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# NEW POSSIBILITIES OF ADDITIVE MANUFACTURING USING XBEAM 3D METAL PRINTING TECHNOLOGY (Review)*

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New technology called xBeam 3D Metal Printing was developed by PJSC SPA «Chervona Hvilya» to solve the most important engineering and economic problems of the currently available methods of additive manufacturing. It is based on application of shaped electron beam as the heat source and of wire as consumable material. The key element of the new engineering solution is a special low-voltage gas-discharge electron gun, with a guide built-in along its axis for consumable wire feeding. A unique hollow conical electron beam generated by such a gun, creates exceptional physical conditions for melting of consumable and its layer-by-layer deposition that not only provides the capabilities of precisely controlled and repeatable manufacturing of products, but also opens up the possibilities for development of new technologies and materials. At present xBeam 3D Metal Printing technology has successfully passed laboratory and practical trials in an experimental 3D-printer. 16 Ref., 13 Figures.

***Keywords:*** *electron beam, gas-discharge electron beam guns, additive manufacturing of metals, 3D metal printing*

Over the last decade additive manufacturing has become one of the most important directions of development of world industry. Additive technologies open up the possibilities of rapid and accurate manufacturing of products by the customer individual requirements, which is a long-standing dream of any manufacturer. Owing to this unique capability, additive manufacturing is even called the third industrial revolution, alongside robotization and information technologies [1–3].

Additive manufacturing is defined as a process of product manufacturing according to a 3D model by layer-by-layer joining of materials using CAD/CAM. Additive manufacturing technologies are also called industrial 3D printing, and equipment for their realization — 3D-printers [4–6].

Particularly important is additive manufacturing of products from metals, as metals still are the main industrial structural material [7].

A variety of additive manufacturing technologies have been developed so far, differing by:

- consumable: powder, wire or powder in a mixture with binder;
- heat source: laser, electron beam, plasma, electric arc, etc;
- method of layer forming: selective melting (sintering) of the prepared powder layer (powder bed); direct deposition of powder or wire on the previous layer (direct energy deposition) or injection molding (binder jetting) [4, 5, 8].

Despite continuous research and numerous experiments, however, additive manufacturing technologies, developed so far, still have a number of drawbacks, restraining their extensive implementation in industry. The main shortcomings of additive technologies developed to date are as follows [9, 10]:

- sophisticated and expensive equipment;
- expensive initial materials;
- limited dimensions of manufactured 3D products and low efficiency (for technologies with application of powder as initial material);
- thick walls and rough surface of manufactured 3D products (for technologies with application of wire as initial material);
- residual porosity, non-uniform structure, residual stresses and strains;
- need for additional operations;
- complex control requiring highly skilled staff.

All that eventually leads to high product cost that markedly restrains the really wide acceptance of additive technologies in the world industrial production [11].

Specialists of PJSC SPA «Chervona Hvilya» developed a new method of manufacturing 3D objects and a device for its implementation [12], in which the product is formed by layer-by-layer deposition of consumable on a base. The consumable is fed into the

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deposition zone, moved along the set trajectory, melted there by the electron beam and then it solidifies as it leaves the heating zone, forming the deposited material layer. The heat source in the above method and device is a gas-discharge electron beam gun with an annular cathode, directly generating the electron beam in the form of a hollow inverted cone.

The new technology called xBeam 3D Metal Printing, according to the generally accepted classification of different types of additive technologies, relates to direct energy deposition processes, where the focused thermal energy is used to melt materials at their deposition [4, 5].

In the opinion of both the developers and a number of experts in the field of additive manufacturing, xBeam 3D Metal Printing technology is capable of solving many engineering and technological problems of currently available additive technologies: primarily, eliminate the contradiction between the manufacturing accuracy and high productivity, and thus ensure a cardinal reduction of the cost of manufacturing 3D metal products.

Development of the new method is based on a unique ability of gas-discharge electron beam guns to generate shaped electron beams by direct emission from the cathode without application of additional deflecting and focusing devices [13]. Other characteristic capabilities of gas-discharge electron beam guns are also important for realization of the above technology and achievement of positive technological and economic effects. These features include the ability to operate stably in a broad range of residual pressures in the working chamber ($10^{-2}$–10 Pa), also at partial pressure of various gases, ability to generate and form the electron beam at relatively low accelerating voltage (from 5 kV), simple and compact design, convenient maintenance, long cathode life and flexible control of technological parameters.

The main distinctive features of the method and device underlying xBeam 3D Metal Printing technology are as follows:

- electron beam in the form of a hollow inverted cone, generated by a special gas-discharge electron beam gun, is used to form the melt pool on the substrate and to melt the consumable;
- consumable in the form of wire is fed through the guide precisely into the center of the melt pool on the substrate, coaxially with the above-mentioned conical electron beam;
- above-mentioned special gas-discharge electron beam gun and guide for feeding the consumable are combined into one common process module (Figure 1).

The above configuration of the electron beam, relative position of this beam and the fed consumable with respect to the substrate create several critically important physical and metallurgical conditions for deposition of molten material and formation of the deposited bead. This results in controllable formation of the next layer with certain geometrical parameters and required structure of the deposited material. The following technological features of xBeam 3D Metal Printing should be noted first of all.

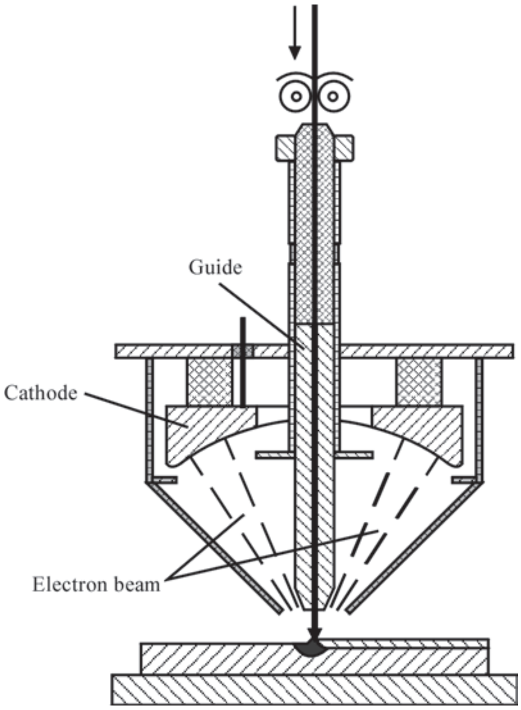

**Figure 1.** Schematic of a device for realization of xBeam 3D Metal Printing technology

Round shape of the melt pool and vertical feed of the consumable precisely into the melt pool center (Figure 2) ensure absence of shaded areas on the substrate (preventing porosity and lacks-of-fusion in the deposited layers), possibility of forming a bead of a width only slightly exceeding the consumable wire diameter (that allows manufacturing products with thin and precise walls), overall high efficiency of the process due to effective use of the total power applied to the deposition zone.

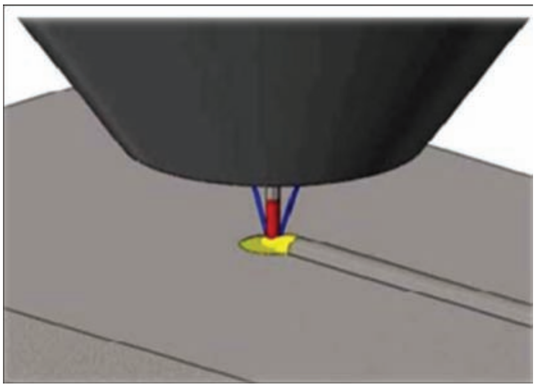

**Figure 2.** Schematic of the deposition process

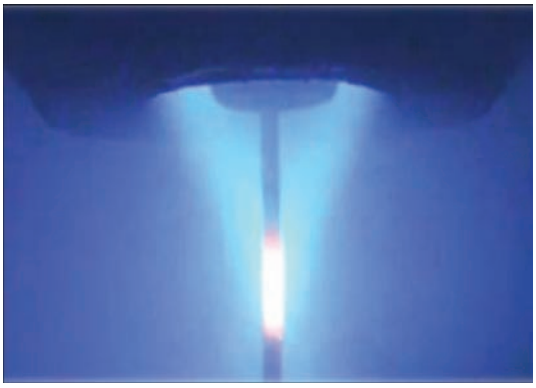

**Figure 3.** Impact of a hollow conical electron beam on consumable wire

Such an axisymmetric configuration of heat flows and mass transfer greatly simplifies mathematical modeling of the process that is very important for improvement of technological operations control to obtain the specified material properties [14].

The consumable is completely enclosed by precisely and flexibly controlled energy flow (Figure 3) that ensures its absolutely axisymmetric and uniform preheating and controlled melting. It is important to emphasize that the hollow beam configuration produced without scanning application, provides a really constantly uniform heating of both the wire and the substrate. Moreover, this property also opens up interesting possibilities in terms of technology, for instance use of complex consumable variants, such as flux-cored wire or bundle of several wires from different materials.

Continuous stationary mass transfer of liquid metal from the tip of melted consumable wire to the substrate is reliably contained by surface tension forces (Figure 4). As soon as liquid metal formed at the tip of fed wire touches liquid metal in the pool on the substrate, a bridge immediately forms between the wire tip and the substrate, which is contained by surface tension forces and along which the liquid metal smoothly and evenly flows onto the substrate, its speed being also influenced by the force of universal gravitation. The liquid metal, which has reached the substrate, immediately spreads within the boundaries of the melt pool existing at this moment of time, which is defined by the boundaries of the zone of electron beam impact on the substrate, due to complete adhesion between homogeneous liquids. As soon as liquid metal has reached solid metal on the substrate, it immediately solidifies. This is the way for realization of a reliable and at the same time flexible mechanism of forming a deposited bead of specified width and wall thickness of the manufactured 3D product, respectively.

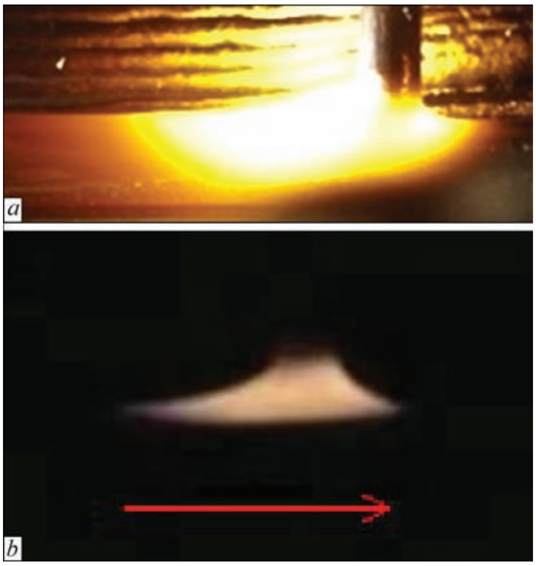

**Figure 4.** Liquid metal spreading from wire tip over the substrate: *a* — direct filming; *b* — filming through dark glass

It should be noted separately that the above property of continuous mass transfer of liquid metal from the wire tip to the substrate ensures the feasibility of xBeam 3D Metal Printing technology under the conditions of zero gravity, as the surface tension forces act there as they do on the Earth. The need for additive manufacturing of metal parts under zero gravity conditions on board the space vehicles, as well as in the missions to explore the Moon and Mars, is constantly emphasized in the plans of the respective organizations and companies, such as NASA, ESA, SpaceX and others [15, 16].

An extremely important property of xBeam 3D Metal Printing technology is significantly lower concentration of power of the heat source — the electron beam, generated by low-voltage gas-discharge electron beam gun, compared to heat sources of all the other currently known processes of additive manufacturing of metals. Developers of 3D-printers for metal usually apply devices (thermoionic electron beam guns, lasers, plasmatrons) developed for realization of welding processes, where the minimum possible focus (as a rule from tens up to hundreds of microns) and high power concentration (up to $10^5$–$10^7$ kW/mm$^2$) are important process parameters. In additive manufacturing excessive power concentration can lead to a too deep penetration of the previous layers, right up to formation of defects in the product. Therefore, highly concentrated power has to be distributed over the surface by high-frequency scanning that, firstly, is a complex engineering task, and, secondly, violates the continuity of the process of deposited layer formation.

Special gas-discharge electron beam gun developed for implementation of xBeam 3D Metal Printing technology generates the electron beam at low accelerating voltage of up to 20 kV that at up to 20 kW power level and minimum focus of about 1.5 mm

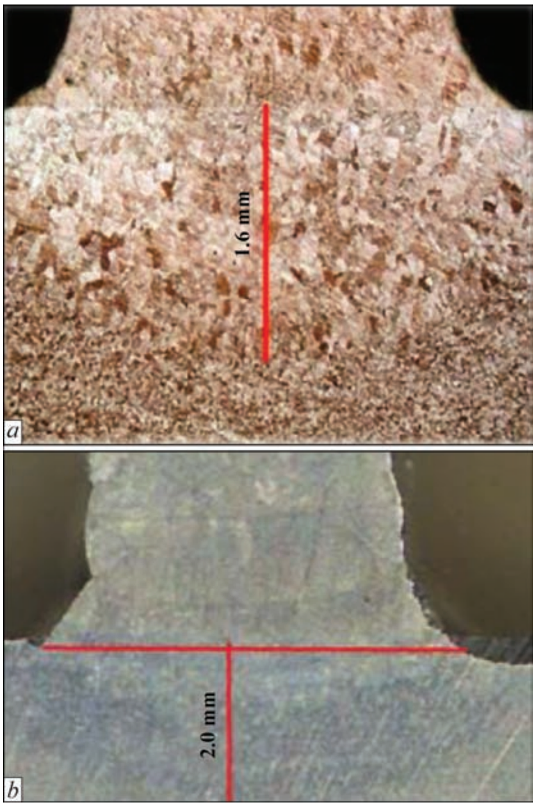

**Figure 5.** Macrosection of HAZ metal at wire deposition: *a* — 1.6 mm VT1-0 titanium wire on VT1-0 titanium plate; *b* — 3 mm Ti–6Al–4V titanium alloy wire on Ti–6Al–4V alloy plate

diameter provides a very soft and smooth heating of the processed surfaces without scanning application. Power concentration in electron beam focus does not exceed $10^3$ kW/cm$^2$.

Impact of such a beam on the surface allows forming a quite shallow melt pool on it, sufficient only for creation of the conditions for spreading of entering liquid metal within the liquid phase on the surface, and having a minimum impact on substrate material.

Maintaining a shallow melt pool on the substrate during deposition (Figure 5) provides a higher deposition rate and rapid solidification of molten substrate material and deposited material, thus resulting in a better structure of the produced metal.

A smaller amount of material, being in the liquid phase per a unit of time, essentially reduces alloying element losses for evaporation that is particularly important for many alloys of titanium, niobium and other refractory metals. So, investigations of the change of chemical composition of titanium alloy Ti–6Al–4V during deposition by xBeam 3D Metal Printing technology showed a significant lowering of aluminium content from 5.91 % in the initial wire to 5.72–5.79 % (depending on process parameters) in the deposited material.

Lower power concentration on the deposition surface essentially reduces temperature gradients on the substrate and in the earlier deposited layers this provides lowering of residual stresses and strains.

**Figure 6.** Sample produced using wire as deposition substrate: *a* — side view; *b* — top view; *c* — bottom view

In order to demonstrate the positive effect from application of low-voltage electron beam, an experiment was conducted, in which wire was used as a substrate instead of the traditional thick plate, the wire ends being fastened by clamps. 3 mm wire from titanium alloy Ti–6Al–4V was used as the deposition material, and 3.2 mm wire from VT1-00 titanium was the substrate.

Set power of electron beam gun was 3 kW at accelerating voltage of 15 kV. The wire was fed at the rate of 14 mm/s, the substrate was also moved with the speed of 14 mm/s. The substrate was not preheated. The experiment resulted in building an even wall (Figure 6), corresponding by the main parameters (wall width and height, layer thickness) to a similar wall, deposited on a massive substrate. Here, residual buckling (distortion) of the substrate was completely absent, that is practically inevitable at application of a massive plate [14].

This feature can be quite effectively used in the case of building a product, where the base plate is not its part and should be removed completely by machining.

An important feature of xBeam 3D Metal Printing technology is a small number of basic process parameters and simplicity of their control that is extremely important for guaranteeing the repeatability and improvement of overall production efficiency. The main parameters of the process are as follows:

- electron beam gun power;
- size of gap *Z* between wire outlet and substrate (Figure 7);
- consumable wire feed rate;

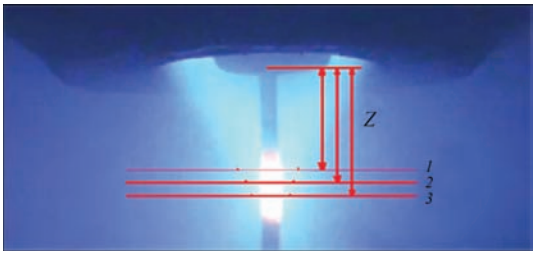

**Figure 7.** Gap *Z* between wire outlet and substrate

**Figure 8.** Walls formed from 2 mm wire: *a* — stainless steel 304L, 0.6 mm layer thickness; *b* — Ti–6Al–4V titanium alloy, 1.2 mm layer thickness

- linear speed of displacement of the substrate (deposition zone).

Note that wire of one diameter is used in the process.

The key parameter determining the main characteristics of the process of 3D product forming is exactly gap *Z* between the wire outlet and the substrate.

Size of gap *Z* determines electron beam power distribution between consumable wire and substrate, as well as the width of the zone of electron beam impact on the substrate (i.e. width of melt pool on the substrate), practically corresponding to that of the deposited bead. Thus, at constant power of electron beam, maintaining a stable size of gap *Z* ensures stable deposition rate, i.e. constant efficiency of deposition process.

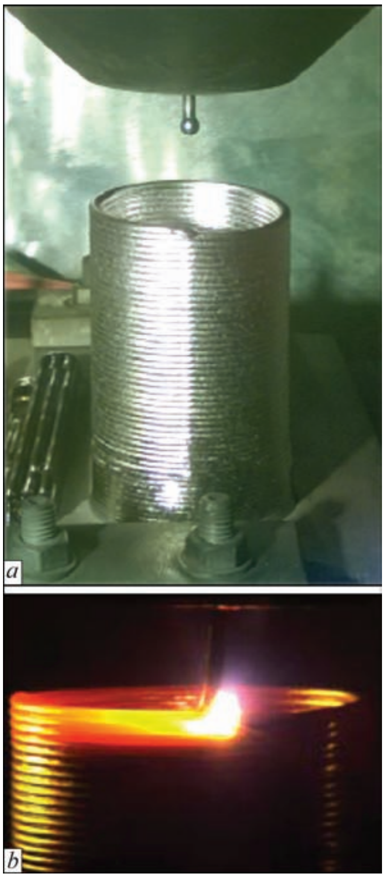

**Figure 9.** Sleeve from Ti-Grade 4 titanium (*a*), made by xBeam 3D Metal Printing technology (*b*) with 3 mm wire deposited in 50 layers at about 2.5 kg/h rate

An important advantage of the technology is the fact that stability of this key parameter of the process is ensured by simple observance of constant geometrical configuration of equipment components that is easily implemented by mechanical means and is also readily controlled.

Then, given the constant electron beam power and gap *Z*, i.e. at constant deposition rate and width of produced bead deposit, the height of deposited layer can be varied by changing linear speed of substrate displacement, as here the same quantity of entering liquid metal will be distributed over another area in direct proportion to the change of linear speed of substrate displacement.

Figure 8 shows walls with different parameters of deposited layers, formed from wire of the same diameter.

Thus, control of just several simple parameters of equipment provides flexible control of 3D product forming and guarantees repeatability of the main parameters of deposition of each layer (Figure 9).

At determination of the full set of controlled process parameters, the following can be also taken into account and controlled, accordingly: vacuum parameters, type of working gas in gas-discharge electron beam gun, temperature of deposition substrate, ratio of accelerating voltage and beam current at the same power.

An essential factor for choosing the right strategy of 3D product forming is selection of consumable wire diameter. xBeam 3D Metal Printing technology was initially oriented mainly to application of standard commercial wire of 1 to 3 mm diameter. This is an important argument in favour of improvement of cost effectiveness of the technology, as standard wire is always less expensive than the specially ordered one. More over, the wire price decreases considerably with increase of its diameter. Here, it is obvious that thin walls with less roughness can be more readily formed with smaller diameter wire.

Selection of optimum diameter of consumable wire becomes particularly important in manufacturing products with thick walls, exceeding the limit width of one bead deposit. In this case, the strategy of deposition of several parallel beads with a certain overlap between the adjacent passes is applied, as shown in Figure 10.

Figure 11 shows the macrostructure of a thick wall formed in several parallel passes.

One of the serious technological problems of currently available processes of additive manufacturing

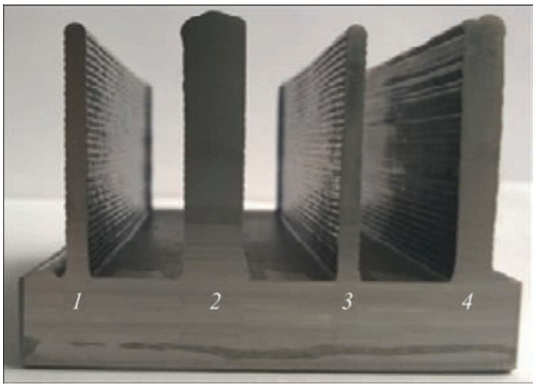

**Figure 10.** Walls of different thickness formed using xBeam 3D Metal Printing technology with 2 mm wire from titanium alloy Ti–6Al–4V at about 1.1. kg/h deposition rate: walls *1* and *3* in one pass, 3.1–3.3 mm thickness; *2* — in three passes; 10.0–10.3 mm thickness; *4* — in two passes, 6.0–6.2 mm thickness

of metals is formation of a columnar structure with upward growth, when the columnar grains grow through all the deposited layers. Such a structure is highly undesirable, as it leads to non-uniformity of properties in different directions. Owing to flexible possibilities of power distribution control and dynamic deposition process, providing quite high rates of solidification and subsequent cooling, xBeam 3D Metal Printing technology demonstrated the ability to prevent formation of a columnar structure in 3D metal products.

Figure 12 shows the macrostructure of a sample of titanium alloy Ti–6Al–4V, made from 2 mm wire with the deposition rate of about 0.9 kg/h. A structure of cast type was produced with grains close to equiaxed ones in their shape. Here, the grains grow through the adjacent deposited layers (not more than two), that confirms the absence of any interlayer peculiarities, segregations or defects. Investigations are carried on to determine mechanical properties, as well as the influence of process parameters on the structure and properties of materials, produced by layer-by-layer deposition by xBeam 3D Metal Printing technology.

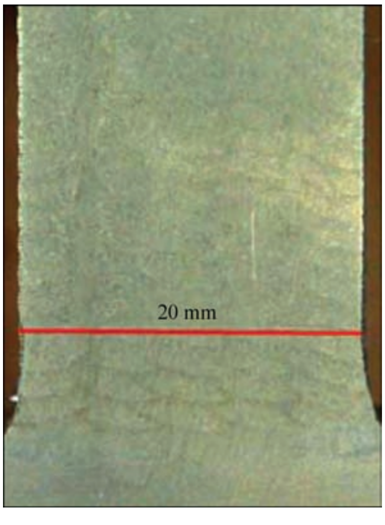

**Figure 11.** Macrostructure of a thick wall formed in five parallel passes. Titanium alloy Ti–6Al–4V, 3 mm wire, about 2 kg/h deposition rate

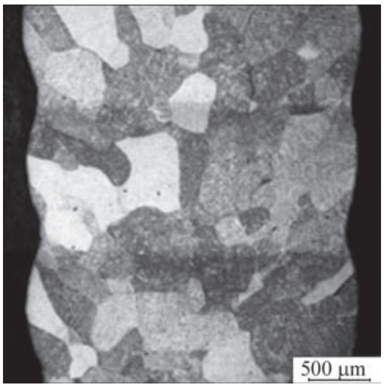

**Figure 12.** Macrostructure of a sample of titanium alloy Ti–6Al–4V

During trial manufacturing of real industrial parts from titanium alloys, direct and associated operating costs, as well as the yield were assessed in manufacturing products by xBeam 3D Metal Printing technology. Received estimates showed operating cost for titanium alloys on the level of 40 USD per 1 kg of finished product, taking into account the final machining to bring the part to its finished shape. This corresponds to the value of not less 0.01 USD per 1 cm$^3$ of deposited material, being the lowest index among all of the currently available processes of additive manufacturing of metals.

A pilot unit xBeam-01 was developed and manufactured for realization of xBeam 3D Metal Printing technology, studying its capabilities and optimizing the basic process techniques (Figure 13). The unit features a simple and compact design: 10 m$^2$ of useful area is enough for its operation, i.e. it can be installed even in a university laboratory. Consumable can be loaded in without breaking the vacuum in the working chamber that is very convenient for research

**Figure 13.** xBeam-01 unit

performance. Features of operation of gas-discharge electron beam gun allow conducting the process in low vacuum — within $10^{-2}$–$10^{-1}$ mbar, so that the unit is fitted with one mechanical backing pump. Application of low accelerating voltage in the electron gun (10–15 kV) results in improvement of personnel safety in terms of the impact of X-ray radiation from the chamber.

Specification of xBeam-01 unit is given below.

| | |
|---|---|
| Useful size (L×W×H), mm | 300×300×300 |
| Positioning system | Three-axis, linear |
| Maximum power, kW | 20 |
| Limit accelerating voltage, kV | 20 |
| Maximum power consumption, kW | 30 |
| Limit vacuum, Pa | $5.10^{-1}$ |
| Working vacuum, Pa | 10–50 |
| Possible kinds of consumables | Wire, rods, flux-cored wire of 1–3 mm dia. |
| Working gas (helium) flow rate, at 0.1 MPa, l/min | 2.5 |
| Recommended working space (W×L×H), mm | 330×3000×2400 |
| Total weight, kg, approximately | 1500 |

During performance of experimental work in xBeam-01 unit deposition rate of 700 cm$^3$/h has been achieved so far that corresponds to more than 3 kg/h for titanium alloys. Here, the accuracy of 3D product manufacturing and surface roughness require subsequent finish machining of not more than 1 mm on each wall that is much better than for the currently available analogs. Electron beam gun rated power on the level of just about 7 kW was sufficient to achieve such efficiency. This allows anticipating achievement of not less than 2000 cm$^3$/h deposition rate at maximum rated power of the gun that corresponds to maximum values demonstrated so far in the market of additive technologies.

Development of CAM software is carried on, as well as testing of means of monitoring and analysis of process parameters and equipment.

Proceeding from pilot unit experimental operation and performed upgrades, PSJC SPA «Chervona Khylya» specialists are developing prototypes of serial units of laboratory and commercial grade.

New additive manufacturing electron beam technology xBeam 3D Metal Printing and 3D-printers of xBeam family promise to become reliable and efficient equipment for rapid and high-quality manufacturing of complex parts and for research work, owing to application of inexpensive standard commercial materials (wires) as consumables, minimum material losses at final machining, defectfree structure, simple and safe operation and reasonable price of equipment.

1. *A third industrial revolution*. The Economist, http://www.economist.com.node/21552901.
2. *Is 3D printing the next industrial revolution?* TechCrunch, https://techcrunch.com/2016/02/26/is-3d-printing-the-next-industrial-revolution/
3. (2013) *Additive manufacturing market outlook. Value chain-Market size-Key players-Business models*. Additive manufacturing. A game changer for the manufacturing industry? Strategy Consultants GmbH, Roland Berger, 19–24.
4. *ISO/ASTM 52900:2015 (ASTM F2792)*: Additive manufacturing. General principles. Terminology.
5. *Wohlers Report 2017. 3D printing and additive manufacturing: State of the industry annual worldwide progress report*. ISBN 978-0-9913332-3-3.
6. *What is additive manufacturing?* AdditiveManufacturing.com, http:// additivemanufacturing.com/basics/
7. Zaleski, A. (2015) Here's 3D printing needs more metal. *Fortune*, **11**.
8. *3D printing processes*: The free beginner's guide, http://3dprintingindustry.com/3d-printing-basics-free-beginners-guide/processes/
9. Chaplais, Ch. (2016) *7 challenges to a wider adoption of additive manufacturing in the industry. Manufacturing transformation*, http://www.apriso.com/blog/2016/07/7-challenges-to-a-wider-adoption-of-additive-manufacturing-in-the-industry-part-1/
10. Gao, W., Zhang, Y., Ramanujan, D. et al. (2015) The status, challenges, and future of additive manufacturing in engineering. *Computer-Aided Design*, **69**, 65–89.
11. Douglas, S.T., Stanley, W.G. (2014) *Costs and cost effectiveness of additive manufacturing*. NIST Special Publication 1176.
12. Kovalchuk, D.V., Melnyk, V.G., Melnyk, I.V., Tugaj, B.A. (2016) *Method of manufacturing of 3D objects and device for its realization*. Pat. 112682 Ukraine [in Ukrainian].
13. Kovalchuk, D., Melnyk, V., Melnyk, I., Tugai, B. (2016) Prospects of application of gas-discharge electron beam guns in additive manufacturing. *Electrotechnics and Electronics (E+E)*, **5–6**, 36–42.
14. Makhnenko, O.V., Milenin, A.S., Velikoivanenko, E.A. et al. (2017) Modelling of temperature fields and stress-strain state of small 3D sample in its layer-by-layer forming. *The Paton Welding J.*, **3**, 7–14.
15. Ghidini, T. (2013) *An overview of current AM activities at the European Space Agency*. 3D printing & additive manufacturing — Industrial applications. Global Summit 2013 (London, UK).
16. Clinton, R.G. Jr. (2017) NASA Marshall Space Flight Center Additive Manufacturing: Rocket engines and in space manufacturing. In: *Proc. of 2nd Int. Symp. on Additive Manufacturing* (February 8–9, 2017, Dresden, Germany).

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