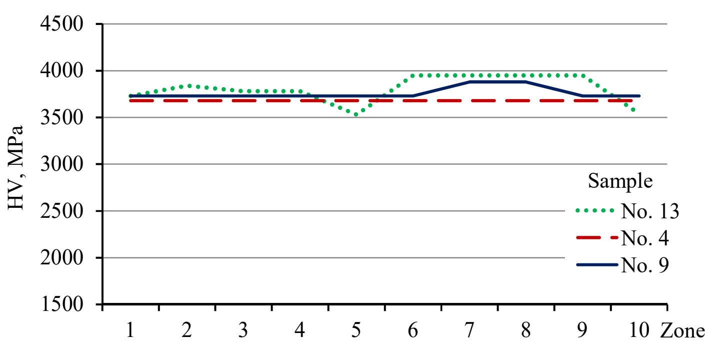


Fig. 9. Variations in microhardness (*HV*) in the layers of the middle part of the sample

By measuring the microhardness of sample No. 4, it was established that in the lower part of the sample (Fig. 7) at a distance of 0.5 mm from the base, the hardness decreased by an average of 18 % (*HV*=3010 MPa) from the general level (*HV*=3630...3750 MPa).

On the surface of sample No. 4, the level of microhardness is mostly uniform (Fig. 8) with an average increase of 6 % from the total level of hardness by height. Small hardness gradients of up to 300 MPa are observed from *HV*=3680 to *HV*=4010 MPa.

Measurements of a chain of indenter impressions in a row in several local layers of the middle part of the sample at a distance of about 2.5 mm from the base show that the level of microhardness in the local layers is uniform *HV*=3680 MPa (Fig. 9).

Therefore, the study of sample No. 4 established that the structure in the cross-section of the section is uniform in height, mostly without defects (several pores are present) with uniform hardness along the height of the sample and along its surface.

The study of the microhardness of sample No. 9 showed that the microhardness has a uniform character. The values of the *HV* hardness in steps of 500 μm and its variations over the entire height from the base to the surface of the sample (vertically) and along the surface (horizontally) are shown in Fig. 7, 8, respectively.

In the lower part of the sample (Fig. 7), at a distance of 1 mm from the base, the hardness level (4070 MPa) is slightly higher, on average by 9 % of the total hardness level by height (*HV*=3600...3840 MPa).

Over the entire surface of sample No. 9 (Fig. 8), the level of microhardness is uniform (*HV*=3830...3910 MPa) without gradients and with some increase on average by 6 % of the total hardness level by height (Fig. 7).

Measurements of a chain of indenter impressions (Fig. 9) in a row in several local layers of the middle part of the sample at a distance of about 2.5 mm from the base show that the level of microhardness in the local layers is uniform (*HV*=3730...3880 MPa).

5. 4. Establishing print modes that enable the formation of the best structural state

The influence of the speed and power of the electron beam on the microhardness and microstructure formed during electron-beam surfacing was determined by researching samples from the alloy of the Ti-6Al-4V system obtained at different technological parameters of printing. It was established that the structure in the cross section of all sections is homogeneous, mostly without defects with a uniform level of microhardness both along the height of the samples and along their surface. When the power of the electron beam is 240 W and the speed of its movement is 270 mm/s (sample No. 13), the width of the crystallites is 80...500 μm, while the average value of microhardness along the height of the sample is 3844 MPa. When the power of the electron beam is increased to 540 W and 780 W at speeds of its movement up to 540 mm/s and 780 mm/s, the width of the crystallites increases, respectively, to 80...600 μm and 100...800 μm. At the same time, a decrease in microhardness is observed on average to 3844 MPa (sample No. 4) and to 3676 MPa (sample No. 9). Thus, the mode of power of the electron beam of 240 W at the speed of its movement of 270 mm/s leads to the formation of a finer structure with an increase in microhardness indicators. It can be noted that this mode will provide a set of properties of the strength and viscosity of the material of the obtained articles and is the most rational technological mode of printing for the additive method of manufacturing articles from the Ti-6Al-4V alloy with the necessary strength properties.

6. Discussion of results of investigating experimental samples

Studies of the microstructure of the resulting samples showed that large crystallites with a uniform lamellar-acicular structure of the α'-phase are formed in all samples as a result of heat treatment during layering. Microhardness is *HV*=3600...3880 MPa for sample No. 9; *HV*=3630...3680 MPa for sample No. 4; *HV*=3680...4030 MPa for sample No. 13. For the upper layers on the side of the outer surface of the samples, thinning of the acicular component of the α'-phase is characteristic (Fig. 6). Thickening of the acicular component of the α'-phase is characteristic for the middle and lower layers. This is related to the speed of metal cooling [7]. With a decrease in the cooling rate of the metal of the lower layers of the samples, needle-like discharges (phases) thicken. When obtaining the upper layers of the samples, the rate of cooling of the metal increases. Therefore, the sizes of needles and plates are getting thinner [11].

Studies of the microhardness of the metal of the obtained samples showed that at a distance of 400...500 μm from the edge of the surface, the microhardness increases by 5...6 % compared to the general level of hardness by height to the values: HV=3830...3910 MPa for sample No. 9; HV=3680...4010 MPa for sample No. 4; HV=3680...4070 MPa for sample No. 13. The highest level of microhardness by height in the upper layers is characteristic of sample No. 13 (beam speed 240 mm/s; power 270 W). Under this mode, there is also some grinding of the structure. The width of the crystallites is hкр=80...500 μm compared to sample No. 9 (780 mm/s; 675 W), where h_{cr}=100...800 μm. The width of the crystallites decreases by a total of 1.55 times. In comparison with sample No. 4 (540 mm/s; 495 W), where h_{cr}=80...600 μm, the width of the crystallites decreases by a total of 1.17 times. This is demonstrated by microstructures with a magnification of ×100 (Fig. 6).

Some increase in the microhardness of the metal of sample No. 13 (beam speed 240 mm/s; power 270 W) is explained by the general grinding of the structure (reduction in the width of the crystallites). This is due to a change in the printing parameters, namely a decrease in the beam power and, accordingly, the structure formation time.

Variations of microhardness depending on printing parameters in test samples are associated with structural and phase components: changes in the internal (fine) structure of crystallites, namely substructure; by the size of the dispersed needle-plate components of the α'-phase; the level of dislocation density. Also, microhardness variations can be related to the content of α- and β-phases.

According to the research results, it can be noted that the surfacing mode such as beam speed 240 mm/s; the power of 270 W is the most rational mode of printing by the method of additive surfacing from the Ti-6Al-4V alloy. Under this mode, the structure is crushed: the width of the crystallites is reduced by 1.55 and 1.17 times compared to other modes.

For a detailed assessment, and even more so when articles are obtained under non-equilibrium conditions, it is necessary to use a more accurate approach to information about the volume fraction of structural components, parameters of the subgrain and dislocation structure.

A feature of our studies is establishing the relationship between the formation of the microstructure and the microhardness of the metal and the parameters of printing the samples. The main limitation of the research is the use of only metallographic studies. In the future, it is advisable to carry out a study by the method of transmission microscopy to establish the effect of printing technological modes on the fine structure, namely the substructure, the dimensions of the dispersed acicular-lamella components of the α'-phase, and the level of the density of dislocations. Investigations at the dislocation level by the method of transmission electron microscopy will allow obtaining more accurate information about the structural and phase features of the metal.

The disadvantage of research is the lack of study of the content of α- and β-phases in test samples from the alloy of the Ti-6Al-4V system, obtained using different printing modes during electron beam deposition. In the future, this shortcoming can be eliminated through additional research. In order to determine the exact phase composition of the samples obtained using Ti-6Al-4V alloy powder, namely the content (%) of α-titanium and β-titanium, it is necessary to conduct a study by the method of X-ray structural phase analysis. It is possible that the content of β-titanium may vary within a few percent for different speeds of the production process.

The development of our studies may be the use of printing from titanium alloy powders for the formation of titanium-based composite materials with additives of powders of strengthening phases. This will make it possible to make articles of the predefined shape with high strength characteristics.

7. Conclusions

1. Based on the additive technology of electron-beam surfacing, experimental samples of the Ti-6Al-4V system alloy were made with individual printing parameters at electron beam power modes of 240; 540; 780 W with speeds of its movement, respectively, 240; 540; 780 mm/s.

2. Metallographic studies of the microstructure of the metal in the cross-section of the test samples established:

– large crystallites with a uniform lamellar-acicular structure of the α′-phase with a small amount of the β-phase are formed along the entire height of the samples, mostly without defects with uniform microhardness both along the height and along the surface of the samples;

– for the upper layers of the metal on the side of the outer surface, the thinning of the acicular component of the α'-phase is characteristic, which is associated with an increase in the cooling rate. Thickening of the acicular component of the α'-phase is characteristic for the middle and lower layers;

– under the surfacing mode with a beam speed of 270 mm/s at a power of 240 W, the structure is crushed: the width of the crystallites is reduced by 1.55 and 1.17 times compared to other modes.

3. Studies of the microhardness of the samples have established that in the upper near-surface layers at a distance of up to 500 μm from the edge, the microhardness increases to 5...6 % compared to the general level of hardness by height. A general increase in the level of microhardness up to 5 %, both in height and in the surface layers, is characteristic of sample No. 13 with the following surfacing mode: beam speed 240 mm/s; power 270 W.

4. The printing mode of sample No. 13 can be considered the most rational from the point of view of forming the best structural state. The application of the electron beam surfacing mode at a beam speed of 240 mm/s and a power of 270 W contributes to a slight increase in the microhardness of the metal and the formation of a finer structure. This will provide a set of properties of the strength and viscosity of the material of articles made of the Ti-6Al-4V system alloy.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The work was financed within the framework of the target program of scientific research at the National Academy of Sciences on the topic "Development of additive electron beam technologies for the manufacture and repair of articles for the aerospace industry and turbine construction" (State registration number 0117U001264).

Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgements

The authors are grateful to the State Enterprise "Engineering center electron beam welding" of E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine for technical support in conducting research.

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