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MANUFACTURE OF INDUSTRIAL PRODUCTS USING ELECTRON BEAM TECHNOLOGIES FOR 3D-PRINTING*

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The prospects of manufacturing a wide range of parts and units of flying vehicles and engines using electron beam technologies, were noted In the work the peculiarities of developing such technology are considered using the domestic raw materials in the form of powder materials or filler wire. In the laboratory equipment the cylindrical and rectangular specimens were manufactured, thus proving the possibility of implementing the additive technology for the needs of industry. 6 Ref., 1 Table, 7 Figures.

Key words: *electron beam surfacing, products of preset shape, 3D-printing method, powder materials, filler wires, laboratory equipment*

The innovative technologies of layer-by-layer manufacture of products using the method of a rapid prototyping open up the new opportunities for manufacturing parts of a preset shape and structure with predetermined properties.

The process of manufacturing products by this method applying electron beam is relatively new, but it has already successfully demonstrated great prospects of its use in industry for manufacturing a wide range of both parts and units of flying vehicles as well as gas turbine engines. It is based on the operation of layer-by-layer fusion of metallic powder or filler wire in vacuum by electron beam. This approach is distinguished by a rapid transition to manufacture of three-dimensional products directly from the system of automated designing with the opportunity of applying a wide range of metals and alloys, including refractory and chemically active ones. All existing industrial developments for today belong to foreign companies [1]. The use of technologies and machines for prototyping in our country is associated with their purchase abroad with subsequent significant expenses for buying necessary powders [2] being a consuming and expensive component of this technology.

The aim of the present work is creating the additive technologies for manufacture of products of a preset shape and structure using the methods of layer-by-layer electron beam melting of metals in vacuum with powder materials, i.e. Electron Beam Melting (EBM), and with filler wire made in Ukraine, i.e. Direct Manufacturing (DM).

To achieve this aim it is necessary:

- to carry out investigation of properties and possibility of application of metallic powders and filler wires for realizing the additive process of manufacturing and repair of products of aerospace industry, turbine construction, machine building and medicine;
- to work out the designing documentation for basic units of 3D-printer for each of the investigating additive processes and to manufacture the experimental laboratory equipment;
- to develop software for investigations of two additive processes using electron beam (EBM and DM) [3];
- to develop additive electron beam technologies EBM and DM, and also to investigate the properties of multilayer deposited metal;
- to create an industrial mock-up of the equipment in the set with the software as-applied to the industry of Ukraine.

Topicality of work. The technologies and equipment developed will allow manufacturing metal products using the method of rapid prototyping applying the domestic raw materials.

The developing technologies and equipment are initially oriented to the needs of national enterprises. For manufacture it is supposed to use inexpensive domestic raw materials necessary for the manufacturer. This approach will also provide manufacturing parts and units by rapid prototyping, coming from the needs of a consumer and in close contact with him. The developed technologies will allow shortening the terms for implementation of new types of products, expanding

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their range, and also creating the fundamentally new types of products with preset properties, the manufacture of which is impossible without 3D-printing methods.

Since there is no equipment for 3D-printing of national designing, it is relevant to create its hardware and software in Ukraine for realizing the additive electron beam manufacturing, free from the imported raw materials, oriented to implementation at the enterprises of aerospace industry and turbine construction: SE Research and Production Complex «Zorya»–«Mashproekt», SE «LRZ» Motor», Share-holding Company «Motor Sich» and SE «KB «Yuzhnoye».

Technology of layer-by-layer electron beam melting of metals in vacuum with application of powder materials by EBM. The technology of electron beam surfacing by EBM is similar to the selective laser melting applied in industry. Its main difference consists in using an electron gun instead of laser as a power source for melting. The technology is based on using a high-power electron beam for fusion of metallic powder in the vacuum chamber with the formation of successive layers repeating the contours of a digital model. Unlike the technology of laser sintering, the electron beam melting allows increasing the efficiency due to a high power of guns and electromagnetic, but not electromechanic, scanning of the electron beam.

As to mechanical properties, the ready products almost do not differ from cast parts. The device reads data from a file, containing a three-dimensional digital model, and deposits the successive layers of powder material. The contours of layers of the model are plotted by an electron beam, thus melting the powder at the contact areas. The melting is performed in vacuum working chambers, which allows working with chemically active metals, sensitive to oxidation, for example, with titanium and its alloys.

The electron beam melting is carried out at elevated temperatures, reaching the order of 700–1000 °C, which allows creating the parts with lower residual stresses, caused by a temperature gradient between already cooled and still hot layers. In addition, the full melting of consumable powder allows manufacturing monolithic products. Therefore, they have the maximum strength.

For development of additive technologies in Ukraine, the SE «State Research and Design Institute of Titanium» together with the Research Center «Titan of Zaporozhye» offer an innovative technology for production of low-cost titanium powders by the method of hydrogenation-dehydrogenation (HDH) from titanium sponge or other titanium-containing materials of different quality and fractional composition [4]. The use of such powders for additive manufacturing seems challenging with the availability of the appropriate equipment for 3D-printing.

Considering the abovementioned, the specialists of the E.O. Paton Electric Welding Institute started investigations in the field of developing technologies and equipment for additive manufacturing of metal products by the method of rapid prototyping applying the raw material of the SE «State Research and Design Institute of Titanium» and the Research Center «Titan of Zaporozhye». The experimental specimens of the products of the preset shape were produced and laboratory equipment for 3D-printing was designed on the basis of the installation for electron beam welding of SV-212 type. A block diagram of the equipment is shown in Figure 1.

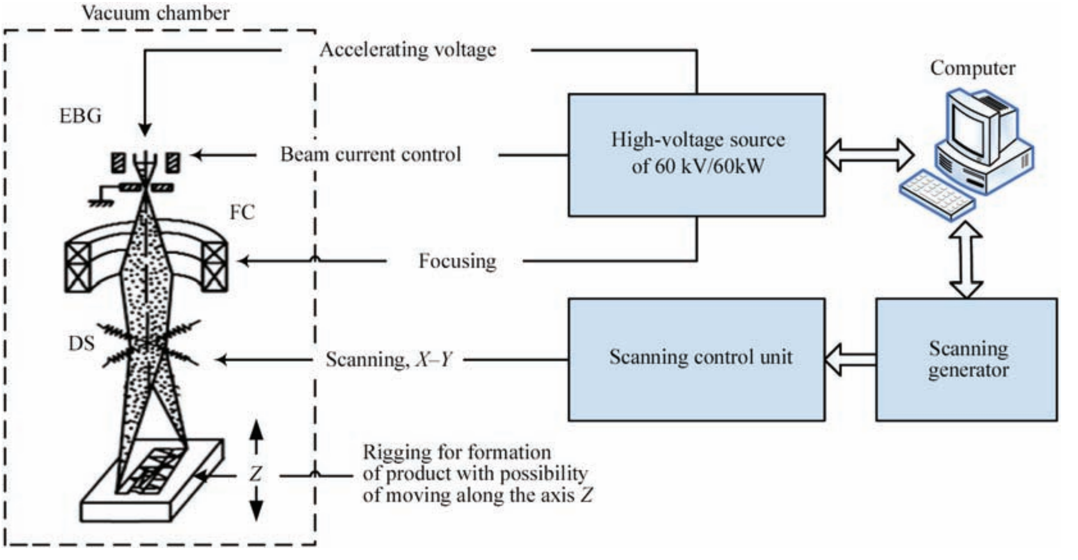

Figure 1. Block diagram of equipment for additive electron beam surfacing: EBG — electron beam gun; FC — focusing coil of EBG; DS — deflecting system of EBG

Technological characteristics and chemical composition of powder materials HDH of titanium VT1-0

Fraction, μm	Density, g/cm³	Content of impurities, wt.%					
		N	C	H	Fe	Si	O
100–160	1.7	≤0.05	≤0.1	0.01–2.00	≤0.3	≤0.15	≤0.15
63–100	1.8	≤0.05	≤0.1	0.01–2.00	≤0.3	≤0.15	≤0.15

To form melting zone, the computer-controlled scanning generator was applied. The electron beam deflects along the axes *X* and *Y* and creates the melting zone of a preset shape. The surfacing process is performed in compliance with the program according to the set technological modes. The objects of control are the beam current, focusing current, beam deflection along the axes *X* and *Y*.

The process of electron beam melting occurs in the vacuum chamber at the vacuum value being less than $1\cdot10^{-4}$ torr. A focused beam of electrons creates a melting zone and forms a product by moving along the preset trajectory. Then, the table in the rigging is lowered and the next layer of powder is applied. The part is layer-by-layer «grown».

As powder materials, the titanium HDH powders were used, representing granules of a non-spherical shape of the titanium alloy VT1-0.

The technological characteristics and chemical composition of HDH powder materials of titanium VT 1-0 are presented in Table.

According to the scheme mentioned above, the specimens of a rectilinear shape with the dimensions of 12×12×100 mm were produced (Figure 2). In Figure 2, the upper layer of product *1* and substrate *3* with intermediate layers of deposited metal are seen. On the lateral surface the particles of unmelted metallic powder *2* are present. This powder is further removed, and the metal surface is machined. After practicing the deposition modes, taking into account the powder fraction, the size of the layer and that of the layers overlapping, the specimens for further investigations were produced. Figure 3 shows the specimen after machining.

In different sections of the specimen, metallographic examinations of microstructure of the deposited metal were carried out (the powder from the titanium alloy VT1-0 was deposited on the base of the titanium alloy VT-20).

The structure of the deposited metal represents α-phase characteristic of the lithium titanium alloys, the defects like pores and lacks of fusion were not detected in the investigated specimens.

The designed elements of technology of layer-by-layer growing with the use of HDH powders allows manufacturing parts with a dense cast metal structure without defects [5]. The obtained results provided the basis for designing an industrial equipment for the additive manufacturing of products using powder materials.

The equipment is created on the base of the installation of type SV-212M for electron beam welding. The modernization of vacuum chamber, the development of control systems of actuators for moving the table along the vertical and the unit for powder distribution in the chamber, as well as the development of the appropriate software for reproduction of additive manufacturing are envisaged.

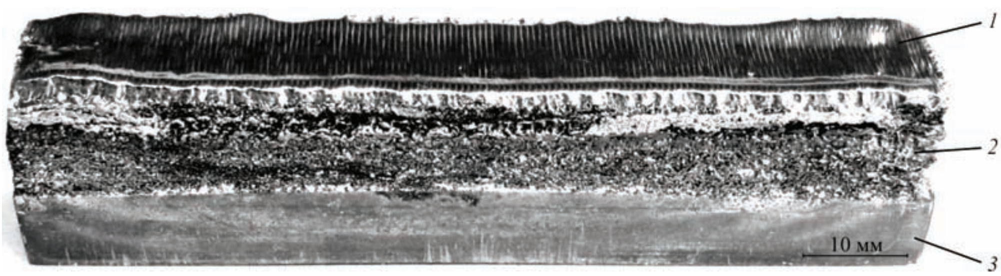

Figure 2. Specimen manufactured by electron beam 3D-deposition: *1* — upper layer of deposited metal; *2* — intermediate layer of metal with particles of unmelted powder on the sides of specimen; *3* — titanium substrate

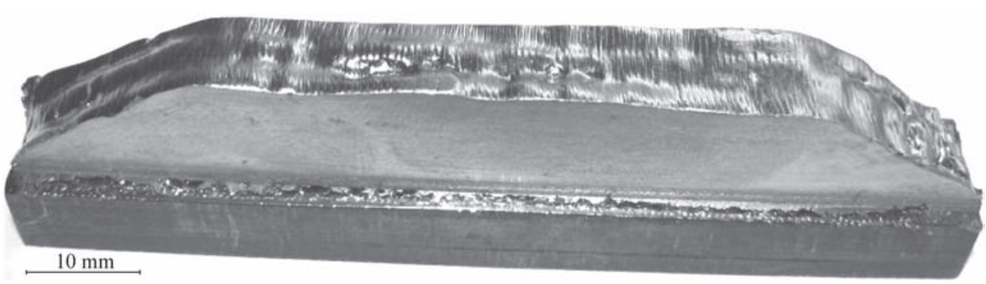

Figure 3. Appearance of specimen after machining

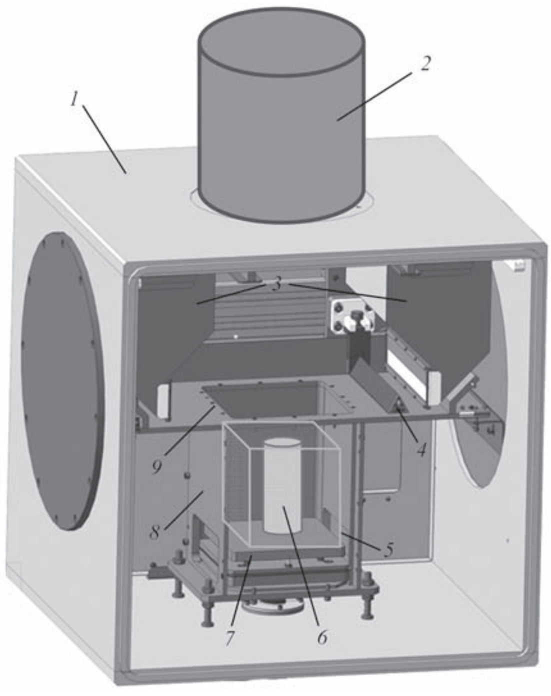

Figure 4. Scheme of installation for additive manufacturing with application of metallic powder materials (description *1–9* see in the text)

The scheme of installation is shown in Figure 4.

The process of electron beam melting occurs in the vacuum chamber *1* at the vacuum value being less than $1\cdot10^{-4}$ torr. The metal powder is fed in bulk to the working table *9* from the hoppers *3*. The rack *4*, moving along the table *9*, forms a layer of powder of the preset thickness on the surface of the pallet *7*. In the initial position the pallet is located at the top of the shaft *8*. The focused electron beam, formed by EBG *2*, flashes the surface of the powder along the preset trajectory. Thus, in accordance with the algorithm, the contours of a product and its layer are formed. Further, the pallet *7* is lowered to a preset value and the next layer of powder is deposited. The process is repeated. The product *6* is layer-by-layer grown. At the end of the production cycle a part is extracted from the vacuum chamber, cleaned from unmelted powder *5* and machined.

The technology of layer-by-layer electron beam melting of metals in vacuum applying powder materials allows creating dense metal products of a preset shape at the high geometric accuracy. The overall dimensions of products are 200×200×200 mm, and the efficiency of electron beam deposition according to the EBM technology does not exceed 0.3 kg of metal powder per hour.

Technology DM of layer-by-layer electron beam melting of metals in vacuum with filler wire. The second investigated DM process of electron beam melting of metals is the process of melting the metal wire in vacuum with the formation of successive layers. For heating and melting of the wire, an electron beam of the required power is used.

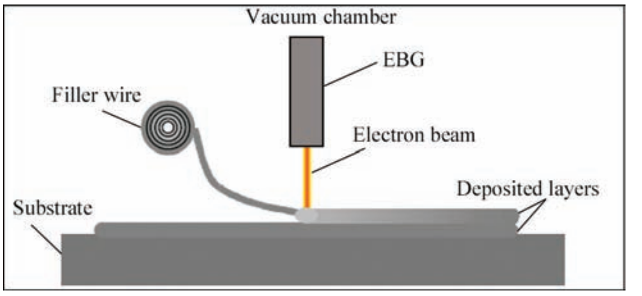

Figure 5. Scheme of layer-by-layer electron beam melting of filler wire

The scheme of DM process is shown in Figure 5.

The deposition is performed in the vacuum chamber. The filler wire is fed into the zone of electron beam effect, where it is heated and melted. The EBG and/or the substrate, on which a product is formed, are moving, forming a layer of deposited metal. The product is built by a digital model. The data of the CAD-program are converted into the CNC code. A part is layer-by-layer formed: each subsequent layer of metal is deposited on the previous one, i.e.layer-by-layer, until the product reaches the preset shape. After that, it undergoes heat and mechanical treatment.

The efficiency of electron beam melting according to DM technology varies from 3 to 9 kg of metal per hour depending on the material selected and the characteristics of a product, which makes it the fastest process of additive manufacturing [6].

The dimensions of products can vary from millimeters to several meters and are limited only by the dimensions of vacuum chamber. The DM technology allows manufacturing high-quality large-sized metal structures with more than 5 m length.

The process of electron beam melting is performed at the vacuum of less than $1\cdot10^{-4}$ torr, which allows working efficiently with chemically active metals like titanium, aluminium and their alloys, metals of refrac-

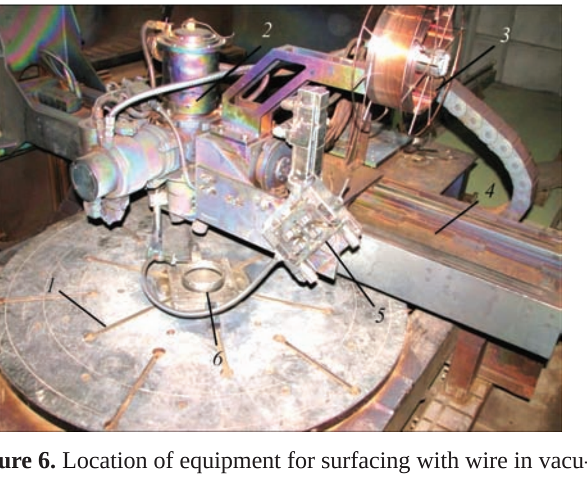

Figure 6. Location of equipment for surfacing with wire in vacuum chamber (description *1–6* see in the text)

Figure 7. Specimens manufactured according to DM technology

tory and other alloys, widely applied at the aerospace and turbine construction enterprises. The structure of products manufactured according to the DM technology is cast and defect-free.

The efficiency factor of installations for electron beam melting reaches 95 %, and the amount of wastes during machining of a final product is negligible. All this allows confirming the high efficiency and environmental cleanliness of DM additive manufacturing.

The possibility of applying filler wires of titanium alloy VT1-0, aluminium alloy ER 4043, steel welding wire Sv-08G2S and stainless steel wire ER 308 was studied.

On the base of the equipment of type KL-209 for electron beam welding, the laboratory installation for realization of DM additive process was designed. In the vacuum chamber of the installation (Figure 6) such units are located: EBG *2* of type ELA-60; multicoordinate module for movement of EBG *4*; mechanism for filler wire feeding *5* with coil *3* and rotator *1*. On the rotator the product *6* is located, manufactured according to the DM technology.

In the laboratory equipment, a satisfactory formation of round and rectangular specimens was obtained, from which it is possible to compose complex geometric shapes in the form of combination of bodies of revolution and rectangles. The wall thickness of specimens varied from 6 to 10 mm in use of four types of wires (Figure 7).

The cross-sections of all the deposited specimens are formed as a cast metal without inclusions and porosity.

As a result of carried out works, the possibility of manufacturing products of a preset shape was shown applying the methods of additive electron beam melting using domestic raw materials, which allowed proceeding with the development and manufacture of an pilot installation for realizing 3D technologies in industry.

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