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ELECTRON BEAM TECHNOLOGIES OF WELDING, SURFACING, PROTOTYPING: RESULTS AND PROSPECTS

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For many decades the E.O. Paton Electric Welding Institute of the NAS of Ukraine has been specializing in the development of technology and equipment for electron beam welding of modern structural alloys. The electron beam equipment developed at the Institute allows solving problems of joining the elements of complex structures of different branches of industry. The examples and technical capabilities of the installations, mostly demanded by industry, are shown. A number of products are given, in the production of which both equipment and new technological processes were successfully applied, which include restoration repair of parts of gas turbine engines and the technologies of layer-by-layer manufacturing of products using the method of rapid prototyping.

Keywords: *electron beam welding, equipment, repair, 3D technologies*

For many decades the E.O. Paton Electric Welding Institute of the NAS of Ukraine has been specializing in the development of technology and equipment for electron beam welding of modern structural alloys. A new generation of electron beam equipment, developed at the Institute, allows solving problems of joining elements of complex structures of the aerospace industry, which occupy a leading place in the use of light and strength alloys of nonferrous metals.

The study of physical processes of melting metals in vacuum began at the Institute in 1958, when, by the initiative of the academician B.E. Paton, the first installation for electron beam welding (EBW) was created. Already within a year, the results of the E.O. Paton Electric Welding Institute turned out to be in demand by the industry and, first of all, in the production of jet engines. With the growth in the number of tasks put forward by the industry and their complexity, installations with different volumes of vacuum chambers, control systems, powerful high-voltage power sources and welding guns were required.

Today, at the E.O Paton Electric Welding Institute the installations are designing and manufacturing for EBW of all sorts of products of different industry branches. All these installations can be conditionally divided into several types according to the dimensions of welding chambers, and, accordingly, to the sizes of parts to be welded: «small» with a volume of 0.26–5.70 m^3 (Figure 1), «medium» with a volume of 19–42 m^3 (Figure 2) and «large» with a volume of 80–100 m^3 (Figure 3). The Institute is designing and manufacturing the welding chambers of different sizes and appropriate configurations of the vacuum system, as well as configurations of the mechanism for moving the electron beam gun and a part welded for specific customer tasks, namely: the sizes and shape of welded assemblies, type and location of welded joints in the assembly. Moreover, in the latter case, except of the equipment itself, also a specific technology for welding such assemblies is being developed, i.e. the customer purchases a welding installation together with the technology for EBW of a specific list of products. The similar technical ideology is followed by well-known manufacturers of EBW equipment like Sciaky Inc. (USA), PTR Group (Germany) and Techmeta (France) [1].

Using the modern means of pumping-out, in the widely applied installations with a volume of vacuum chambers of 19–42 m^3, a working vacuum of $2\cdot10^4$ Torr is achieved for 18–20 min. If necessary, a complete set of a vacuum system is possible, providing a pressure of less than $5\cdot10^5$ Torr in a chamber for less than 20 min.

A typical mechanical configuration of the installation provides a movable intra-chamber electron beam welding gun fixed on a precision mechanism of the multi-axial movement. This mechanism provides a linear movement of the gun, controlled by CNC, along three Cartesian coordinate axes (along the chamber — X, across the chamber — Y and vertically — Z), as well as rotation of the gun at an angle of 0 — 90° in the Z–X plane (from vertical orientation of the gun to the horizontal one) [2].

The rotation of a part welded is usually provided by precision welding manipulators with horizontal and vertical axes of rotation. The greatest technolog-

Figure 1. Appearance of small-sized electron beam installation

ical flexibility is provided by welding manipulator with an inclined axis of rotation. It allows inclining the rotation axis of the faceplate in the range from 30° to +90° (from vertical), which provides electron beam welding of intricate concentric sections of aircraft engines or aircraft assemblies with a varying geometry (Figure 4).

Depending on the specific purpose (the material to be welded and its thickness), the considered installations are completed with the latest high-voltage inverter welding power sources of 15, 30, 60 and 120 kW operating at a fixed accelerating voltage of 60 and 120 kV [3]. The basis of the power part of the power sources is a high-voltage inverter power unit, for example, of a domestic company «Torsion» (Kharkov, Ukraine) or the companies Guth (Germany) and Technics (France). The welding source is designed in such a way that it represents actually a separate self-contained hardware complex, all interaction with which is carried out through the industrial interface (bus CAN). At the same time, the communication with the «outer world» is realized by the corresponding microcontroller units connected to the bus CAN and designed for control and diagnostics of all the welding source channels.

The welding source is quite compact in sizes and at a power of up to 30 kW it is usually located in one power cabinet (Figure 5). In the case of higher power, the welding source is divided into two parts and occupies two cabinets.

Together with a high-voltage welding power source, all the electron beam installations of the Institute are completed with the system of secondary emission electronic visualization RASTR-6, which is inseparably integrated into this source. Such integration is predetermined by the fact that the functioning of this system itself is directly associated with the formation of a beam of electrons irradiating the product observed. The block diagram of the classical system «RASTR-6» is shown in Figure 6 [4].

Figure 2. Appearance of medium-sized installation with a mobile intra-chamber welding gun and wheel-out working table

Approximately 3 times per second after a special command pulse, the units for setting and amplifying of the system RASTR-6 form, respectively, for a short period of time the line and frame signals of the raster scanning, supplied to the welding gun deflecting coil. Then, based on the modulation signal generated by the system RASTR 6, the microcontroller of the welding current channel of the welding power source, acting according to a special algorithm, switches off the momentary welding current and forms a short-term low-power current pulse. As a result of this interaction between the two subsystems of the installation (its welding power source and the system RASTR6), the front surface of a part welded is irradiated by a formed electronic raster. By passing along the lines of the raster of the «probing» electron beam at the point of spot bombardment of the part surface by its electrons («primary»), the secondary electrons are emitted. The power of the electron beam is chosen as sufficient in the given specific conditions, for example, depending on the distance of the welding gun to the part for the formation of the required level of such secondary-emission radiation. This short-term pulse of secondary electrons is picked up by a special passive sensor (Figure 7, *a*), usually located at the end of the welding gun, and which can have a different

Figure 3. Electron beam installation with a vacuum chamber of 100 m^3

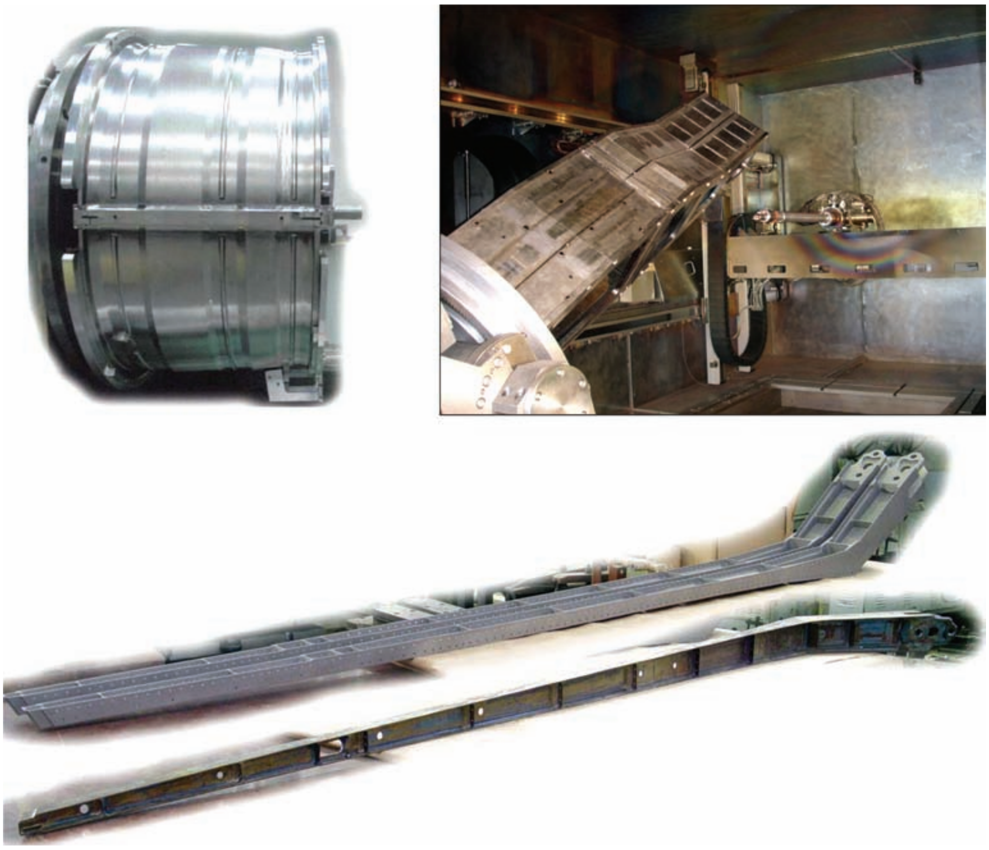

Figure 4. Examples of aircraft assemblies with intricate geometry, manufactured by EBW in the installations of medium and large overall dimensions

design performance. In the direct vicinity from this sensor a compact unit of the preliminary amplifier is located, which forms and amplifies a useful signal, the voltage of which is proportional to the current signal taken from the sensor. This already amplified signal is withdrawn from the welding chamber along the screened coaxial line and is supplied to the main video amplifier of the system. As a result, the signal is digitized by a specialized computer board WLCA and issued to the operator interface in the form of an image (Figure 7, *b*), used both for the visual observation and manual guidance to the butt welded, as well as for the operation of special software algorithms, which help the user (welding operator) in making new welding programs and reproduction of existing programs for welding of repetitive standard parts. The system allows forming a fairly stable image of the welding zone, both before and after welding, as well as directly during welding.

Figure 5. Appearance of inverter high-voltage power source

The installations for EBW, designed and manufactured by our Institute, have a modern control system. The part of the equipment, on which the welding process directly depends, is under the continuous program control.

Here the concept of high-level program control is used, in which the user interacts with the equipment exclusively through a Windows-based graphical user interface (GUI). The interface is operated using standard tools: a keyboard and a mouse-type manipulator. The interface is self-explanatory and does not require special skills, as in the «low-level» machine programming. Each of the subsystems of the installation is served by a corresponding window graphic toolset

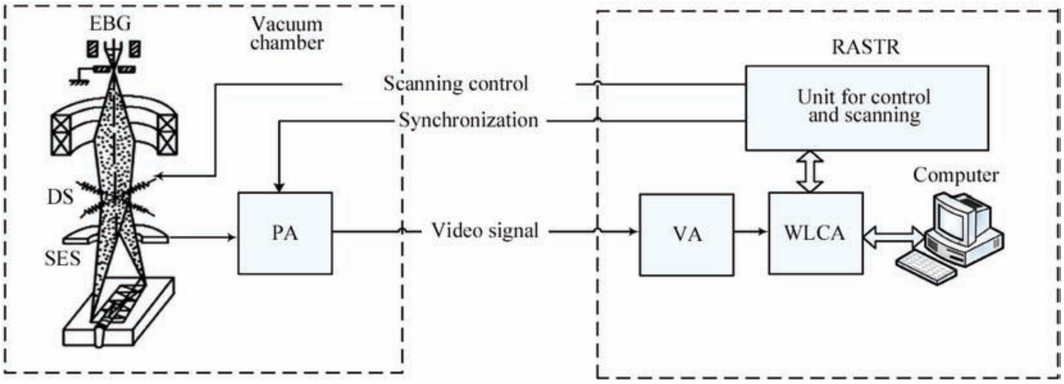

Figure 6. Block diagram of the classical system RASTR-6, where: EBG is the electron beam (welding) gun; DS is the deflecting system of the gun; SES is the secondary electron sensor; PA is the preliminary amplifier; VA is the video amplifier; WLCA is the specialized computerized visualization board

with input data checking and blocks to provide the safety of the user and equipment.

Hierarchically, the control system is divided into two software/hardware levels: upper and lower. The upper level includes all means of communication with the user, including graphical interface, means of creating and storage of welding programs, acquisition and storage of diagnostic data, administration, etc. The lower level deals with the direct performance of all the procedures set by the commands from the upper level.

Currently, we are using two basic configurations of the EBW software system for installations control. The first one involves the use of full industrial system Sinumeric 840D of Siemens Company, and the second one — the «shortened» industrial system Synamics S120 of the same Company.

In case of using the system Sinumeric 840, the main program is installed in the standard industrial computer of the upper level Sinumerik PCU-50. The upper level directly interacts with the elements of the lower level: the machine control panel MCP, the main module NCU and the connecting module Basic PN, to which the control panel of manual movement of the gun or a part is connected.

In addition, the upper level interacts with the computer system RASTR. As a result, the upper level program (in PCU-50) can display the secondary emission image of the surface of a part welded, formed by the system RASTR.

The welding movement is under the full control of the CNC in both manual mode of displacement, as well as in automatic welding. In the latter case, the text script of the prepared welding program is transmitted from the upper level to NCU, where CNC calculates the trajectories, interpolations, velocities and accelerations by each of the participating axes using its own algorithms. In automatic welding, CNC provides a complete synchronization of all axes, both mechanical and virtual, which use channels of welding and focusing currents, as well as technological scanning of the electron beam.

The use of means of numerical program control for the technological process of EBW allowed solving the complex problems of joining different critical-purpose structures. The existing possibilities of precision control of the trajectory of the electron beam movement during welding due to its mechanical movement or its electromagnetic deviation, as well as the ability to control the power of the electron beam and the shape of distribution of this power in space led to a significant expansion of technological capabilities of EBW and to a dramatic improvement in repeatability of the process of welding of the serial parts in the preliminary programmed welding mode. Below (Figures 8, 9) the examples of implementation of the developed control system during EBW of intricate products are given.

In our installations, the restoration repair of expensive parts of gas turbine engines is successfully performed [5].

Thus, during operation of aircraft gas turbine engines, one of the main causes for their early replacement is the damage of titanium fan blades and compressor as a result of foreign objects entering the engine. Usually, at negligible defects of the input and output edges of the blade airfoil without tears, the op-

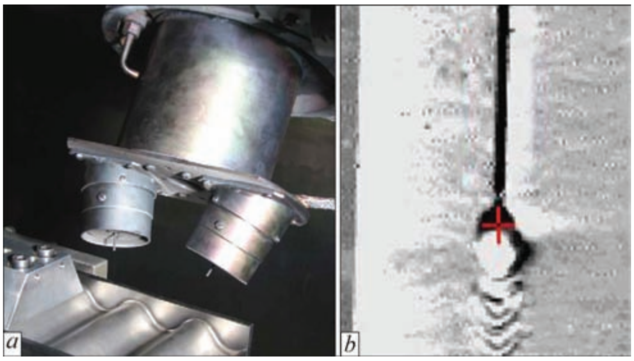

Figure 7. Secondary electron sensor of the system RASTR-6 (*a*) and the image formed by it in the welding zone (*b*)

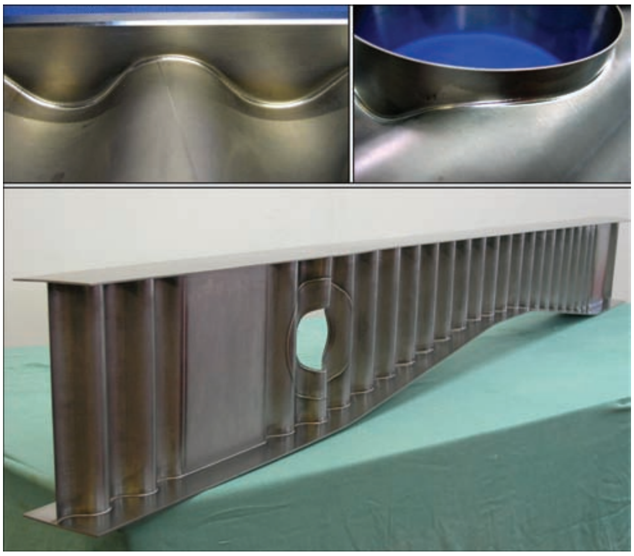

Figure 8. Appearance of welded thin-sheet aircraft structures of titanium alloys

eration of engine is admitted. A part of the defects are admitted to be repaired directly on the engine. So, for example, raised edges of the material near the nicks are dressed, the bends of the blades are eliminated by straightening. The corrected places are then polished. Sometimes it is allowed to eliminate the nicks by smooth rounding of the edge with a radius of 10–12 mm. The correction of local damages of the blades exceeding the admissible norms, already requires dismantling of the damaged blade and repair in the production conditions. Usually, the repair consists in mechanical removing of the defect area up to the borders of the deliberately undamaged metal of the blade with the following attachment (welding, brazing) of an insert of the same metal of the appropriate size and with a technological tolerance in thickness to obtain a required blade profile by the subsequent machining. In order to realize the repair technology using electron beam welding, a scheme of a welded joint of a repair insert and a blade airfoil was developed, regardless of whether it is a spot or extensive defect. The joint is produced by a single-pass EBW, and a smooth transition from the surface of the insert to the base metal is provided both by a moderate concentration of the electron beam and also by a sufficient amount of additional metal due to the applied design of welded joint with an overhanging flange. This allows obtaining a smooth transition of metal from the insert to the surfaces of the blade airfoil, both in the places with a sufficiently large thickness of the airfoil, as well as in the thinnest places adjacent to the very edge of the airfoil.

Figure 9. Appearance of welded thick-sheet aircraft structures of high-strength aluminum alloys

Figure 10. Examples of fan blades, repaired by electron beam

The technology of repairing three types of blade airfoil defects was mastered: «spot» damage to the blade angle, «spot» damage of the edge of the main part of the blade airfoil and extended local defects of the edge starting from the blade angle.

The repair of both types of «spot» defects is carried out using cylindrical inserts of different diameters, depending on the size of the airfoil edge defect. The works initially were carried out on the specimens, simulating the real products. Then, the technology was successfully tested on the experimental batches of defective blades given to the SE LRZ «Motor» and the SE «Ivchenko-Progress» (Figures 10, 11).

In addition to repairing of local defects of blades, an equally important task is to replace the separate elements of the permanently assembled components of the gas turbine engine. The guiding devices from the 3rd to the 8th stage of stator of the high-pressure compressor of a gas turbine engine are composed of semi-rings with a set of cantilever blades brazed

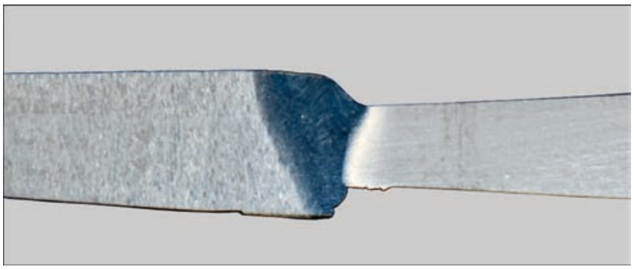

Figure 11. General view of welded joint of the blade repair shop bay

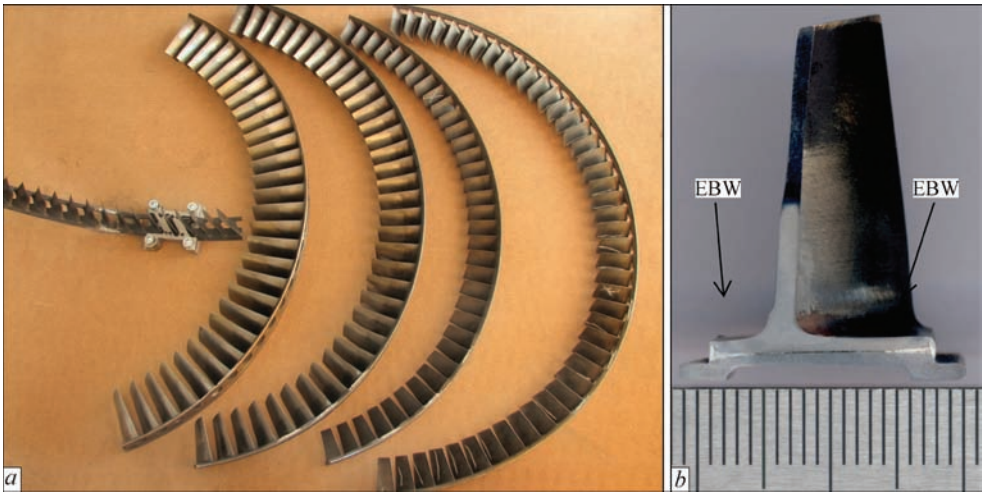

Figure 12. Scheme of assembly of the blade-donor with a semi-ring (*a*) and the macrosection of the joint (*b*) of the high-pressure compressor stator guiding device

into them. The blades from the 3rd to the 6th stage are made of the alloy EP-866 (15Kh16K5N2MFAB-sh), and the blades of the 7th, 8th stages are made of the alloy EP-718-ID (KhN45MVTYuBR-ID); the working temperature of the assemblies is 300–500 °C.

During operation of such engines, there are also cases of arising nicks and cracks on the blades, as well as their tearing off because of a local lack of brazing with the semi-ring wall. For this case, the following scheme of repair is proposed. A defective blade is removed by milling from the semi-ring till the very wall, including the whole brazing alloy, maintaining the blade earlier, and on its place an undamaged blade-donor is selected. In other words, in the semi-ring a fully cleaned platform is made for mounting the blade-donor. It is obvious that it is impossible to repeat the initial brazing process without touching the adjacent, still serviceable blades. Therefore, a method of fixing with a local and concentrated temperature effect on the entire assembled unit is required.

The EBW method is ideally suited in this case, providing a reliable welded joint of sufficient depth with a relatively small heat input into the product welded.

A scheme of the welded joint of a blade-donor with a wall of a semi-ring of a guiding device was developed. The joining of the blade with the wall is produced by a double-sided EBW with an intermediate turnover of the product by 180°. The design strength of two similar welds is sufficient for reliable fixation of the blade, not inferior to the adjacent, brazed ones.

To improve the weld formation and reduce the total heat input, the EBW pulsed mode was used, which allowed producing high-quality joints of parts with local gaps in the joint of up to 0.1 mm. Then the selected EBW modes were corrected already on the real joints of blades with the semi-ring of the guiding device. Figure 12 shows the scheme of assembly of a blade-donor with a semi-ring and macrosection of the produced joints.

The technology was successfully tested in the repair of a batch of real semi-rings of guiding devices of different stator stages of a high-pressure compressor.

The electron beam equipment and technologies developed at the Institute open up new opportunities for the rapid prototyping of parts of the specified shape and structure with preliminary predicted properties [6].

The developed technologies and equipment were initially focused on the needs of domestic enterprises. For the production it was proposed to use low-cost domestic raw materials required by the manufacturer. This approach will provide the feasibility of manufacturing parts and assemblies by rapid prototyping, coming from the needs of the consumer and in close contact with him. The developed technologies will reduce the time of implementation of new types of products, expand their range, as well as create fundamentally new types of products with preliminary predicted properties, the manufacture of which is impossible without applying 3D-printing methods.

Since installations for 3D-printing of domestic development do not exist yet, the project was started at the Institute for creating the equipment and software for realization of additive electron beam manufacturing, which is unique to Ukraine, free from imported raw materials and focused on the implementation at the aerospace and turbine-building enterprises like SE NPKG «Zorya-Mashproekt», LRZ «Motor», JSC «Motor Sich» and SE KB «Yuzhnoye» [7].

The equipment is created on the basis of the installation for electron beam welding of type SV-212M. It involves modernization of vacuum chamber, development of systems of control of drives for moving the table in vertical and the unit for powder distribution in

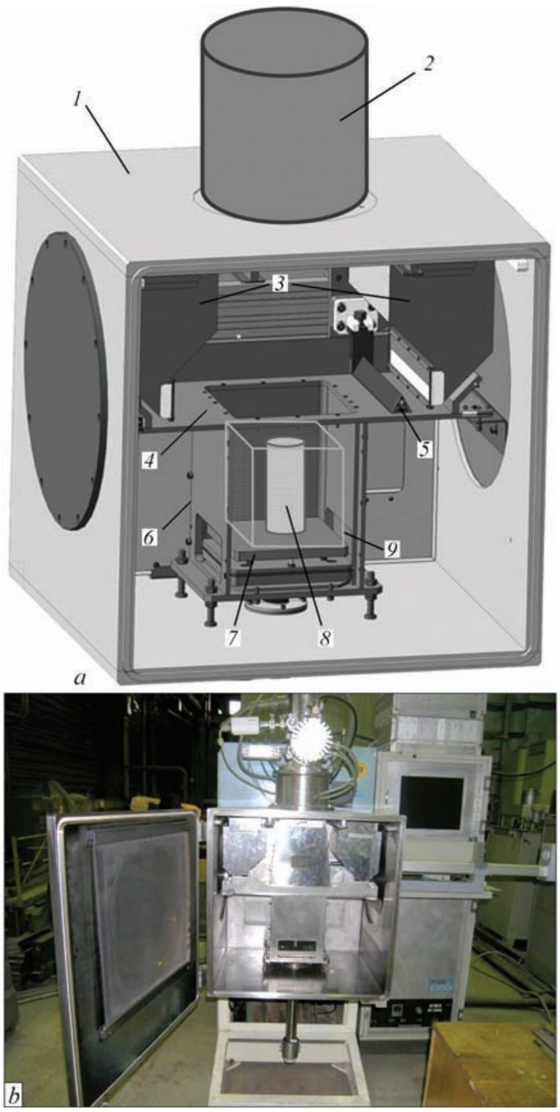

Figure 13. Scheme (*a*) and industrial model (*b*) of installation for additive manufacturing using metallic powder materials, where *1* — vacuum chamber; *2* — electron beam gun; *3* — hopper; *4* — table; *5* — rack; *6* — shaft; *7* — pallet; *8* — product; *9* – powder

the chamber, as well as the development of appropriate software for realizing the additive manufacturing.

The scheme of installation and its industrial model are presented in Figure 13. The process of electron beam surfacing takes place in a vacuum chamber *1* in vacuum of less than $1\cdot10^{-4}$ Torr. The metal powder is supplied in bulk to the working table *4* from hoppers *3*. The rack *5*, moving along the table *4*, forms the layer of powder of a preset thickness on the surface of the pallet *7*. In the initial position, the pallet is located at the top of the shaft *6*. The focused electron beam, formed by the electron beam gun *2* melts the surface of the powder along the preset trajectory. Thus, according to the algorithm, the contours of the product and its layer are formed. Further, the pallet *7* is lowered to the preset value and the next layer of powder is applied. The process is repeated and the product is layer-by-layer deposited. At the end of the manufacturing cycle the part is removed from the vacuum chamber, cleaned from nonmelted powder *9* and machined.

The technology of layer-by-layer electron beam fusion of metals in vacuum using powder materials allows creating dense metal products of a preset shape with a high geometric accuracy. The overall dimensions of the products are 250×250×250 mm, and the efficiency of electron beam surfacing according to EBM technology does not exceed 0.3 kg of metallic powder per hour.

The second investigated process of electron beam melting of metals is the process of melting metal wire in vacuum with the formation of successive layers (DM). To heat and melt the wire, an electron beam of the required power is used. The scheme of the DM process is shown in Figure 14.

The surfacing takes place in a vacuum chamber. The filler wire is fed into the zone of the electron beam action, where it is heated and melted. The electron beam gun and/or the substrate, on which the product is formed, are moved, forming a layer of deposited metal. The product is made by a digital model. The data of the CAD program are converted to the CNC code. The part is formed in layers: each subsequent layer of metal is deposited onto the previous one, and so it continues layer-by-layer until the product reaches the preset shape. Then, it is subjected to heat and mechanical treatment.

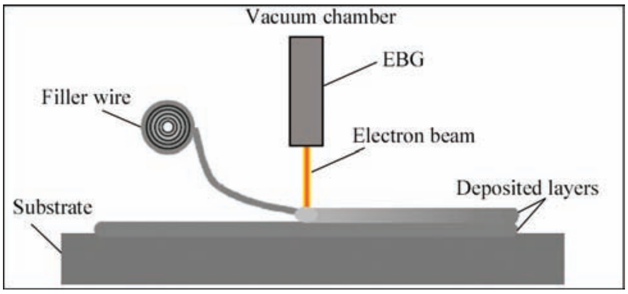

Figure 14. Scheme of layer-by-layer electron beam melting of filler wire

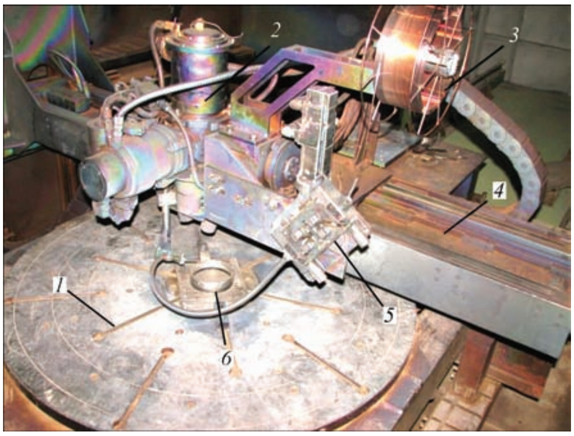

Figure 15. Arrangement of equipment for surfacing using wire in vacuum chamber

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

On the basis of equipment for electron beam welding of the type KL-209, a laboratory installation was created to implement the additive DM process. In the vacuum chamber of the installation (Figure 15) the following items are located: *2* — electron beam gun (EBG) of type ELA-60, *4* — multicoordinate module for EBG movement, mechanism for feeding filler wire *5* with coil *3*, rotator *1*. On the rotator a product *6* is located, produced by the DM technology.

In the laboratory equipment, a satisfactory formation of round and rectangular specimens was obtained, of which it is possible to form intricate geometric shapes in the form of a combination of rotation bodies and rectangles. The wall thickness of the specimens ranged from 6 to 10 mm using four types of wires.

Our Institute is in the process of continuous improvement of both the system for control of EBW equipment and the functionality of the developed equipment, taking into account the evolution of hardware and element base, as well as gained many years experience in the development of technology and equipment for EBW of various materials with different thicknesses.

In conclusion, it can be said that the above information on the manufacture of equipment for electron beam welding of assemblies and parts used in aircraft construction, according to the technologies developed at the E.O. The Paton Electric Welding Institute, as well as the installations themselves, have found application both in the domestic industry and abroad, and are the significant achievement of the Institute specialists.

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