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ADDITIVE ELECTRON BEAM TECHNOLOGY FOR MANUFACTURE OF METAL PRODUCTS FROM POWDER MATERIALS

V.A. Matviichuk, V.M. Nesterenkov, O.M. Berdnikova

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

The aim of the work is to create additive electron beam technology for layer-by-layer manufacture of metal parts from powder materials. To carry out investigations, an experimental model of additive equipment was made, a software and hardware platform for additive manufacturing was designed, technological methods and modes of printing products of a set shape with predicted strength properties were invented. Applying the additive method, 25 experimental samples for further tests were printed. For each of the products, the speed of beam movement, its power and dynamic focusing current were determined. The influence of basic parameters of the technological process of surfacing on the formation and features of the surface structure and chemical composition of the samples were studied. It was found that the chemical composition of products corresponds to the composition of raw materials except for the content of aluminium, which is underestimated by 0.6–1.96 % relative to the chemical composition of the powder. To eliminate this drawback, it is necessary to maintain the aluminium content in titanium alloy powders at the highest level. According to the results of investigations in the created equipment, according to computer models, the products of industrial and medical purpose were printed, the printing modes of which are optimized. From the powders of titanium alloys, the models of stator blades of a gas turbine aircraft engine, human skull implant and bioprosthesis were manufactured.

KEYWORDS: additive technologies; 3D printer, electron beam surfacing, metal powder, titanium alloy, chemical composition, surface microrelief

INTRODUCTION

Innovative technologies of layer-by-layer manufacturing of products by the method of rapid prototyping open up new opportunities for the manufacture of parts of a set shape with predicted properties.

The process of creating products by such a method with the use of an electron beam is relatively new, but it successfully opened up great prospects for the manufacture of a wide range of industrial and medical products. It is based on the operation of layer-by-layer melting of metals in vacuum using electron beam. This approach is distinguished by a quick transition to the manufacture of three-dimensional products directly from the system of automated designing with the ability of using a wide range of metals and alloys, including refractory and chemically active ones [1].

In Ukraine and in the world, creation of additive technologies for growing products by electron beam surfacing is urgent. As far as domestic equipment does not exist, it is relevant to create the equipment and software for it to realize additive manufacturing oriented to be introduced at the enterprises of the aerospace industry and turbine building, and also for the needs of biomedical branch.

The specialists of the E.O. Paton Electric Welding Institute of the NAS of Ukraine carried out investigations on the development of technologies and equipment for additive manufacturing of metallic parts by the method of rapid prototyping.

OBJECT, AIM, TASKS AND RESULTS OF INVESTIGATIONS

The results of previous research works showed the possibility of creating industrial equipment for electron beam melting of metal powder materials, as well as the ability of manufacturing products of a complex shape by an additive method [2].

The authors set the aim of developing additive electron beam technology for manufacturing products of aerospace industry and turbine building and create an experimental model of additive equipment.

The object of investigations was electron beam technologies for growing products using metallic powder materials. The basic tasks are the development of an experimental model of additive equipment and software, creation of printing technology, manufacture of experimental samples, studies of their properties and manufacture of industrial parts.

As a result of the project realization, a unique equipment for realization of additive electron beam manufacturing was created, which is oriented on the introduction at domestic enterprises of aerospace industry and turbine building: JSC “Motor Sich”, SE “LRZ” Motor, “SE EDB “Pivdenne” and “Zorya-Mashproekt” Gas Turbine Research and Development Complex. The equipment is also relevant for the needs in the biomedical industry and mechanical engineering.

TECHNOLOGY OF ELECTRON BEAM SURFACING

The technology of electron beam surfacing is similar to the technology of selective laser sintering, which is widely used in industry. Its main difference consists in using an electron beam as a power source instead of a laser. The technology is based on the possibility of using a high-power electron beam for melting of a metal powder in a vacuum chamber with the formation of successive layers that repeat the contours of a digital model of a product. Unlike the technologies of laser sintering, electron beam surfacing allows increasing the efficiency due to a high power of the guns and electromagnetic unlike electromechanical beam scanning [2].

The technology provides an opportunity to maintain a thermostable process of manufacturing parts throughout the whole manufacturing cycle. The temperature in the bed, where a product is created, is maintained as a result of action of electron beam as a power source. Before surfacing, the powder layer is heated to a temperature of about 700–1000 °C, which allows creating parts with lower residual stresses caused by a gradient of temperatures between already cooled and still hot layers. The thermostable process makes it impossible or significantly reduces the formation of cracks and shaping defects.

In addition, a complete remelting of a metal powder allows manufacturing monolithic products, which provides the maximum strength. As to mechanical properties, finished products almost do not differ from cast parts.

In the process of printing, the device reads data from a file, containing a three-dimensional digital model of a product and creates successive layers of the powder material. The contours of layers are formed by a focused electron beam, which melts a metal powder in the collision places. The surfacing is carried out in protected vacuum chambers, which provides an opportunity to work with chemically active metals, sensitive to oxidation, for example, with titanium and its alloys [1].

The technology of layer-by-layer electron beam surfacing in vacuum allows creating dense metal products of a set shape with a high geometric precision [2].

ADDITIVE ELECTRON BEAM EQUIPMENT

Technologies and equipment created by the staff colleagues of PWI, from the very beginning are oriented on the needs of Ukrainian enterprises. For manufacture it is predicted to involve raw materials necessary for the manufacturer. This approach makes it possible to provide a manufacture of parts and assemblies based on the needs of the consumer and in a close contact with him. The developed technologies will allow reducing terms of introduction of new types of products into manufacture, expanding its assortment, and also creating basically new types of products with the properties predicted in advance, the manufacture of which is impossible without application of the methods of 3D printing [1].

In recent years, a noticeable trend is observed in the introduction of additive technologies in the leading domestic companies in the aerospace industry and turbine building: SE EDB “Pivdenne”, JSC “Motor Sich “and SE “Zorya-Mashproekt” Gas Turbine Research and Development Complex [2].

To solve the set problems, investigations were carried out with the use of equipment for 3D printing.

PRINCIPLE OF EQUIPMENT OPERATION

The created equipment operates as a part of the additive electron beam equipment for melting of metal powder materials (Figure 1). The supply and dosing of metal powder takes place directly in the vacuum chamber from the hoppers, from which the metal powder enters the working table under the action of gravity. According to this principle of powder supply, the use of any dosing mechanisms is not provided. After selecting a certain amount, the powder from the hoppers is automatically fed in bulk to maintain a sufficient level on the table.

Metal powder melts under the action of electron beam, which is created by an electron beam gun,

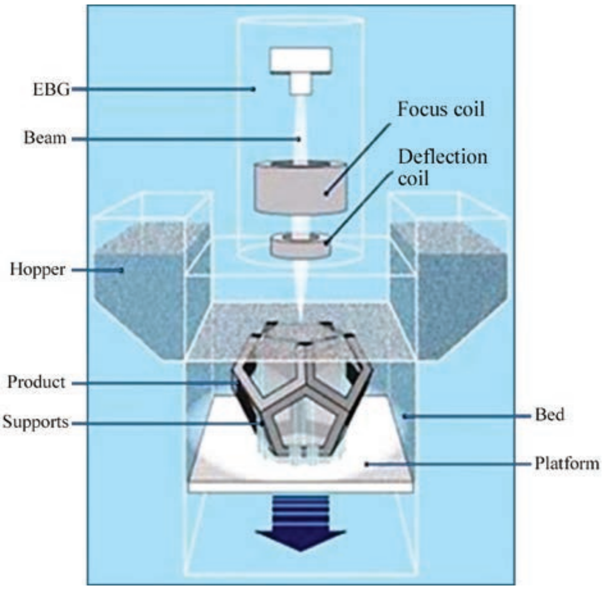

Figure 1. Scheme of additive process

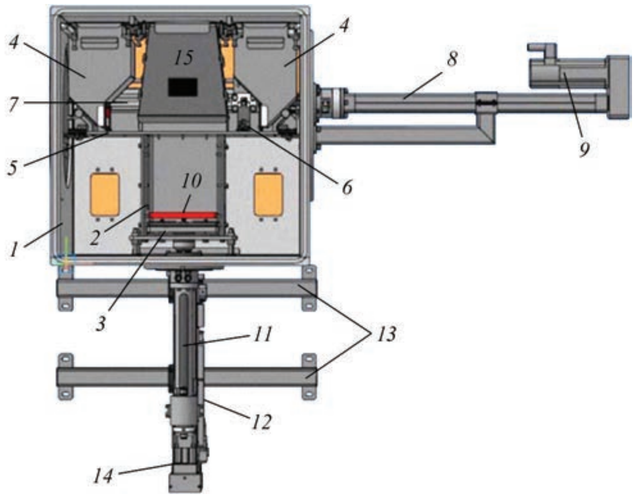

Figure 2. Equipping of vacuum chamber (designations *1–15* see in the text)

where the beam is focused and deflected by appropriate systems.

A product is formed layer-by-layer, while the platform, on which a part is grown, is lowered after the formation of each layer.

TECHNOLOGICAL EQUIPMENT

For investigations, an experimental model of additive equipment based on a small-sized installation of type SV-212M for electron beam welding was designed, manufactured and set up.

The created equipment (Figure 2) consists of vacuum chamber *7*, bed *2*, where platform *3* with pallet *10* is located, on which a product is grown. In the hoppers *4*, a metal powder is located, which is fed in bulk on the table *5*. The rail *6* moves along the table *5* and distributes the metal powder on the surface of the pallet *10*. The rail is fixed on the guides *7*. In a horizontal plane, the rail is moved by the actuator *8* with electric motor *9*.

Platform *3* with pallet *10* are located in the bed *2* and moves along the vertical axis by means of a movable sleeve *11*, which is fixed to the rail *12* mounted on the brackets *13*. The movement is controlled by electric motor *14*.

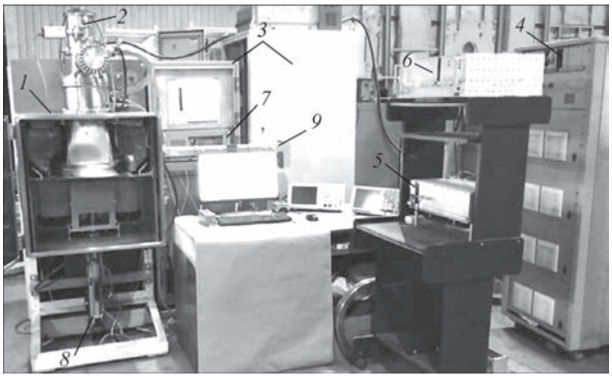

Figure 3. Equipment for electron beam 3D-printing (designation *1–9* see in the text)

Reflector *15* protects the vacuum chamber from the action of a high temperature, that arises on the surface of the layer, where a product is formed.

A photo of the created additive equipment is given in Figure 3.

The equipment (Figure 3) consists of a small-sized vacuum chamber 1 with the mechanisms for moving the platform *8* and the mechanisms for supply and distribution of powder *9*. The power unit includes electron beam gun *2* and high-voltage power source *4*. The electron beam gun *2* is placed on the vacuum chamber. The vacuum system of the equipment provides working pressure in the chamber better than 10^{-4} Torr. The elements of the system for control of the equipment are located in the cabinets *3*, where the units for control of the following units are located: high-voltage source, vacuum system and MCP controller. High-voltage source *4* allows generating a voltage of 60 kV and an electron beam current of up to 100 mA. The amplifiers of scanning waveforms *5* and dynamic focusing *6* form the technological scannings of the electron beam and its focusing. The equipment is controlled by an industrial computer *7*.

ELECTRIC EQUIPMENT

To control the electron beam and technological equipment, the following units were designed, assembled and set up:

■ Power unit, consisting of:
- 60 kV high-voltage source;
- electron beam gun with a high-voltage cable.

■ Scan control system, consisting of:
- two-channel scanning waveform amplifier;
- dynamic focusing signal amplifier.

■ MCP controller that controls the printing process.

■ Electric drive Siemens Sinamics S120 for movement mechanisms with electric motors Siemens Simotics 1FK7.

■ Industrial computer with Windows 10 operating system.

■ Control cabinet, where switching equipment and MCP controller are located.

■ Vacuum system control cabinet.

CONTROL SYSTEM

The system for control of additive equipment (Figure 4) is built on the base of the MCP hardware controller, which controls the current of the electron beam, its scannings, focusing and movement mechanisms. The controller interacts with the industrial PC computer, where models of products are formed and a job-file is created, in which the algorithms of product construction are written. From the computer, a job-file via the Ethernet network goes to the MCP controller, which controls the 3D printer equipment.

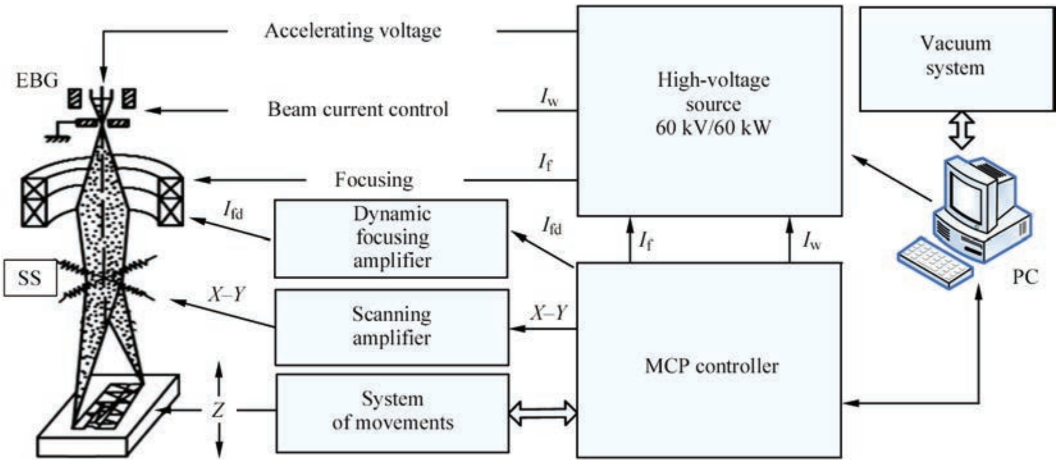

Figure 4. Flow chart of equipment control: EBG — electron beam gun; FC — focus coil; SS — scanning system (other see in the text)

The controller generates analog signals to control the electron beam scannings (Figure 4), coming to the scan amplifiers, to which the deflecting coils of EBG are connected.

The electron beam along the *X* and *Y* axes deflects and creates a surfacing zone of the desired shape. The surfacing process is performed by the program according to the computer model of a product according to preliminary set technological modes.

Electron beam current I_w, currents of static I_f and dynamic I_{fd} focusing are also objects of control.

In addition, the controller controls the system of 3D printer movements, which switches the mechanisms for vertical movement of the platform (*Z* axis) and horizontal distribution of metal powder on the platform.

The industrial computer controls the vacuum system of the equipment and a high-voltage power source.

SOFTWARE AND HARDWARE PLATFORM

To control the additive equipment, in cooperation with Materialise, Belgium, a software and hardware platform was created, which consists of process controller and package of application software for realization of additive manufacturing [2].

The structure of control platform and the state of interactions between its components are given in Figure 5 [2].

SOFTWARE

Creating 3D models of products is possible using any software of CAD type. Analysis and editing of models is performed by the Materialize Magics software.

The ready-to-print computer model of products is further processed by the BuildProcessor software, which allows decomposing models into layers, setting parameters and structure of their formation, specifying power, speed of its movement, focusing and settings of the electron beam for each product. The software also allows choosing the layer thickness, product material and texture variants for filling the layers [2].

BuildProcessor forms a job-file that goes to the MCP controller. Using a job-file, the controller directs the printing process.

For control of the equipment during printing, the MCP Operator interface software is used, where technological parameters of the equipment are set, and also the printing process is controlled and displayed in real time with the possibility of correcting the parameters. The software allows selecting a file of products, determining the start and end time of manufacturing cycle and its stage. The software provides a three-dimensional visualization.

Setting of the MCP controller and calibration of the 3D printer are performed in the Toolbox software (Figure 5).

STAGES OF ADDITIVE MANUFACTURING

The sequence of stages of additive electron beam manufacturing is given in Figure 6 [3].

First, a 3D model of the object is created. This model can be developed using computer-aided design (CAD) systems or reverse engineering methods, such as object laser scanning. The obtained CAD file should be converted into a standard format for addi-

Figure 5. Structure of control platform

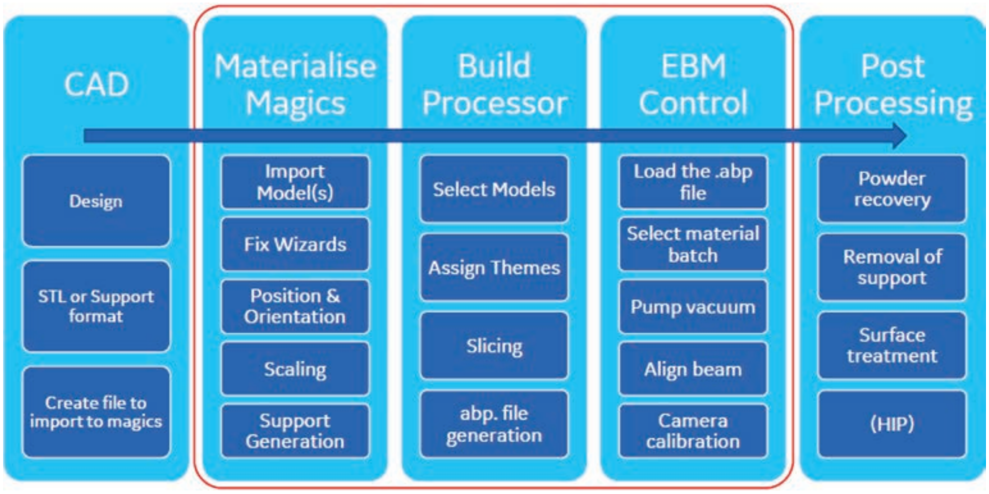

Figure 6. Stages of additive electron beam manufacturing

tive manufacturing, which represents usually a STL file. To maximize cost savings and reduce waste, it is necessary to optimize the location and a number of objects on the assembly platform. Usually, several parts are printed at once. The computer model of assembling products using software is “cut” into layers.

The next stage requires transferring a file to the additive hardware and configure it.

Next, the 3D printer builds products layer-by-layer. The thickness of the layer determines the final quality and depends on the features of printing technology. The size of products depends on the capabilities of the equipment.

After building and cooling, the assembly can be removed from the equipment.

Then, cleaning, polishing and finishing of parts surface is performed. It is also possible to further finish them to the desired standard. This requires using of other machines and tools [4].

SAMPLES OF PRODUCTS AND THEIR INVESTIGATION

On the created experimental model of additive electron beam equipment, experimental products are printed for further testing.

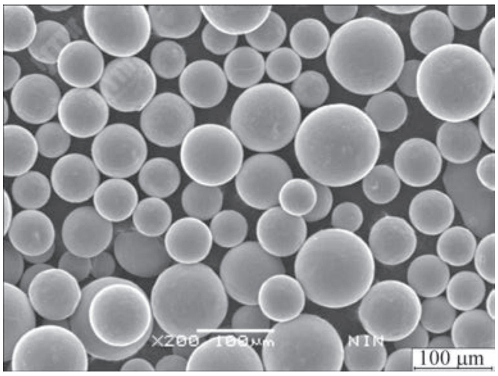

Figure 7. Ti6Al4V ELI powder

The aim of the experiment is to investigate the influence of the basic parameters of the technological process of surfacing on qualitative indices of products [5].

For this purpose, it is expected to print experimental samples and test their properties. It was necessary to investigate: the influence of printing parameters on the formation of surfaces of products; features of the structure of surfaces; chemical composition of samples; based on the results of tests, invent the optimal printing modes.

Ti6Al4V ELI POWDER

To print samples, the powder of the titanium TiAl6Al4V ELI alloy is used, produced by the Chinese company Sino-Euro Materials Technologies of Xi’an Co., Ltd. The powder was produced by the method of plasma melting and centrifugal spraying (PREP technology) [6]. The powder granules have a spherical shape with minimal defects (Figure 7). PREP powder is the best for electron beam additive manufacturing [7].

Technological characteristics and chemical composition of Ti6Al4V ELI powder are provided in Table 1 and Table 2, respectively [8].

Table 1. Technological characteristics of Ti6Al4V ELI powder

Fraction, µm		45–106
Particle-size distribution (PSD), µm	D10	53–58
	D50	85–90
	D90	125–130
Yield, s/50 g		20–25
Density, g/cm^3		2.5–2.7
Oxygen content, ppm		500–1800

Table 2. Chemical composition of Ti6Al4V ELI powder

Composition of alloying elements, wt.% of particles				Composition of impurities, wt.% of particles		
Al	V	Fe	Ti	C	N	H
5.5–6.75	3.5–4.5	≤ 0.3	Base	≤0.08	≤0.05	≤0.015

Table 3. Technological modes of sample surfacing

Number of sample	Beam parameters		Dynamic focusing 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

EXPERIMENTAL SAMPLES

For further tests, from the powder of the titanium Ti6Al4V ELI alloy, experimental samples of products were manufactured (Figure 8).

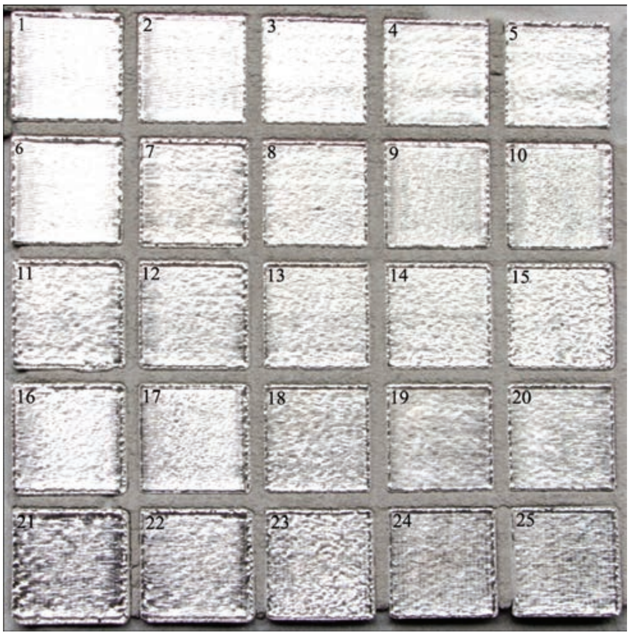

Figure 8. Experimental samples

The produced samples (Figure 9) have a rectangular shape of 24×24 mm and a thickness of 10 mm. 55 mm from this thickness are technological supports and another 5 mm is the body of a product. A quantity of printed samples is 25 pcs.

For printing samples, the following technological parameters were set:

- beam trajectory shift step is 0.2 mm;
- thickness of the powder layer is 0.1 mm;
- scanning strategy: two-directional with the direction of rotation by 90° for each layer.

For each sample, the speed of movement of the beam and its power and a set dynamic focusing current were determined. The parameters of sample printing are given in Table 3.

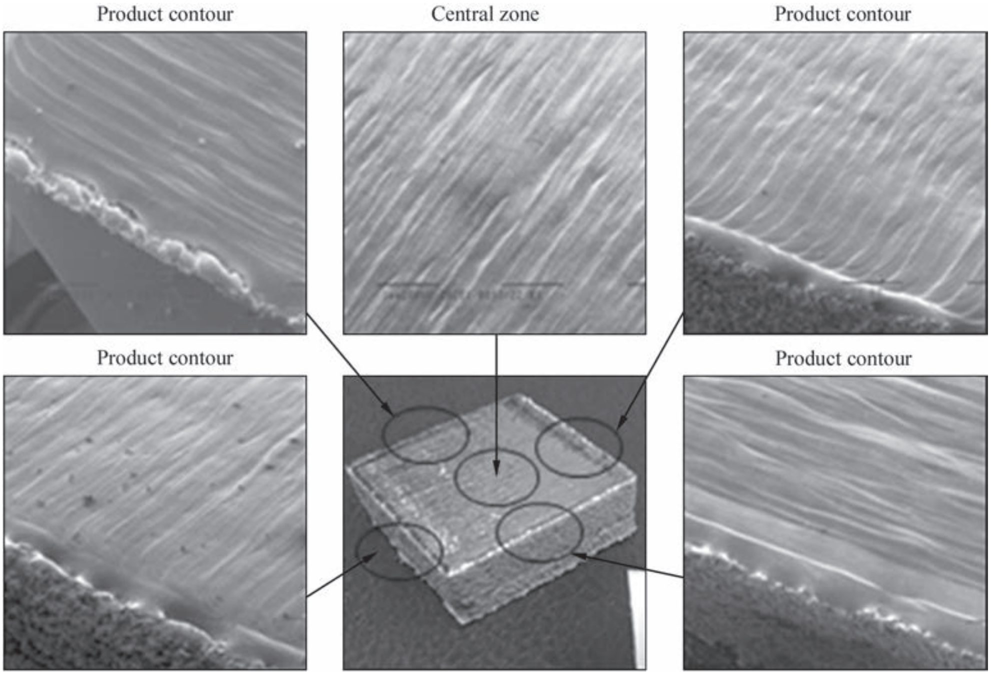

Figure 9. Product sample

Table 4. Chemical composition of samples

Number of measurement	Chemical elements, wt.%			
	Al	V	Fe	Ti
Sample No.2				
1	5.04	4.21	0.01	90.75
2	4.85	4.33	0.06	90.76
3	5.09	4.40	0.02	90.48
Sample No.5				
4	4.55	4.32	–	91.13
5	4.32	4.63	–	91.05
6	4.79	4.25	–	90.96
Sample No.8				
7	5.00	4.28	–	90.72
8	5.17	4.04	–	90.79
9	4.90	4.38	–	90.72

INFLUENCE OF TECHNOLOGICAL PARAMETERS ON PRODUCT FORMATION

In order to study the influence of technological parameters on the formation of products of powder of titanium Ti6Al4V ELI alloy, investigations using a method of scanning electron microscopy (SEM, scanning electronic microscope SEM-515 of Philips Company, Netherlands) were conducted. Data on the chemical composition of products were obtained. The samples No.2, No.5 and No.8 were investigated, which were printed on different modes of beam speed and its power: 780 mm/s/675 W (sample No.2); 540 mm/s/495 W (sample No.5); 240 mm/s/270 W (sample No.8), but with the same value of dynamic focusing current I_{df}: –0.61 A. The results of investigations are presented in Table 4.

It was found that the content of aluminium is by 0.6–1.96 % underestimated relative to the chemical composition of powder (see Table 2). The deviation is probable, associated with an increased volatility of aluminium vapour in the conditions of a high vacuum. To eliminate this drawback, it is necessary that in powders of titanium alloys, aluminium content maintained at the highest level. The content of V corresponds to the composition of powder. The peak of Fe in the spectrum (Figure 10) is almost absent (0–0.06 % Fe).

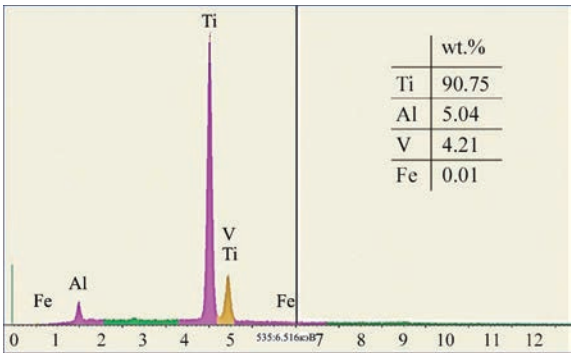

Figure 10. Spectrum of sample No.2

In the course of further studies by SEM method, for each sample, images of surface microrelief were obtained. It was found that products are mostly characterized by a homogeneous profile of microrelief. The structure of the surfaces formed in different zones, differs by its morphology depending on the technological modes.

For example, from Figure 11, it is seen that in the central zone of samples at a beam speed of 780 mm/s and its power of 675 W, depending on the dynamic focusing current (I_{df}), the character of the surface relief and parameters of their roughness are changed.

The surfaces of the produced samples are mostly featured by a banded type in the presence of a clear direction (Figure 11). On some surfaces, the areas with local microroughnesses are observed (Figure 11, *e*–*g*). Also, changes in the roughness parameters of surface microrelief are observed, namely distances (or step) between roughnesses of the surface profile behind the apexes and the height of the relief (Figure 11, *g*–*i*).

In addition to the abovementioned structural characteristics of surfaces, depending on the speed of the beam and its power, the general appearance of surface relief also changes. Thus, while reducing the speed of the beam to 240 mm/s and power to 270 W, surfaces are formed with another relief in the absence of a clearly defined banded structure at some coarsening of the step of the roughnesses of the surfaces behind the apexes (Figure 12). Such structural changes can be reduced to the temperature conditions of heating and cooling while producing samples.

Taking into account the abovementioned, it becomes necessary to conduct more detailed studies of the parameters of surface microrelief in the samples produced on different technological modes and compare these structural characteristics, depending on speeds of the beam and power, as well as the dynamic focusing current.

Therefore, the next investigations will be devoted to the study of the structure of surfaces of samples in several zones (central zone and contour of the sample) at different magnifications, including a top view of surfaces and at inclined position of samples; flaws detection (pores, lacks of fusion, microroughnesses, inclusions); measurement of microrelief roughness parameters in the examined areas, namely the distances between the roughnesses of the surface profile behind the apexes and the height of the relief.

EXPERIMENTAL SAMPLES OF PRODUCTS

In the created additive electron beam equipment according to computer models, industrial and medical products were printed, the modes of whose printing were optimized based on the results of previous studies.

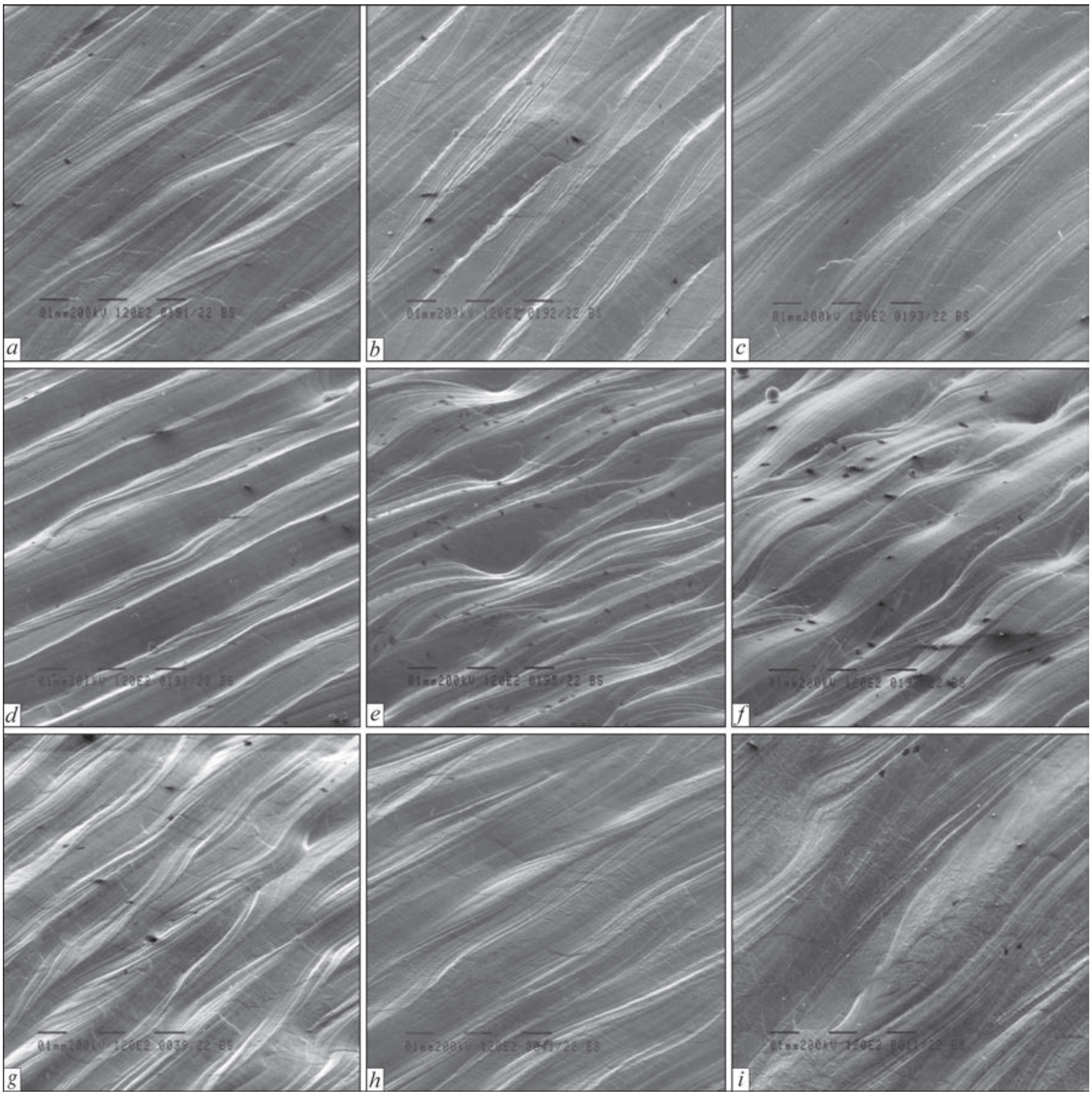

Figure 11. Surface relief (×120) in the central zone of samples at a beam speed being 780 mm/s and power of 675 W, depending on the dynamic focusing current (I_{df}): *a* — I_{df} = –1.2 A (sample No.6); *b* — I_{df} = –0.9 A (sample No.1); *c* — I_{df} = –0.61 A (sample No.2); *d* — I_{df} = –0.31 A (sample No.9); *e* — I_{df} = 0 A (sample No.17); *f* — I_{df} = 0.33 A (sample No.10); *g* — I_{df} = 0.65 A (sample No.16); *h* — I_{df} = = 0.96 A (sample No.22); *i* — I_{df} = 1.27 A (sample No.21)

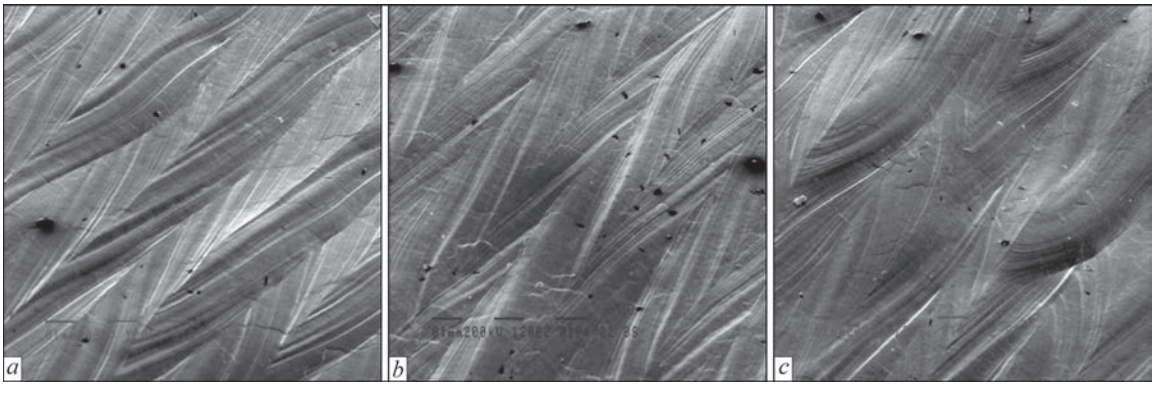

Figure 12. Surface relief (×120) in the central zone of samples at a beam speed of 240 mm/s and the power 270 W depending on dynamic focusing current (I_{df}): *a* — I_{df} = –1.2 A (sample No.18); *b* — I_{df} = –0.31 A (sample No.13); *c* — I_{df} = 0.65 A (sample No.15)

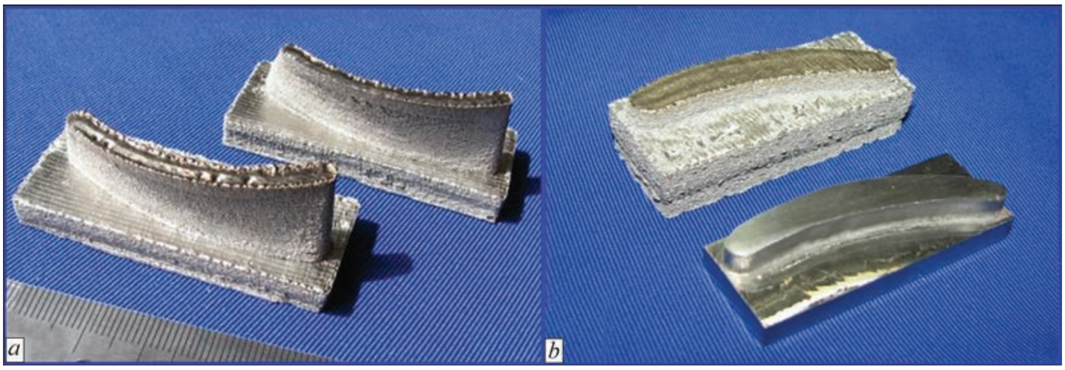

Figure 13. Experimental models of stator blades of gas turbine aircraft engine (description *a*, *b* — see in the text)

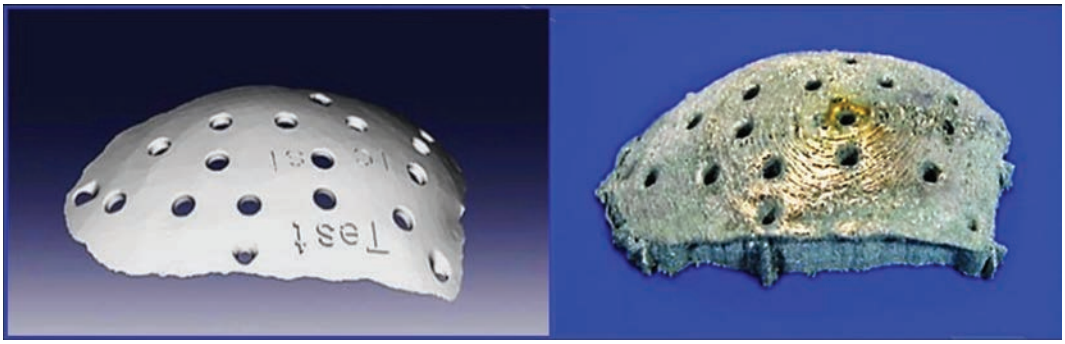

Figure 14. Implant of braincase. Model and printed product

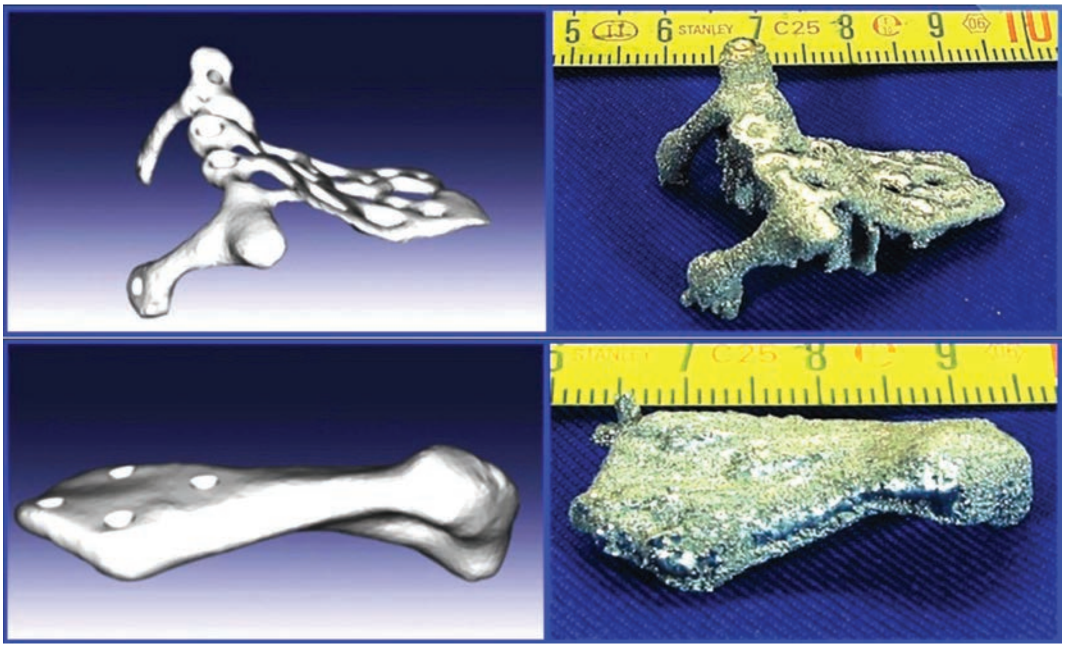

Figure 15. Biopros*thesis. Models and printed products

Figure 13 shows experimental models of stator blades of gas turbine aircraft engine, printed from metal powders of the following titanium alloys:

a) Ti6Al4V ELI, fraction of 45–106 µm, granules of a spherical shape, produced by PREP technology, manufacturer is Sino-Euro Materials Technologies of Xi’an Co., China;

b) VT-20, fraction of 63–160 µm, granules of an arbitrary shape, produced by HDH technology, manufacturer is LLC “Ti Technology”, Ukraine.

Figure 14 shows a computer model and a printed implant of a humane braincase, Figure 15 shows bioprosthesis and their models. Products made of powder of titanium Ti6Al4V ELI alloy.

CONCLUSIONS

Based on the results of research works, an experimental model of additive equipment was designed and manufactured, electron beam technology of layer-by-layer surfacing of metal products of powder materials was created, experimental samples of products were printed; laboratory examinations of samples were carried out, industrial and medical products were manufactured.

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ORCID

V.A. Matviichuk: 0000-0002-9304-6862,
V.M. Nesterenkov: 0000-0002-7973-1986,
O.M. Berdnikova: 0000-0001-9754-9478

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

V.M. Nesterenkov
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine
E-mail: nesterenkov@technobeam.com.ua

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