doi.org/10.15407/tpwj2016.06.20

3D-PRINTING OF METALLIC VOLUMETRIC PARTS OF COMPLEX SHAPE BASED ON WELDING PLASMA-ARC TECHNOLOGIES (Review)

V.N. KORZHIK[1], **V.Yu. KHASKIN**[1], **A.A. GRINYUK**[1, 2], **V.I. TKACHUK**[1], **S.I. PELESHENKO**[3], **V.V. KOROTENKO**[1, 2] and **A.A. BABICH**[1]

[1]E.O. Paton Electric Welding Institute, NASU
11 Kazimir Malevich Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

[2]NTUU «Kiev Polytechnic Institute»
37 Pobeda Ave., 03056, Kiev, Ukraine. E-mail: mail@KPI.ua

[3]South China University of Technology
510641, Guangzhou, PRC. E-mail: sviatoslav@qq.com

Manufacturing complex-shaped metal products by 3D-printing is becoming ever more urgent in modern industry. Laser technologies (SLS- and SLM-processes) are most often applied for this purpose, while electron beam technologies (EBF_3) are used less often. Both of them are characterized by quite high cost and low efficiency. This paper deals with new tendencies in application of welding technology for 3D-printing of complex metallic products, including those complemented by concurrent or subsequent machining. It is shown that application of welding technologies to produce volumetric metallic products significantly lowers their manufacturing cost at simultaneous increase in productivity, compared to SLS- and SLM-processes. The most promising welding technology of 3D-printing is plasma-arc process with application of wires or powders. It allows at comparatively low heat input creating quality volumetric products with 3–50 mm thickness from Fe, Ni, Co, Cu, Ti, Al alloys, as well as composite materials containing refractory components. Application of welding technologies allows producing both comparatively small and long products, not requiring any finish machining (for instance, growing stiffeners on large-sized panels, manufacturing honeycomb panels, building structures, etc.). Combination of welding technologies of 3D-printing with concurrent or finish machining (mostly, by CNC milling) allows manufacturing ready for use metal products of complex profile. 19 Ref., 2 Tables, 8 Figures.

Keywords: *3D-printing, metal products, welding technologies, machining, materials, equipment*

At present 3D-printing or rapid prototyping of complex-shaped volumetric products is considered to be the technology of XXI century, which will fundamentally change the structure of industrial production and economy, will enable computer-aided design of parts, flexible and fast manufacturing of different products, redistribution of production from large enterprises to small ones or manufacturing parts directly at user facility [1]. 3D-printing is the technology of additive manufacturing. The process starts with obtaining virtual design data through computer modeling with application of CAD software. The machine for 3D-printing reads the data from CAD model file; CAM program modules are used to divide (cut) the part into layers, for each of which the tool movement trajectory is automatically generated, which can take into account a multitude of technological and geometrical factors. In total, all the programs for each layer form a control program, in keeping with which the CNC manipulator tool moves. The tool deposits successive layers of liquid, powder or sheet material, creating a physical model from a set of cross-sections. These layers, corresponding to virtual cross-sections created in CAD model, are automatically connected to create the final shape.

There are different processes of 3D-printing, but they are united by that the prototype is made by layer-by-layer deposition of material. The main advantage of rapid prototyping consists in that the prototype is created in one step, and the geometrical model of the part proper is used as input data for it. Therefore, there is not need for planning the sequence of technological processes, special equipment for material processing at each manufacturing stage, transportation from one machine tool to another one, etc.

Among the known and rather widely applied now processes of 3D-printing we can note such techniques as stereolithography [2], fused deposition modeling (FDM) [3], and selective laser sintering (SLS) [4]. Such processes, with all their effectiveness, have one essential limitation: plastic is used in them as the main structural or binder material that considerably limits the range of manufactured items as to operating temperature, loads, mechanical strength and other values.

Enhancing the capabilities of 3D-printing requires availability of technologies of producing high-strength volumetric products from metals and alloys, including those of a high hardness. A number of US research centers (for instance, NASA's Langley Research Center, Houston and Johnson Space Centers, Hampton) perform development of electron beam process of manufacturing freeform metal items (EBF_3) [5]. Here, the electron beam is used as the energy source for melting the fed wire in vacuum. This procedure was demonstrated on aluminium and titanium alloys, which are of interest for aerospace applications [6]. In our opinion, it can be also extended to Ni- and Fe-based alloys. However, application of this process is limited by the need to apply expensive and complex vacuum equipment.

One of the promising technologies of producing high-strength metallic volumetric products is selective laser melting (SLM), ensuring item formation by fusing powders of different metals and alloys by the laser beam [7]. This technology enables producing complex metallic volumetric products with a high degree of detailing of their elements and high density (up to 99 %), as well as high dimensional accuracy (±50 μm).

On the other hand, with all its effectiveness and flexibility SLM process also has a number of limitations, narrowing its application (Table 1):

● need to apply expensive and energy-consuming equipment with a high service cost that results in high cost of 3D-printing process and leads to a high cost of manufactured products;

● relatively low productivity of 3D-printing (usually not more than 10 cm^3/h of incremental metal for the most widely applied machines);

● material limitations, namely for SLM expensive powders with strict requirements on granulometric and chemical composition and other characteristics are used;

● insufficiently high strength characteristics of manufactured items.

In view of the above-said, consideration of welding technologies for 3D-printing of complex-shaped metal products is urgent, as welding, at higher productivity, also allows realization of the principle of additive manufacturing, namely layer-by-layer formation of 3D structures. Moreover, welding technologies were developed long before appearance of 3D-printing, and are much more mature and less costly. Therefore, it is highly relevant to use welding processes in development of cost-effective method of manufacturing maximum dense metallic volumetric parts and tools [8].

Work [9] gives the following chronology of the attempts to apply welding technologies for fabrication of 3D structures of a complex-shape:

● in 1926 Baker patented «application of electric arc as the heat source to produce bulk objects by spraying molten metal into the deposited layers»;

● in 1971 Yujie patented manufacture of a high-pressure vessel, using submerged-arc welding, electroslag technology and TIG welding to produce items with functionally-gradient walls;

● in 1983 Kussmaul used shape welding to manufacture large-sized products from high-strength steel (20MnMoNi5) of 79 t weight;

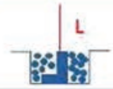
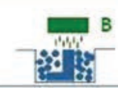
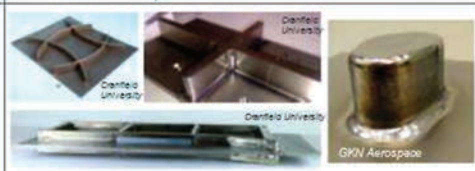
● in 1993 Prinz and Weiss patented a combined technology of incrementing material, using welding with milling in CNC machine tools (shape deposition manufacturing — SDM);

● in 1994–1999 the Cranfield University developed shaped metal deposition (SMD) technology for

Table 1. Comparison of the most widely accepted SLM technologies of 3D-printing of metallic products with new plasma-arc melting technology based on plasma-arc welding

Characteristic	Technology of 3D-printing of metallic products			
	SLM			PAM
	LENS company	POM company	AeroMet company	
Used equipment characteristic	Nd:YAG-laser, 1 kW power	CO_2-laser, 2 kW power	CO_2-laser, 14 kW power	Based on welding, 2–20 kW power
Productivity by incremental metal, cm^3/h	8	8	160	>1000–15000
Capability of processing along axes (degrees of freedom)	3 axes	3 axes	3 axes	4–5 axes
Type of material used for 3D-printing	Metal powder			Powders of metals, alloys, composite materials, powder mixtures. Solid and flux-cored wire
Material utilization factor, %	About 40	About 40	About 70	More than 90
Application fields	Manufacture and repair of small-sized expensive complex-shaped parts			Manufacture and repair of medium- and large-sized expensive complex-shaped parts for various applications
Tentative cost of main equipment units (per 1 kW of power)	Laser cost: 80,000–120,000 USD			Welding equipment cost: 1000–5000 USD

Table 2. Main technologies of additive manufacturing with application of local melting processes [17]

	Spraying				Powder/Mould		
	Plasma (wire)	EB (wire)	Laser (wire)	Laser (powder)	Laser (powder)	EB (powder)	Binder (powder)
Process schematic							
Illustration							
Description	Free spraying of wire using arc plasma	Spraying of wire molten by laser or electron beam in a chamber		Deposition of powder molten by laser in a chamber	Laser or electron beam selective melting in mould located in a chamber		Powder/binder system, requiring melting in the downhand position
Application	 High-rate melting of material and its spraying technology allow growing almost precise items			 Precise and almost finished sprayed parts	 New generation prismatic components with highly complex geometry		 Complex-shaped parts with inner cavities for cars

manufacturing engine shells for Rolls Royce Corporation (Great Britain).

There are also data on attempts made in the 1960s in Germany to create 3D metal structures, using shape welding. Based on this process, such companies as Krupp and Thyssen organized manufacturing of large-sized parts of a simple geometry, for instance, high-pressure vessels of up to 500 t weight [10]. Successful attempts of arc welding application for manufacturing large-sized metal structures and products from austenitic steels were made by the Babcock & Wilcox Company (USA) in the form of development of technology named Shape Melting [11]. As was already noted, Rolls Royce Corporation is pursuing arc welding application as the technology providing high forming productivity and lowering the level of wastes that may be generated at traditional processing during fabrication of items from expensive alloys [12]. At present this Corporation is successfully introducing this technology for manufacturing different aircraft parts from expensive Ni- and Ti-base alloys.

In addition to the above examples, research work on 3D arc welding is conducted in University of Nottingham (Great Britain), Wollongong University (Australia) and Southern Methodist University in Dallas (Texas, USA) [13]. Research teams from Indian Institute of Technology (Mumbai) and Fraunhofer Institute of Production Technology and Automation presented their conceptual ideas of combining a welding operation with milling. Characteristic defects in volumetric product forming by welding methods were also studied and ways to eliminate them were developed [14]. Need to monitor the temperature of incremental layers was also studied. Special attention was given to creation of products from titanium [15] and nickel [16] alloys for aerospace industry applications. On the whole, main welding and related technologies for additive manufacturing can be presented in the form of Table 2 [17].

PWI work also confirmed the fundamental possibility of forming large-sized volumetric structures by arc welding. One of the striking examples can be creation of 3D welded sculptures and pictures from titanium alloy by G. Dochkin using his own unique method developed in mid-1970s [18]. Individual production problems were also solved, related to manufacture of unique products for defense industry.

The above studies were mostly focused on applicability for 3D-printing of such welding processes as gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW). These processes ensure good metallurgical adhesion, as well as protection of weld pool and incremental layers of products from oxide formation. However, these processes with their availability, also have such disadvantages as considerable size of HAZ and quite large dimensions of incremental layer that leads to generation of undesirable temperature gradients and residual stress accumulation. More over, mostly standard welding wire is used as consumable material to form volumetric products that limits the chemical composition and properties of these items.

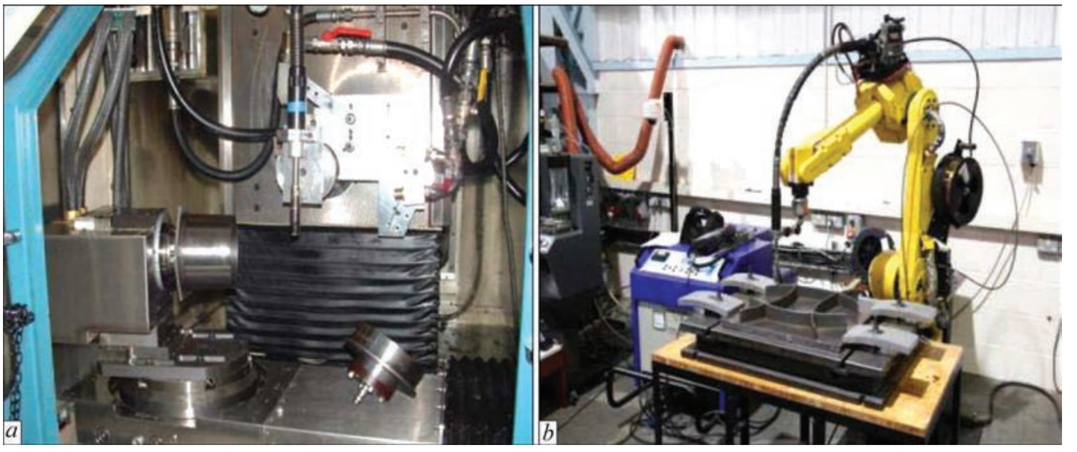


Figure 1. Complexes for realization of additive welding technologies [9]: *a* — five-axes system with CNC milling and WAAM technology; *b* — WAAM process without machining realized using an anthropomorphous robot

The above drawbacks can be eliminated by application of microplasma or plasma-arc melting, as well as microplasma or plasma-arc welding. These welding technologies are capable of providing a new level of 3D-printing, both compared to arc welding processes (GMAW, GTAW), and compared SLM, in view of the following advantages:

● temperature in plasma arc flame can reach 30000 ºC, that is essentially higher than in standard electric arc. Therefore, plasma can melt practically any refractory material for layer-by-layer incremental manufacturing of volumetric products;

● minimum heating of earlier deposited layers at product formation, less than 5 % heat penetration into base metal;

● absence of metal spatter when building-up the layers, their extremely low mixing;

● possibility of adjusting in a broad range the thickness (0.5–5.0 mm) and width (1.5–50.0 mm) of deposited metal layer in additive building-up of volumetric products;

● ability to adjust the composition of gas atmosphere (reducing, inert, oxidizing) during additive building-up of layers in product forming;

● high cost-effectiveness and productivity of the process (by 2–3 times and more);

● applicability of a wide range of consumable materials (powders of metals, alloys, composite materials, powder mixtures, solid and flux-cored wires), including those from Fe, Ni, Co, Cu, Ti, Al alloys, as well as composite materials, containing refractory components (carbides, borides, and other for instance, WC, Cr_3C_2, TiC, TiB_2), refractory materials, composite materials with refractory components;

● possibility of changing metal composition during item formation, producing items with graded structure.

At present, advanced research institutes and industrial corporations of economically developed countries pursue applied research on development of plasma-arc melting and welding technologies, as well as other welding technologies of 3D-printing of metal products. Let us consider some characteristic examples of such studies.

Cranfield University developed different complexes for realization of additive welding technologies — both with machining during layer building-up and without it (Figure 1) [9]. Manufacturing volumetric products in these complexes is based on wire-arc

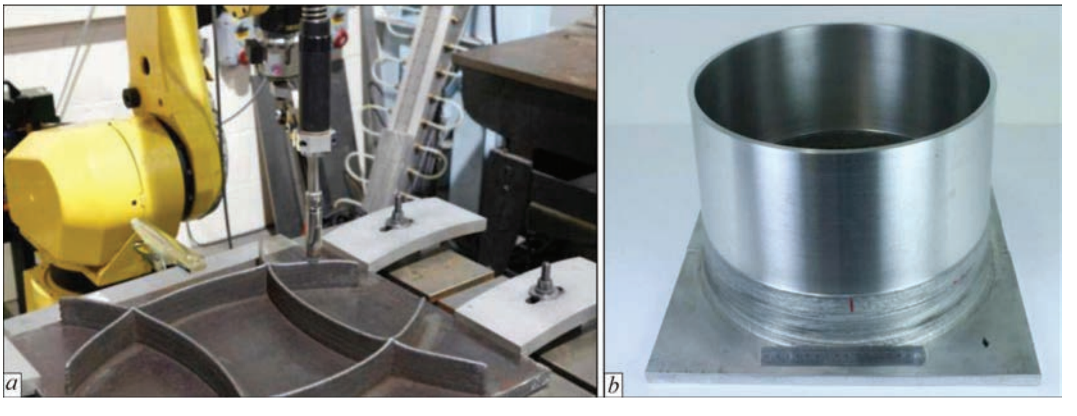


Figure 2. Examples of volumetric products from carbon steel S355 manufactured by WAAM technology [9]: *a* — panels with crossing stiffeners without machining; *b* — cylinder machined after manufacturing

Figure 3. Shell casing of 160 mm diameter and 800 mm length with 8 to 18 mm wall thickness of 32 kg weight from high-strength steel made by WAAM technology (pulsed MIG welding) with productivity of 4 kg/h before (*a*) and after (*b*) machining [9]

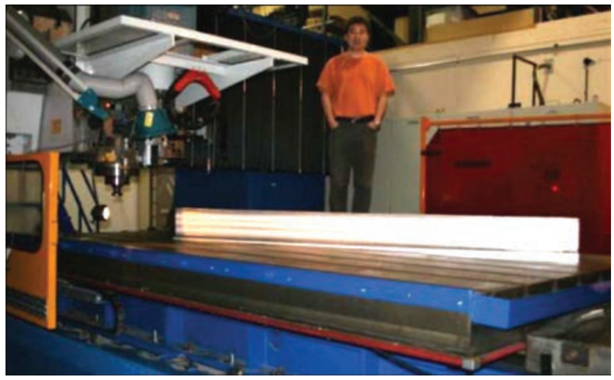


Figure 4. Aluminium honeycomb beam structure of 3 m length with higher rigidity [9]

additive manufacturing (WAAM) technology (Figure 2). Products are made from various materials, for instance, carbon steel, titanium and aluminium alloys, etc. Here, both standard (continuous or pulsed) and constricted electric arc, i.e. plasma, can be used (Figure 3). One of the promising directions of WAAM technology application is fabrication of large-sized honeycomb structures (Figure 4).

Southern Methodist University in Dallas studied the variants of laser, arc and plasma-arc technologies of manufacturing 3D objects with simultaneous or finish machining (CNC milling) [13]. Respective technological complexes were developed, and a number of engineering solutions were proposed, allowing manufacture of both relatively simple and quite complicated products (Figure 5). In particular, investigations were conducted in the field of microplasma powder building-up of volumetric products (Figure 6). Fundamental possibility of producing gradient composite structures by such a method was demonstrated. Analysis of the features and prospects for the above welding technologies showed that for the most high-efficient and cost-effective manufacturing of quality volumetric products with wall thickness of 3 to 50 mm, application of plasma-arc powder deposition of layers of 0.5–5.0 mm height in one pass is the optimum variant.

In addition to machines and mechanisms, welding technologies of 3D-printing also allow creation of building structures. Development of new MX3D technology can be an example [19]. MX3D project was created by JORIS LAARMAN LAB in cooperation with ACOTECH and HAL (Holland). New technology has enormous potential, as it allows quickly creating complex metal constructions without erection of any accompanying supporting structures, for instance, scaffolding or intermediate supports. During 3D welding, the man or welding robot creates his own support and moves ahead on the constructed structure. It speeds up and simplifies construction. More over, MX3D can be fully robotized, and can operate round the clock.

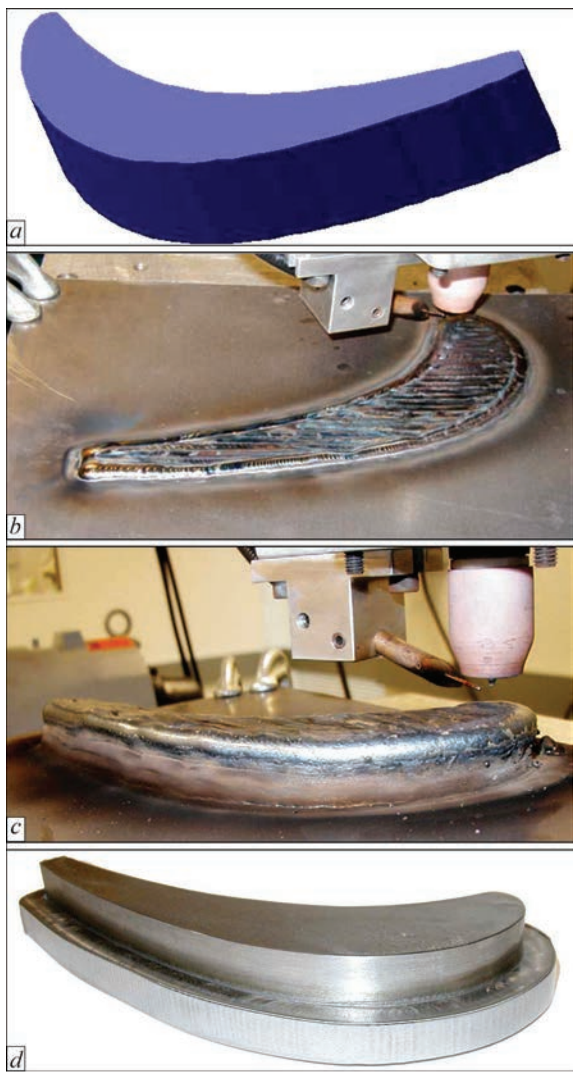


Figure 5. Process of manufacturing blade turbine by combination of arc surfacing and CNC milling: *a* — CAD model; *b* — start of GTA surfacing; *c* — end of GTA surfacing; *d* — blank after CNC milling [13]

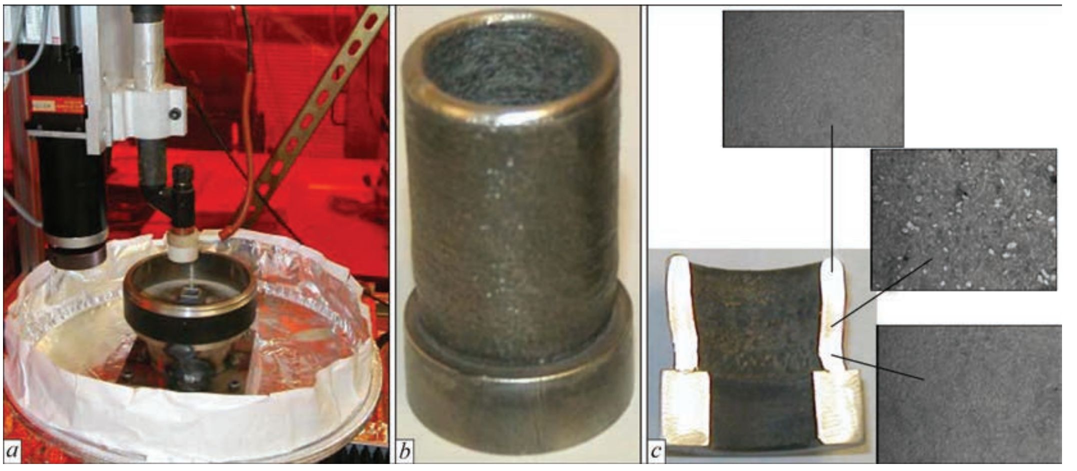


Figure 6. Microplasma powder growing of volumetric products [13]: *a* — laboratory unit; *b* — hollow cylinder of uniform structure (tool steel H-13); *c* — creation of gradient composite H-13 + tungsten carbide structure

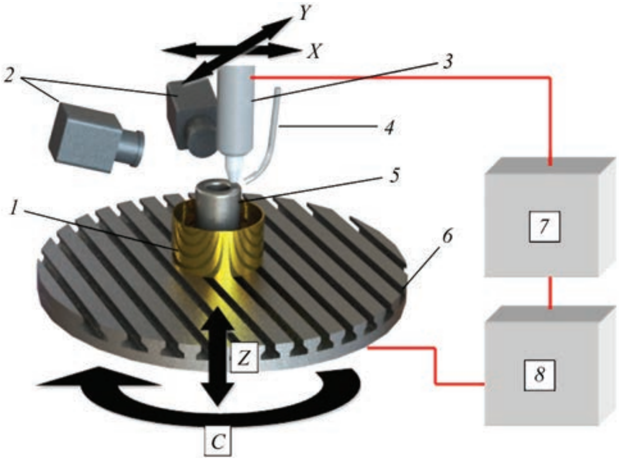


Figure 7. Schematic of unit for plasma-arc 3D-printing of volumetric products (for designations see the text)

Generalization of data, given and analyzed in publications, allows suggesting the following approach to fabrication of volumetric products, using welding technologies: computer modeling of the item, its manufacture by plasma-arc technology with application of wire or powder under the conditions of monitoring temperature and forming, machining of minimum required number of item sections. To realize such an approach, it is rational to separately apply the system for plasma-arc 3D-printing (Figure 7), and to perform machining in CNC milting and/or lathe machine tool. We believe it is not rational to combine the processes of 3D-printing and finish machining within one multi-axis all-purpose unit.

After development of a computer model of the grown part (using CAD system, for instance Solidworks), it is automatically (using CAM system, for instance Lazy CAM, Art CAM) separated into layers with generation of control programs for each of the layers, which are loaded into the system of CNC complex (see Figure 7). Growing of part *5* is performed in shielded (for capturing welding spatter and unused powder) zone *1*, located on rotating table *6*, with the capability of performing rotation *C* and step-by-step vertical displacement *Z*. Transferred arc plasmatron *3* is mounted on the carriage of *xy*-manipulator, providing precise movement along coordinates *X* and *Y*. Filler wire or powder is fed into the torch *3* coverage area using system *4*. Process monitoring is performed by system *2*, including two CCD-cameras, located at 90^{o} angle to each other, and thermal imager. Here, not only forming of part *5*, but also its temperature

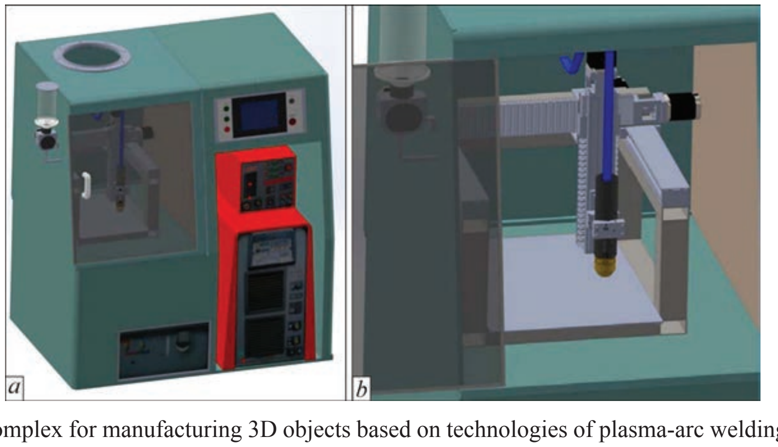


Figure 8. PWI-designed complex for manufacturing 3D objects based on technologies of plasma-arc welding and surfacing: *a* — general view; *b* — three-coordinate manipulator with plasmatron

state, is monitored. Systems *4* and *2* are also located on the carriage. Plasmatron *3* is powered by source *7*, and 3D-printing process is controlled by CNC system *8*. After growing part *5*, it can be transferred to machining station, can be treated directly in the system, in which it was created, or left untreated, if required quality of its surfaces has been achieved.

At present, PWI performs manufacturing of equipment for creation of 3D objects based on plasma-arc welding and surfacing. For this purpose, a complex was designed on the basis of three-coordinate manipulator, fitted with plasmatron with power source, filler wire feeder and CNC system (Figure 8). The complex is controlled using a common controller with the capability of exchange of data on 3D-printing modes and of control commands with the computer. Performed work allowed development of a number of unified systems of different typesizes for 3D-printing of metallic volumetric parts of a complex shape, based on plasma-arc technologies.

Conclusions

1. Application of welding technologies to produce metallic volumetric parts allows considerable lowering of their manufacturing cost at simultaneous increase in productivity, compared to SLS- and SLM-processes.

2. The most promising welding technology of 3D-printing is plasma-arc technology with application of wires or powders. It allows creating at comparatively low heat input quality volumetric products with wall thickness from 3 to 50 mm from alloys based on Fe, Ni, Co, Cu, Ti, Al, as well as composite materials, containing refractory components.

3. Application of welding technologies allows producing both comparatively small and long items, not needing finish machining (for instance, growing stiffeners on large-sized panels, creating honeycomb panels, building structures, etc.).

4. Combination of welding technologies of 3D-printing with concurrent or finish machining (most often CNC milling) allows manufacturing finished metal items of complex profile.

1. Kruth, J.P., Leu, M.C., Nakagawa, T. (1998) Progress in additive manufacturing and rapid prototyping. *CIRP Annals-Manufact. Techn.*, 47(**2**), 525–540.
2. (2009*) Laser technologies for treatment of materials: Current problems of fundamental studies and applied developments:* Monograph, Chapter: Laser technologies of rapid prototyping and direct fabrication of 3D objects. Moscow: Fizmatlit.
3. Slyusar, V.I. (2003) Fabber-technologies. New tool for 3D modeling. *Elektronika: Nauka, Tekhnologiya, Biznes*, **5**, 54–60.
4. Deckard, C.R., Beaman, J.J. (1987) Recent advances in selective laser sintering. In: *Proc. of 14th Conf. on Production Research and Technology* (Michigan, 1987), 447–451.
5. Kablov, E.N. (2015) Additive technologies as the dominant of national technology initiative. *Intellekt & Tekhnologii*, 2(**11**), 52–55.
6. Bruce, M.R., Riley, S.F., Cola, M.J. et al. (2012) Measurement and simulation of titanium alloy deposit temperature in electron beam additive manufacturing. In: *Trends in Welding Research:* Proc. of 9th Int. Conf. (Chicago, USA, 4–8 June 2012), 963–969.
7. Kruth, J.P. (2004) Selective laser melting of iron-based powder. *J. Mater. Process. Technol*., Vol. 149, 616–622.
8. Karunakaran, K.P., Suryakumar, S., Vishal Pushpa et al. (2010) Low cost integration of additive and subtractive processes for hybrid layered manufacturing. *Robotics and Computer-Int. Manufact.,* 26(**5**), 490–499.
9. Colegrove, P., Williams, S. (2013) High deposition rate high quality metal additive manufacture using wire + arc technology. *http*://xyzist.com/wp-content/uploads/2013/12/Paul-Colegrove-Cranfield-Additivemanufacturing.pdf
10. Venuvinod, P.K., Weiyin Ma (2004) Rapid prototyping: Laser-based and other technologies. In: *Springer Science + Buisness Media*. New York.
11. Doyle, T.E., Ryan, P.M. *Cooling workpieces being manufactured by shape melting*. Pat. EP0340939A1 (US4857694). Int. Cl. B23K9/04, B23K37/003, B23K37/00F. Publ. 8.11.89.
12. Martina, F. (2014) Investigation of methods to manipulate geometry, microstructure and mechanical properties in titanium large scale wire + arc additive manufacturing. In: *School of Aerospace, Transport and Manufacturing*. Cranfield University.
13. Kovacevic, R. (2003) Development of machine for rapid manufacturing/repair. In: *The 2003 CTMA Symp*. (Salt Lake City, USA, March 31–April 3,2003), *www*.engr.smu.edu/rcam
14. Alhuzaim, A.F. (2014) *Investigation in the use of plasma arc welding and alternative feedstock delivery method in additive manufacture*: Thesis submitted in partial fulfillment of the requirements for the degree of Master of Sci. General Engineering. University of Motana.
15. Baufeld, B., Van der Biest, O., Gault, R.S. (2010) Additive manufacturing of Ti–6Al–4V components by shaped metal deposition: Microstructure and mechanical properties. *Materials & Design*., Vol. 31, 106–111.
16. Clark, D., Bache, M.R., Whittaker, M.T. (2008) Shaped metal deposition of a nickel alloy for aero engine applications. *J. Materials Proc. Techn.*, Vol. 203, 439–448.
17. Chad, H. (2014) Metallic additive manufacturing: Comprehensive overview and findings on 3D-printing for construction. *http*://www2.iceaustralia.com/ei/images/cmic14/cmicpresentations/plenary/henry.pdf
18. (2015) Art of Grigory Dochkin. In: *CWELD — equipment and materials for welding and cutting,* 01.08.2015; *http*://adios-group.ru/?p=242
19. (2015) 3D-welding from MX3D will print-out the bridge above the water, 17.06.2015; *http*://weldworld.ru/news/razraborki/5583-3d-svarka-ot-mx3d-raspechataet-most-nad-vodoy.html

Received 22.03.2016