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ADDITIVE ELECTRON BEAM EQUIPMENT FOR LAYER-BY-LAYER MANUFACTURE OF METAL PRODUCTS FROM POWDER MATERIALS

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On the basis of small-sized equipment SV-212M for electron beam welding, a mock-up of additive technological equipment was created to reproduce the process of manufacturing parts according to set shape and properties, applying the method of layer-by-layer surfacing with the use of metal powder materials. A hardware and software platform for the control of equipment was developed, which was integrated into additive technological equipment. The platform consists of hardware controller, which was developed on the basis of the industrial controller cRIO-9039 produced by the National Instruments Company (USA) and software for 3D-printing. On the created equipment, a test specimen of the product of a set shape with the following geometric dimensions: outer diameter — 85 mm, inner diameter — 55 mm, height — 35 mm was produced. For manufacturing, the powder of VT-20 titanium of the domestic Ti-Technology Company was used. Metallographic examinations of the specimen were carried out. It was established that the surfacing structure in the body of crystallites mainly has a branchy α′-phase and a small amount of (β-phase, which is characteristic of cast titanium alloy VT-20. The grain boundaries are pure, without inclusions. Parts of the specimen are without pores, which evidences about a complete penetration of the powder layer in the process of 3D-printing. The hardness of the metal in all the areas is not significantly different and is in the range from *HV* 3960 to *HV* 4150 MPa. According to the results of investigations the conclusions were made. 10 Ref., 1 Table, 13 Figures.

Keywords: *additive technologies, electron beam, surfacing, metal powder, titanium alloy, control platform, metallography, investigations*

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

The process of manufacturing products applying this method with the use of the electron beam is relatively new, but it has already successfully demonstrated the great prospects of its application in the industry for the production of a wide range of parts and units. It is based on the operation of layer-by-layer fusion of a metal powder in vacuum by an electron beam. This approach is distinguished by a rapid transition to the production of three-dimensional products directly from the system of automated design with the possibility of using a wide range of metals and alloys, including refractory and chemically active ones [1].

All the existing industrial specimens of similar equipment are owned by foreign companies. There is no domestic equipment of serial production [2].

From the very beginning, the technologies and equipment created by the E.O. Paton Electric Welding Institute of the NAS of Ukraine (PWI) [3] are oriented on the needs of Ukrainian enterprises. For manufacturing the user is supposed to apply necessary domestic inexpensive raw materials. Such an approach allows providing the manufacture of parts and units based on the needs of a customer and staying in close contact with him. The developed technologies will provide shortening of terms for introduction of new types of products into manufacturing, expanding their assortment and also creating principally new types of products with preliminary predicted properties, the production of which is impossible without using the methods of 3D-printing [4].

The aim of the work is the creation of the equipment for additive manufacturing of parts of a preset shape and the structure using the method of layer-by-layer electron beam surfacing of metals in vacuum with the use of powder materials.

For this purpose it is necessary:

● to develop the design documentation of the main units of additive equipment and manufacture the experimental laboratory equipment;

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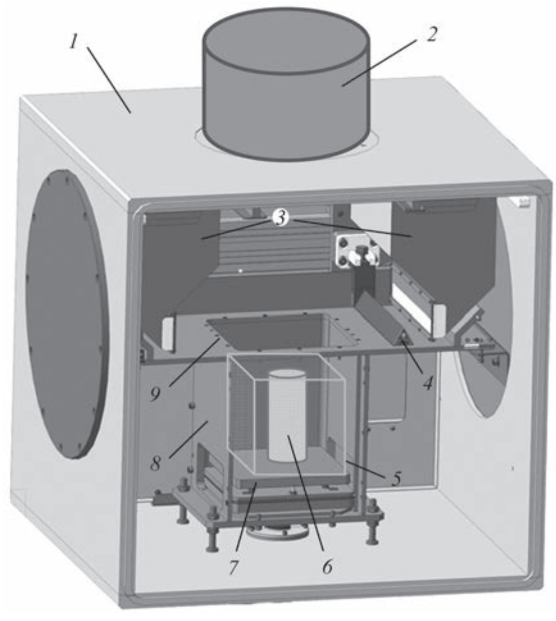

Figure 1. Scheme of equipment for additive production using metallic powder materials (see description *1*−*9* in the text)

● to develop software for investigations;

● to develop additive electron beam technologies and also investigate the properties of multilayer deposited metal;

● to create industrial model of equipment in the set with the software.

The urgent task is to develop installations based on electron beam processes using domestic powder materials, which will be certified and oriented for introduction at domestic enterprises [5].

A significant interest to the developed technologies is in the aerospace industry, power engineering, defense industry, as well as in the enterprises manufacturing products of biomedical purpose. In recent years, there has been a noticeable tendency for the introduction of additive technologies in the leading domestic companies of the aerospace industry and turbine construction: SE «Yuzhoye Design Office», JSC «Motor Sich» and SE «Zorya»−«Mashproekt» [6].

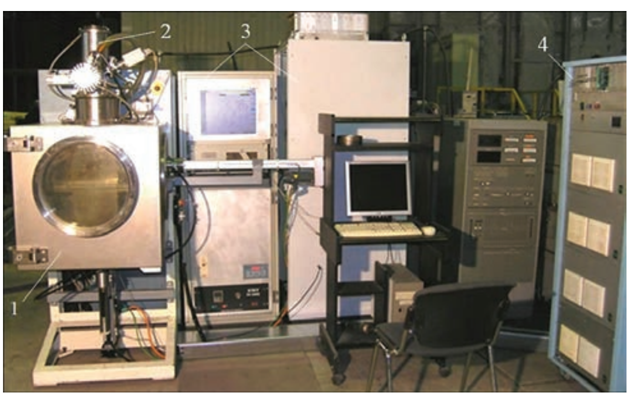

Figure 2. Equipment for electron beam 3D-printing (see description 1−4 in the text)

Equipment. To solve the specified problems, the investigations were carried out using the equipment for 3D-printing, which was created on the basis of small-sized equipment for electron beam welding of type SV-212M [7]. The equipment was used as a part of the pulsed power source of 60kV/60kW and the electron beam gun ELA-60. The equipment was developed at the PWI.

Principle of operation. The process of electron beam surfacing occurs in the vacuum chamber *1* (Figure 1). The metal powder is supplied in a bulk to the worktable *9* from the hoppers *3*. The rail *4* moves along the table *9* and on the surface of the pallet *7* it forms a layer of powder of a set thickness. In the starting position the platform stays at the top of the mine *8*. A focused electron beam formed by the electron beam gun *2* melts the powder surface along a set trajectory. Thus, according to the algorithm, the contour of the product and its layer are formed. Then, the platform *7* is lowered and the next layer of powder is deposited. The process is repeated. The product *6* is grown layer by layer. At the end of the manufacturing cycle, the workpiece should be removed from the vacuum chamber, cleaned from the nonmolten powder *5* and machined [8].

The general view of the laboratory equipment for 3D-printing is given in Figure 2.

The equipment consists of a small-sized vacuum chamber *1* with the mechanisms for moving along the vertical as well as mechanisms for supplying and distribution of the powder in the horizontal plane. The equipment includes electron beam gun *2* and high-voltage power source *4*. The electron beam gun is located on the top of the vacuum chamber. The vacuum system provides a value of vacuum of up to 10^{-4} Torr in the chamber. The elements of the equipment control system are located in cabinets *3*, where industrial computer, process controller, monitor, units for control of high-voltage source and vacuum system are located. A high-voltage source allows obtaining a regulated voltage of up to 60 kV and a beam current of electrons of up to 1000 mA [9].

The photo of the vacuum chamber is shown in Figure 3, and of the high-voltage source is in Figure 4.

Control system. Figure 5 presents a block diagram of the system of equipment control for 3D-printing.

The formation and preliminary treatment of the product model take place in a top-level computer that interacts with the MCP controller through Ethernet.

The MCP controller is created on the platform of the industrial controller cRIO-9039 with a preliminary installed peripheral modules.

To the MCP controller the following components are connected:

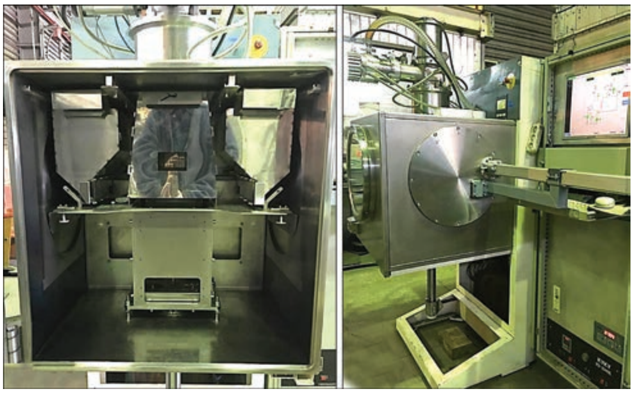

Figure 3. Vacuum chamber of additive equipment

- high-voltage source of 60 kV/60kW;
- electric drive of the movement system Siemens Sinamics S120;
- amplifiers of scanning and dynamic focusing.

MCP generates analog signals for controlling the electron beam scanning along the axis *X*/*Y*, the signals to control focusing — static and dynamic, and a signal for the electron beam current control. The scanning signals are supplied to the power amplifiers which control the current in the deflection coils of the electron beam gun (EBG). The signal of dynamic focusing I_{fd} is supplied to the power amplifier that controls the current in the coil for dynamic focusing of EBG. MCP also generates the analog signals for controlling the electron beam current I_w and the static focusing current I_f. These signals form quick-response modules of analog outputs NI-9263. The signals are supplied to the Normalizer converter, which is located in the crate of the high-voltage source. The converter converts analog signals into digital code according to the CAN bus protocol.

MCP controls the drives of the 3D printer: the drive of the mechanism for moving the platform along the vertical and the mechanism of distribution of metal powder in the horizontal plane. Through the Profibus bus the control signal from the MCP is supplied to the frequency converters Siemens Sinamics S120, which control the electric motors Siemens Simotics 1FK7 for the movement system.

The MCP interacts with the industrial computer that operates under the control of the operating system Windows 10 through the Ethernet network. Through the CAN bus the computer controls the high-voltage source of the 3D printer.

Software and hardware platform. In order to control the equipment and realization of the processes of additive manufacturing, the software and hardware platform was developed, consisting of the process controller-the hardware part and the package of application software.

The hardware part consists of:

Figure 4. High-voltage source with control cabinet

- MCP process controller.

The software consists of:

- Magics — the program for editing files of a model product;
- BuildProcessor — the program for geometric construction of a part on the platform;

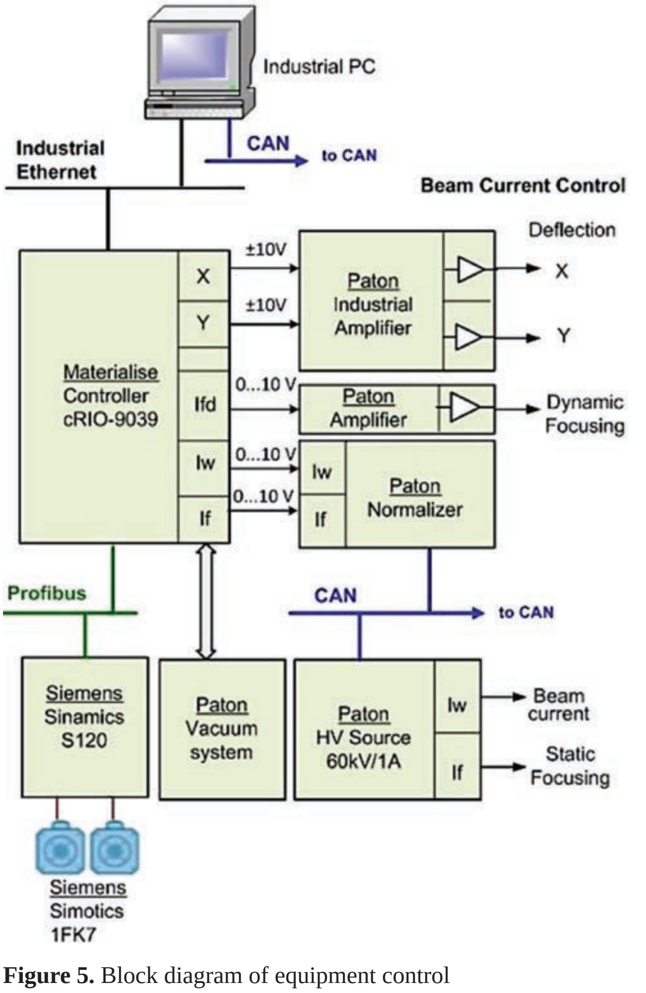

Figure 5. Block diagram of equipment control

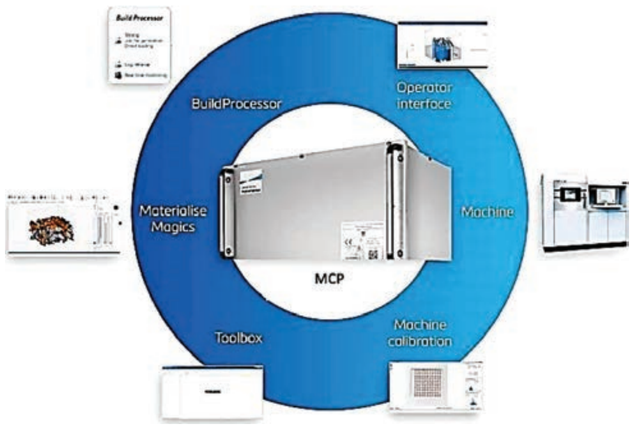

Figure 6. Structure of control platform

Figure 7. Interface of MCP controller

• Operator interface — the human-machine interface;

• Toolbox — the tool for adjustment of the process controller.

The structure of the control platform and the state of interactions between its components are presented in Figure 6.

The function of the Machine calibration is realized in the program Toolbox.

Peripheral modules of MCP controller

Type	Description
CS-PBMC	Profibus bus module
NI-9263	4-channel module of analog outputs, ±10 V
NI-9401	8-channel module of quick-response TTL outputs
NI-9425	32-channel module of discrete inputs, 24 VDC
NI-9477	32-channel module of discrete outputs
NI-9205	32-channel module of analog inputs, ±10 V

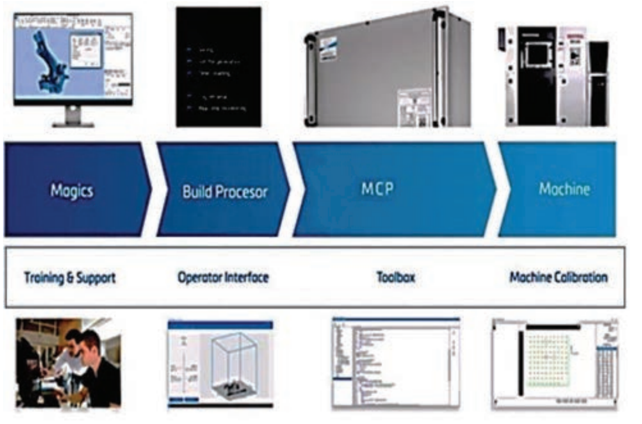

Figure 8. Interconnection between structural elements of control platform

The MCP controller is required to control the additive process equipment. The controller was developed by the experts of PWI together with the Company Materialise (Belgium) on the platform of the industrial controller cRIO-9039 produced by National Instruments (USA) (Figure 7).

The controller is equipped with peripheral modules (Table).

Software. The interconnection between the structural elements of the control platform is shown in Figure 8.

3D models of the product were created and edited using the program Magics. For this purposes any other software of the type CAD, such as NX Program of Siemens Company is also may be used.

Figure 9 provides the interface of the program Magics, where the model of a product is located — rotor blade of the gas turbine engine and technological supports are formed, which in the process of printing allow maintaining the shape of a part and reducing thermal contact with the platform.

The computer model of a product, which is prepared for printing, is further processed by the program BuildProcessor. This program allows creating assemblies of different parts on the equipment platform, de-

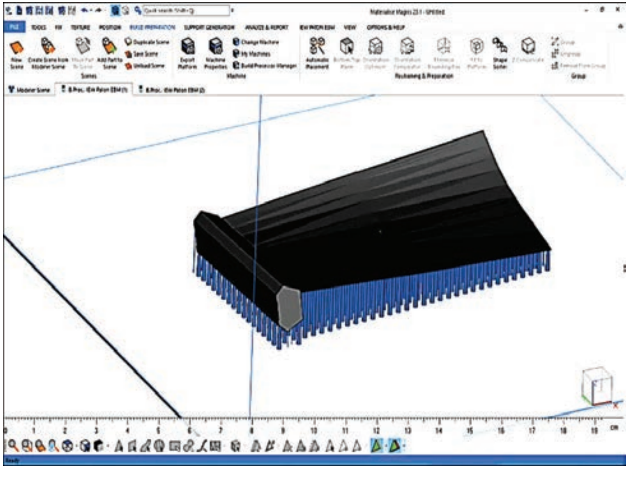

Figure 9. Interface of Magics program

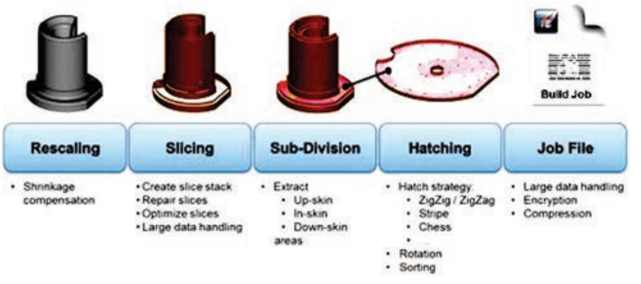

Figure 10. Functions of BuildProcessor program

composing models into layers, setting parameters and structure of forming each of the layers, determining the electron beam power, the speed of its movement and the diameter of the electron beam. The program allows choosing the material of a product and the variants of a texture to fill the layers during printing.

BuildProcessor forms an executive job-file, which is supplied to the MCP controller. Using job-file, MCP controls the process of 3D-printing.

The functions of BuildProcessor and the sequence of technological operations are presented in Figure 10.

The process of 3D-printing is controlled by the Operator interface program. In this program the technological parameters of the equipment are set and also the process of printing is monitored and displayed in real time. The program allows selecting a file of a model product, determining the time of beginning and end of the manufacturing process and its stage. The program has a three-dimensional print visualization. The appearance of the interface of the Operator interface program is shown in Figure 11.

The adjustment of the process controller and calibration of the 3D printer is performed by using the Toolbox program.

The PLC program was created to control the high-voltage source. This program allows controlling the voltage of high-voltage source, electron beam current, current and voltage of cathode bombardment, focusing current and also controlling these parameters.

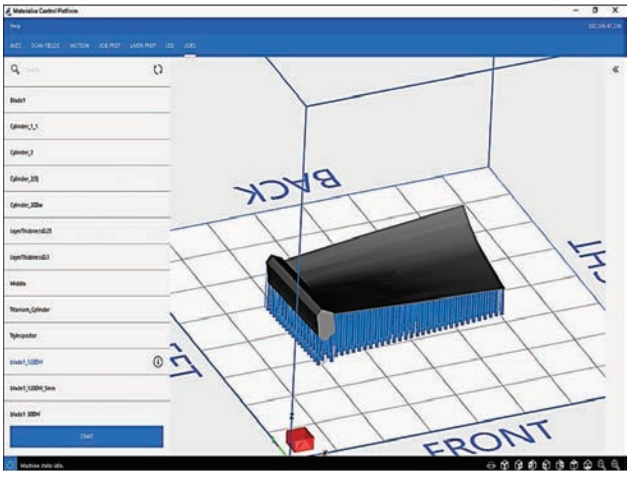

Figure 11. Operator interface program

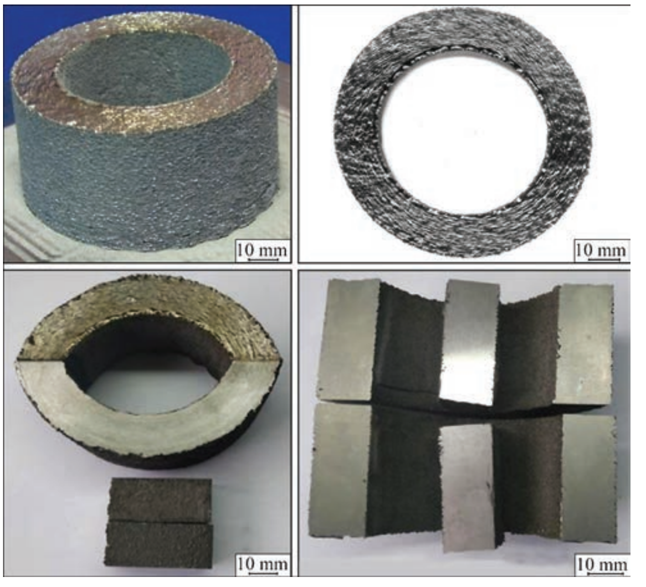

Figure 12. Specimen of product

The program has a function of monitoring and recording the current state of the high-voltage source in time.

Specimens of products. In the created equipment, an experimental product of a set shape (Figure 12) was produced with the following geometric dimensions: outer diameter — 85 mm, inner diameter — 55 mm, height — 35 mm. A photo of the printed product located on the platform in the vacuum chamber of the equipment is shown in Figure 13.

The parts were manufactured from the powder of titanium VT-20 produced by the domestic Ti Technology Company. The powder is an alloy of the Ti–Mo–Al–V–Zr system with granules of a nonspherical shape and a cast microstructure of particles. The choice of the alloy of this alloying system was predetermined by the fact that it is characterized by excellent anticorrosive, heat-resistant and mechanical properties. The alloy VT-20 is used for manufacturing parts of aircraft purpose, that are capable of operating for a long time at a temperatures of up to 500 °C [5].

The produced specimen was prepared for further metallographic examinations of the peculiarities of

Figure 13. Specimen of printed product

forming the structure of a product along and across the surfacing axis [10].

The carried out tests showed that the surfacing structure in the body of crystallites mainly has a branched α′-phase (supersaturated solid substitutional solution of alloying elements in α-titanium) and a small amount of β-phase. This is characteristic of the cast titanium alloy VT-20. The grain boundaries are clean, without inclusions.

The produced parts of the specimen are nonporous, which indicates a complete penetration of the powder layer in the process of 3D-printing.

The hardness of the metal in all the areas was not significantly different and ranged from *HV* 3960 to *HV* 4150 MPa.

Conclusions

As a result of the research and development works, the following was created:

- additive laboratory electron beam equipment;
- software and hardware platform for control of additive equipment;
- elements of additive electron beam technology of manufacturing metal parts applying layer-by-layer method with the use of powder materials;
- products of a set shape and with predicted properties which are manufactured according to the additive technology.

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