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ANALYSIS OF THE CURRENT STATE OF ADDITIVE WELDING TECHNOLOGIES FOR MANUFACTURING VOLUME METALLIC PRODUCTS (REVIEW)

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Узагальнено досвід застосування зварювальних дугових технологій для виготовлення великогабаритних об'ємних деталей з різних типів сталей і сплавів. Показана можливість досягнення при цьому істотної економії (до 5 разів) дорогих сплавів. Обґрунтовано переваги застосування плазмово-дугових технологій для 3D-друку. Описано зразок промислового 3D-принтера для вирощування металевих виробів розмірами до 900×900×900 мм із застосуванням порошкового мікроплазмового та плазмового наплавлення

Ключові слова: 3D друк, адитивне виробництво, зварювальні технології, тривимірні металеві вироби

Обобщен опыт применения сварочных дуговых технологий для изготовления крупногабаритных объемных деталей из различных типов сталей и сплавов. Показана возможность достижения при этом существенной экономии (до 5 раз) дорогостоящих сплавов. Обоснованы преимущества применения плазменно-дуговых технологий для 3D-печати. Описан образец промышленного 3D-принтера для выращивания металлических изделий размерами до 900×900×900 мм с применением порошковой микроплазменной и плазменной наплавки

Ключевые слова: 3D печать, аддитивное производство, сварочные технологии, трехмерные металлические изделия

1. Introduction

At present, there is a great interest in additive manufacturing processes (3D printing technologies). It is expected that their use will bring a fundamental change in the industrial production. The basis of this are the realization of automatic design of parts, the flexibility and speed of their manufacturing, the redistribution of production from large enterprises to small ones, manufacturing of parts directly at the consumer's site [1]. 3D printing technologies allow you to «grow» products of any shape complexity with minimal expenses. At the same time, there is practically no production waste and the number of maintenance personnel is reduced. In addition to obvious advantages in speed and cost of manufacturing, these technologies have an important advantage in terms of environmental protection. They, in particular, reduce greenhouse gas emissions and «thermal» pollution. Additive technologies have great potential in reducing energy and material costs for creating a wide variety of products. Finally, the degree of use of 3D technologies in industrial production is an indicator of the real industrial power of the country, an indicator of its innovative development.

The various processes of three-dimensional printing are united by the fact that the prototype is made by the layer-by-layer (additive) material deposition. The main advantage of rapid prototyping is that the prototype is created in one step, and the initial data for it is the geometric model of the part. Consequently, there is no need for sequencing technological processes, special equipment for processing of materials at each stage of manufacturing, transportation from machine to machine, etc.

At present, such processes of three-dimensional printing, as stereolithography [1, 2] and jet growth of thermoplastic polymer material (Fused Deposition Modeling – FDM) [3, 4] are widely used. A significant drawback of such processes is the use of plastic as the main structural or bonding material. This significantly limits the range of manufactured products by operating temperature, loads, mechanical strength and other parameters.

Therefore, expanding the capabilities of three-dimensional printing requires availability of the technologies for obtaining high-strength volumetric products of metals, alloys, including high hardness [3, 4]. The use of such materials will make it possible to obtain finished products. Therefore, it is actual to create technologies for additive manufacturing of finished metal volumetric products. Such technologies, in the first place, include welding processes (for example, cladding).

2. Literature review and problem statement

Table 1 presents a classification of widely used at present additive technologies for growing three-dimensional objects by powder and wire methods [4–6].

Table 1

Basic methods of additive manufacturing

Method	Technology	Used materials
Extrusion-type	Fused Deposition Modeling (FDM or FFF)	Thermoplastic (such as polylactide (PLA), acrylonitrile butadiene styrene (ABS), etc.)
Wire	Free-shapes production by electron-beam melting (EBF_3)	Virtually any metal alloys
Powder	Direct Metal Laser Sintering (DMLS)	Virtually any metal alloys
	Electron-beam melting (EBM)	Titanium alloys
	Selective laser melting (SLM)	Titanium alloys, cobalt-chromium alloys, stainless steel, aluminum
	Selective Hot Sintering (SHS)	Powder thermoplastic
	Selective laser Sintering (SLS)	Thermoplastic, metallic powders, ceramic powders
Jet	Jet 3D printing (3DP)	Gypsum, plastics, metal powders, sand mixtures
Laminating	Laminated object manufacturing (LOM)	Paper, metal foil, plastic film
Polymerization	Stereolithography (SLA)	Resins
	Digital Light emitting diodes projection (DLP)	Resins

From the point of view of obtaining three-dimensional metal products of the highest quality, selective laser melting (SLM) and electron-beam melting (EBM) are promising.

The SLM processes at present became widely used for obtaining high-strength volumetric metal products [5]. This process allows obtaining products by fusing powders of various metals and alloys with a laser beam. The advantage is a high degree of detailing of elements, high density (up to 99 %), as well as accuracy about ±5 μm.

At the same time, for all its efficiency and flexibility, the SLM process also has a number of limitations that narrow its wide application (Table 1):

– the need to use expensive and energy-intensive equipment with a high cost of maintenance, which causes a high production cost of the process of three-dimensional printing and leads to a high cost of manufactured products;

– relatively low productivity of three-dimensional printing (usually for the most common machines no more than 10 cm^3/h of building-up metal);

– limitations on material – for SLM the expensive powders are used with stringent requirements for granulometric and chemical composition, yielding and other characteristics;

– insufficient strength characteristics of manufactured products.

A number of US research centers carry out development of electron-beam manufacturing process for free-shape metal products (Electron beam freeform fabrication – EBF_3). For example, NASA's Langley Research Center, Houston and Johnson Space Center, Hampton) [7]. In this case, the electron beam is used as an energy source for melting of the fed wire in a vacuum medium. This technology was demonstrated on aluminum and titanium alloys of interest for aerospace applications [7]. There is a possibility to use alloys based on nickel and iron. However, the wide application of this process is limited by the need for the use of expensive and difficult to maintain vacuum equipment, which also leads to an increased cost of manufactured metal parts.

It should be noted that in the classification of additive technologies in Table 1 there are no additive welding arc technologies. The following chronology of attempts to use welding technologies for obtaining three-dimensional metal structures of complex shape by the method of layer-by-layer build-up of deposited layers is given in the work [8]:

– 1926 – «the use of an electric arc as a source of heat to obtain three-dimensional objects by spraying of molten metal into laid-on layers» was patented;

– 1971 – manufacture of pressure vessel using submerged arc welding (Mitsubishi, Japan), electroslagging technology and TIG for producing products with functional gradient walls;

– 1983 – Shape Welding (shaped welding or welding with molding) for the production of large-sized products of high-alloy steel ($20MnMoNi_5$) weighing 79 tons was used in the USA;

– 1993 – the combined technology of building-up of material with the help of welding with milling on CNC machines (Shape Deposition Manufacturing (SDM) was patented in the USA;

– 1994–99 – the technology of Shaped Metal Deposition (SMD) for the manufacture of engine shells for the Rolls-Royce corporation (UK) was developed.

There is also evidence of attempts to create three-dimensional metal structures using Shape Welding in Germany in the 1960s. Based on this process, companies such as Krupp (Germany) and Thyssen (Germany) have organized the production of large parts of simple geometry, for example, pressure vessels weighing up to 500 tons [9]. The Babcock & Wilcox Company (USA) used the «Shape Melting» process for the manufacture of large metal structures and products from austenitic steels [10]. The Rolls-Royce Corporation (UK) is working on the use of arc welding as a technology that provides high molding productivity and a reduction in the level of waste in the manufacture of products from expensive alloys [11]. This technology has been successfully introduced for the production of various aircraft parts from alloys based on nickel and titanium.

In addition to the above examples, research work on three-dimensional arc welding is being conducted at the University of Nottingham, UK, Wollongong University (Australia) and Southern Methodist University, Dallas, TX, USA [12]. Groups of researchers from the Indian Institute of Technology in Bombay and the Fraunhofer Institute of Production Technology and Automation (Germany) presented their conceptual ideas of combining a welding operation with milling. The characteristic defects in the formation of three-dimensional products by welding methods were also investigated and ways of their elimination were developed [13]. The need to control the temperature of the build-up layers was shown. Particular attention was paid to the creation of products of titanium [14] and nickel [15] alloys for the aerospace industry.

Thus, for today there is an increase in the share of welding technologies in the additive manufacturing of metal volumetric products. This is due to both high welding efficiency and low cost. Therefore, it is important to study in detail the features and prospects of using welding technologies for three-dimensional printing of metal products.

3. The purpose and objectives of the work

The purpose of this work is to develop recommendations for the selection of welding technologies for the additive manufacturing of volumetric metal products on the basis of an analysis of the current state of 3D technologies and studies of trends in their industrial application.

To achieve this goal, the following tasks were solved:

– analysis of features of the use of welding technologies for the production of three-dimensional metal structures of complex shape by the method of layer-by-layer build-up of weld layers with determining their advantages and disadvantages;

– determination of the advantages and disadvantages of additive welding technologies compared to traditional methods of manufacturing of three-dimensional metal parts;

– determination of the possibility of saving materials and improving the quality of metal parts during their manufacturing using additive welding technologies, compared to traditional methods of mechanical manufacturing;

– determination of characteristic approaches to the manufacture of industrial equipment for 3D printing of metal products, including using plasma arc welding technologies;

– development of the sample of industrial 3D-printer and conducting experiments with it to test the prospects of application of additive plasma-arc technologies.

4. Materials and research methods of Additive Welding Technologies for manufacturing of volumetric products

4. 1. Analysis of currently used materials and welding technologies

In the E. O. Paton Electric Welding Institute (PWI), the principle possibility of forming large-sized three-dimensional structures with the help of arc welding also was confirmed. One of the most striking examples is the creation of three-dimensional welded sculptures and paintings from titanium alloy using a unique method developed in the mid-1970s [16]. Individual production tasks related to the manufacture of unique products of the defense industry had been solved.

The list of materials and technologies approved for obtaining three-dimensional metal products by layer-by-layer additive build-up using arc welding is given in Table 2 [17]. The hardware block diagram for constructing such a technological process is shown in Fig. 1, and its implementation for the technology of consumable electrode (wire) electric arc welding – WAAM (Wire-Arc Additive Manufacturing) is shown in Fig. 2 [17].

Table 2

Materials and processes, tested for obtaining of three-dimensional metal products by layer-by-layer additive manufacturing using arc welding

Materials	Processes
– Low-alloy structural steel; – High-strength steel; – Stainless steel; – Nickel heat-resistant alloys; – Aluminum alloys; – Titan, titanium alloys; – Copper and copper alloys	– TIG (DC and pulsed current) – high quality; – High-frequency TIG (DC and pulsed current) – high precision, high quality; – Pulsed MIG – simplicity, economic efficiency; – Cold Metal Transfer (CMT) – low heat input, high stability of the process; – Tandem Pulsed MIG – high building-up speed; – Plasma PTA – high quality, speed, possibility to adjust the width of the build-up layer

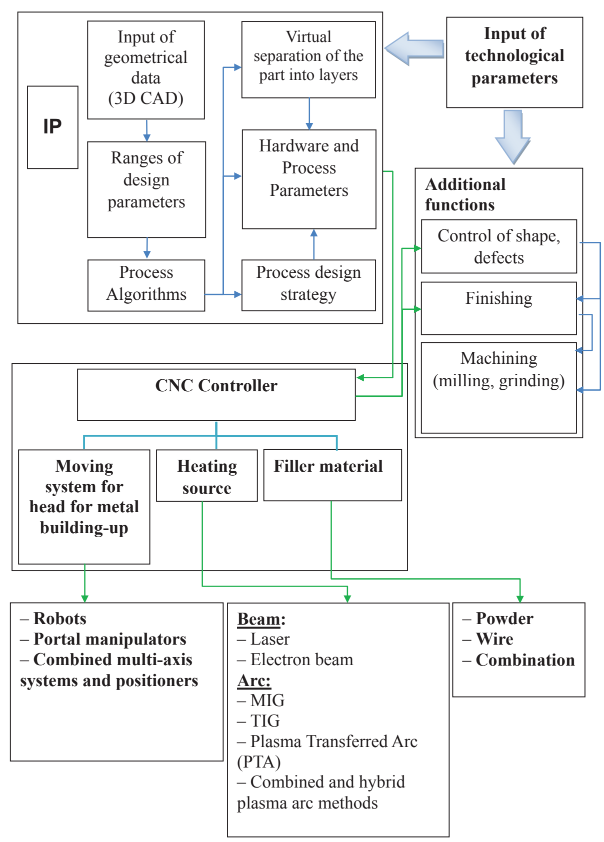
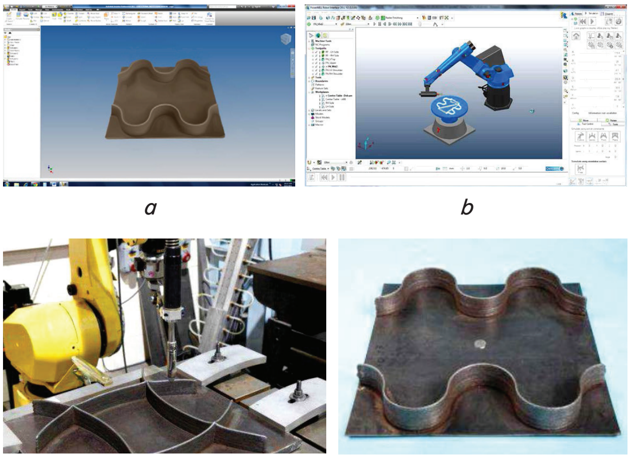


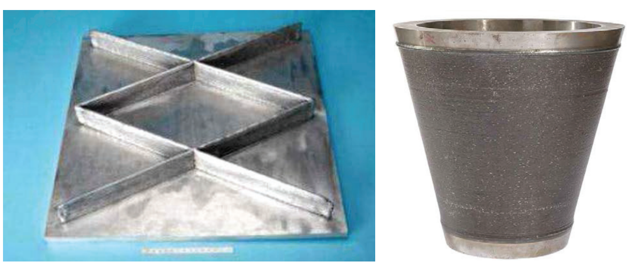
Fig. 1. Principal scheme of the processes of production of three-dimensional metal products using layer-by-layer additive building-up based on welding technologies

With the help of wire-arc additive manufacturing technology WAAM, the volumetric products from various materials are produced, for example, structural low-carbon steel, titanium [18] and aluminum [19] alloys, etc. (Fig. 3–6). To implement this technology, specialized welding equipment was created [20].



a *b* *c* *d*

Fig. 2. Technological process of 3D-printing of three-dimensional metal products with application of the Wire-Arc Additive Manufacturing method [17]: *a* — computer modeling of the part; *b* — software for 3D-positioner or robot with integrated welding equipment; *c* — robotized complex with welding installation; *d* — finished part



a *b*

Fig. 3. Examples of three-dimensional products from carbon steel S355 [17]: *a* — panels with intersecting ribs without machining; *b* — part, machined after manufacturing

a *b*

Fig. 4. Manufacturing of thin-walled conical parts of stainless steel [17]: *a* — before machining; *b* — during machining (the height of the parts is — 1 m, the biggest diameter is 0.5 m)

a *b*

Fig. 5. Manufacturing of satellites cylindrical parts with variable wall thickness, made of aluminum alloys using arc welding (time of the part manufacturing — 6 hours) [17]: *a* — after layer-by-layer building-up; *b* — after machining

a *b* *c* *d* *e*

Fig. 6. Production of complex profile parts with variable wall thickness from high-strength steels using the example of the shell body (height — 800 mm, diameter — 160 mm, wall thickness 18—8 mm, weight — 32 kg, productivity 4 kg/h [17]: *a* — the initial stage; *b* — cylindrical section; *c* — conical section; *d*, *e* — finished parts

Additive welding technologies are one of the only processes of manufacturing of three-dimensional bimetallic parts of complex shape with internal stiffeners. For example, the parts of «structural steel – bronze Cu-3 % Si» obtained in this manner (Fig. 7) are rather difficult to produce with the help of casting technologies, powder metallurgy, etc. The product obtained in this way is characterized by rather high mechanical properties:

– yield strength – 140 MPa;
– ultimate strength – 300 MPa;
– relative elongation – 12 %.

In mechanical tests, the destruction takes place in bronze, and not in the transition zone «steel-bronze» [17].

Also, one of the most promising applications of additive welding arc technologies is the production of volumetric structures from titanium alloys. The possibility of their effective application for the manufacture of panels of complex shape with stiffeners from the alloy Ti-6Al-4V (Fig. 8) has been confirmed [21, 22].

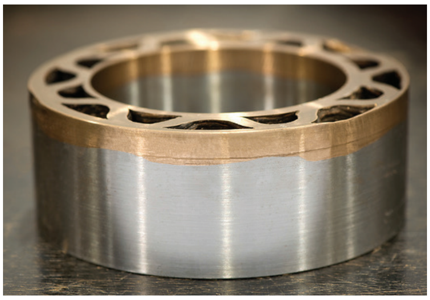
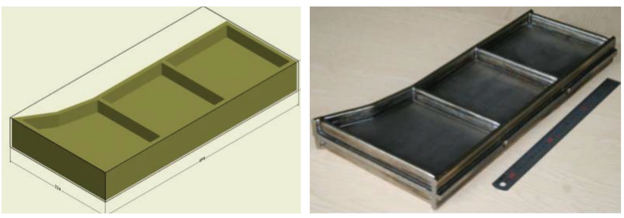


Fig. 7. Volumetric hollow part with internal stiffeners made of bimetal «structural steel – bronze Cu-3 % Si», obtained by means of arc welding (cladding) with current-carrying wire [17]



a *b*

Fig. 8. Panels of complex shape with stiffeners made of Ti-6Al-4V alloy: *a* – volumetric model; *b* – panel, obtained by additive welding technology Wire-Arc Additive Manufacturing

In particular, the use of additive WAAM arc welding technology (Wire-Arc Additive Manufacturing) makes it possible to achieve an increased saving of an expensive titanium alloy in the manufacture of volumetric structures. Thus, for example, the ratio of the weight of the consumed material to the weight of the finished part for WAAM technology is only 1:1. In the manufacture of such a part from sheet billets obtained with cutting and subsequent traditional welding, this index is 4.9 (Table 3) [23]. At the same time, the mechanical properties of obtained parts are close (Table 4) [24]. According to some indicators, the parts made using WAAM technology are superior to those obtained in the traditional way.

In addition, one of the promising directions of WAAM technology use is the manufacture of large-dimension lengthy structures of complex shape made of high-strength aluminum alloys (Fig. 9) [19].

Table 3

Material saving indexes for 3D printing of three-dimensional parts from titanium alloy Ti 6Al 4V using welding technology

Indexes			
Manufacturing method	Initial alloy weight (kg)	Final alloy weight (kg)	Buy-to-fly ratio
Traditional machining of the billet (cutting of sheet billets + their further welding + finish machining)	27.5	5.6	4.9
WAAM + finishing machining	5.0 (billet) + 1.2 (wire)=6.2	5.6	1.1

Table 4

Comparative mechanical characteristics of three-dimensional parts of titanium alloy Ti-6Al-4V, obtained by means of additive welding and traditional technologies

Manufacturing method	Indexes			
	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Crack resistance (MPa*m$^{1/2}$)
Casting + Hot isostatic pressing (Cast and HIP) – AMS 4985 standard	824	896	6.0	75.0
Forging	950	1034	11.7	–
Layer-by-layer building-up using the arc welding method WAAM	805–865	918–965	8.2–14.1	73.9

Fig. 9. Manufacturing of the aluminum structure of the aircraft wing [19]

It should be noted that the WAAM technology is based on the metal inert gas (MIG) welding processes. At this, the mode of pulse modulation of the welding current (for cases of surfacing aluminum alloys) and continuous mode (for other cases) can be used.

4. 2. Typical examples of manufacturing three-dimensional objects using additive welding technologies

At Southern University in Dallas (Texas, USA), the results were obtained that confirmed the effectiveness of the combination of arc technology for the production of three-dimensional objects with simultaneous finish machining (CNC-milling) [11]. A number of technical solutions have been proposed that make it possible to manufacture both relatively simple and rather complex products, including turbine blades made of nickel alloys. Cranfield University (Great Britain) has developed various industrial complexes for the implementation of welding additive welding electric arc technology – both with machining in the process of building up layers, and without it (Fig. 10) [8].

Welding 3D printer Value Arc MA5000-S1 (Japan) was manufactured by the company Mutoh Industries Ltd. in collaboration with the Institute of Advanced Mechanical Systems of the University of Tokyo [25]. In it, unlike most other metal 3D printers, the technology of gas metal arc welding (GMAW) is used for printing of three-dimensional metal products. The use of this technology provides a relatively low cost of the Value Arc MA5000-S1 installation (Japan) and its rather high performance over 500 cm^3/h. This installation has a large enough working space (500×500×500 mm) and can create three-dimensional products of various metals such as steel, titanium, aluminum, nickel alloys, etc. (Fig. 11).

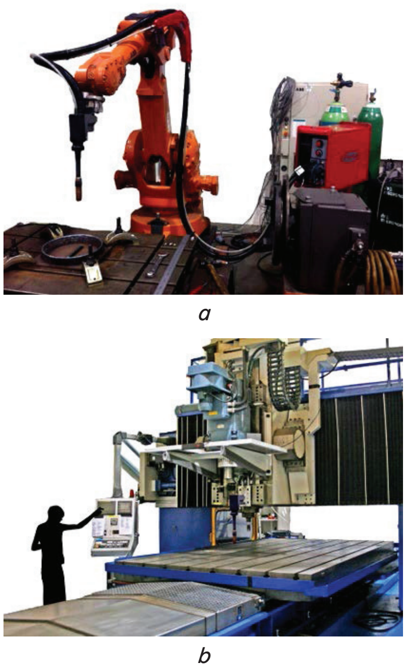


Fig. 10. Complexes for the implementation of welding additive technologies [9]: *a* — on the basis of anthropomorphic robot without machining; *b* — 3-axis complex with CNC-milling system

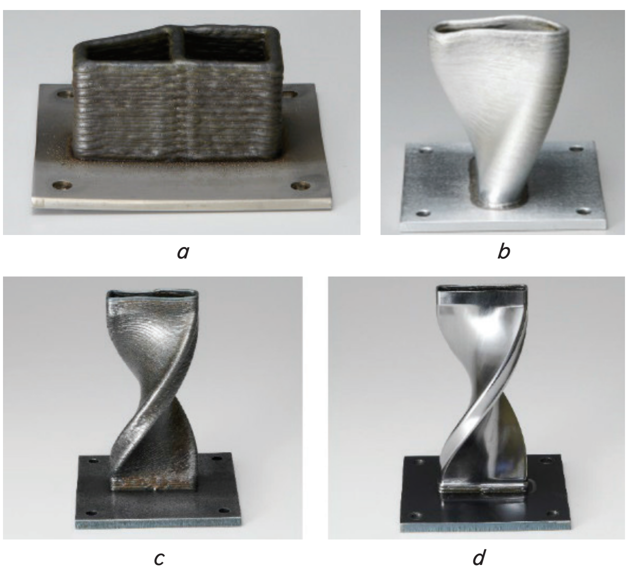


Fig. 11. Three-dimensional products, produced by the arc welding technology with the 3D-printer Value Arc MA5000-S1 (Japan) [25]: *a* — a carbon steel part without machining; *b* — aluminum part without machining; *c* — titanium part without machining; *d* — titanium part after machining

In addition to the described arc technology for three-dimensional printing of metal products, the possibility of using plasma welding technologies is being currently studied. As an example, the results of studies performed at Southern Methodist University TX, USA on studying the process of growing three-dimensional products by microplasma powder layer-by-layer surfacing can be presented [11]. The principal capability of obtaining gradient composite structures by this method is shown (Fig. 12).

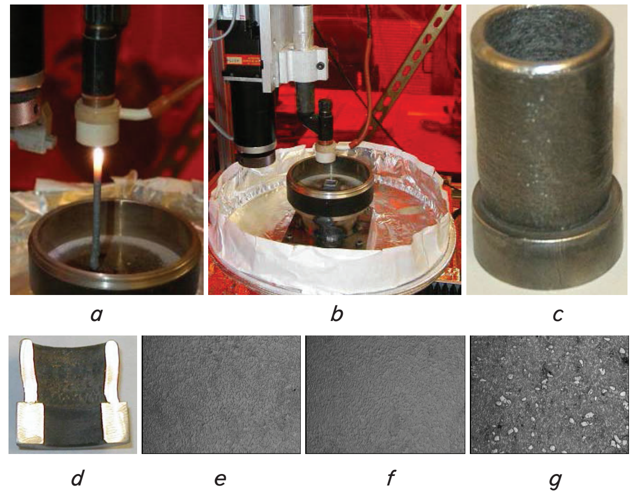


Fig. 12. Microplasma powder growing of volumetric products [11]: *a* — growing process; *b* — laboratory installation; *c* — hollow homogeneous cylinder (tool steel H-13); *d* — cross section of a hollow cylinder with a gradient composite structure (tool steel H13 + tungsten carbide); *e* — structure in the upper part of the cylinder; *f* — structure in the middle part; *g* — structure at the bottom

In addition to the products of machines and mechanisms, welding technologies of three-dimensional printing allow creating large-scale construction metal structures. An example is the creation of a new additive technology based on the arc welding process using a wire, called MX3D (Holland) [26]. The MX3D project was created in the laboratory of JORIS LAARMAN LAB in cooperation with ACOTECH and HAL (Holland). This new technology has great prospects, because it allows you to quickly create complex metal structures without erection any supporting structures, for example, scaffold or temporary intermediate supports (Fig. 13). In the process of three-dimensional welding of MX3D, a person or a welding robot itself builds a support and moves forward along the erected structure. This accelerates and simplifies the construction, in addition, the MX3D can be fully robotic and work around the clock.

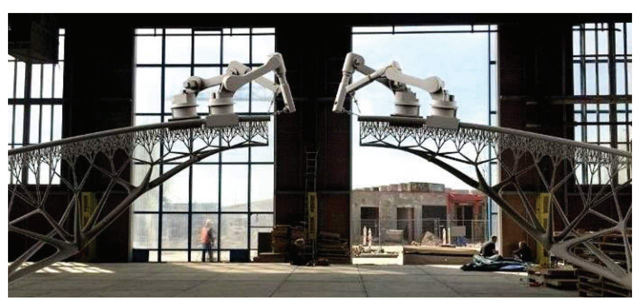


Fig. 13. The process of manufacturing a bridge using a welding 3D-printer [26]

In the analyzed papers, we have mainly studied the possibilities of using welding processes such as gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW) for three-dimensional printing. These processes provide good metallurgical adhesion, as well as protection of the weld pool and built-up layers of the products from the formation of oxides. However, these processes, with their accessibility, also have such drawbacks as the significant size of the heat-affected zone (HAZ) and the relatively large dimensions of the built-up layer, which leads to undesirable temperature gradients and accumulation of residual stresses. In addition, as a consumable (filler) material for forming three-dimensional products, the usual welding wire is used, which limits the chemical composition and properties of these products.

Plasma Transferred Arc Welding (PTA) technologies have a wider technological capability [12]. Their use for manufacturing three-dimensional metal objects instead of the considered arc welding processes can reduce or eliminate some of these disadvantages.

4. 3. Creation of the equipment for the development of new welding technologies for manufacturing volumetric products

The use of such plasma arc welding technologies, which use a jet of laminar plasma [27] is attractive for 3D printing of metal parts. It is also advisable to use known plasma cladding technologies [28]. For this, in the E. O. Paton Electric Welding Institute of the NAS of Ukraine (Kiev, Ukraine) in cooperation with the South China University of Technology (Guangzhou, China), the corresponding industrial equipment was designed [29].

To increase the competitiveness of the equipment, the authors refused to use expensive anthropomorphic robots. Instead, an original inexpensive and technologically advanced 3D positioner for replaceable plasma welding-surfacing heads was developed (Fig. 14). As consumable additives in such heads, both powders and wires are used. The technical advantages of this equipment (in comparison with the welding robot) are the simplicity of manufacturing large-sized products, as well as increased accuracy.

Fig. 15–17 show the nodes of 3D printer PLAZER 3D PW (Scientific and production Center PLAZER, Ukraine). Its power source is designed to implement additive technologies of powder microplasma (welding current up to 50 A) and plasma (welding current up to 120 A) surfacing. The printer includes a 3D positioner of the original design with a working zone for the transfer of the welding head 900×900×900 mm (Fig. 15). The plasmatron is able to operate in modes of constant and pulse current of direct polarity, heteropolar pulse mode, etc. [30] (Fig. 16). The control of the plasmatron positioning is carried out using the CNC system, which is combined with the power source and console panel of the powder feeder (Fig. 17). Control of the 3D printer is carried out by a PLC-controller with the ability to exchange data on the modes of 3D printing and control commands with the computer.

With the use of the created 3D-printer PLAZER 3D PW, a number of experiments were performed, which allowed developing the basic technological methods of additive plasma-arc manufacturing of volumetric metal products. The developed equipment and technology have the following advantages in comparison with the widely used selective laser melting processes SLM (Table 5):

– the yield of the building-up metal for the same power consumption is higher by 1–2 orders, while the specific cost of the equipment (1 kW) is 3–10 times lower;

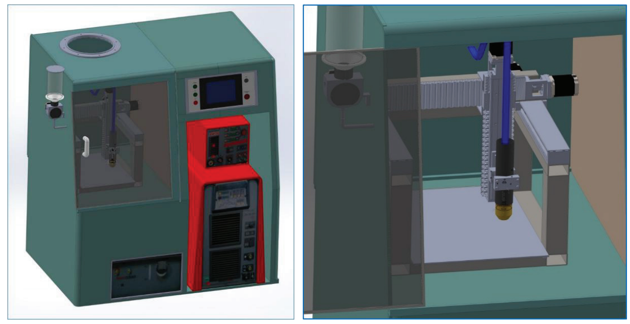
– the possibility of a significant increase (10 times or more) in the overall dimensions of the created parts;

– the possibility of increasing the number of degrees of freedom of the tool;

– the possibility of flexible changeover for the use of powder and wire consumables;

– a wider range of used consumables for 3D printing (powders, wires, composites);

– a higher utilization factor of the filler material (by 20–50 %).



a *b*

Fig. 14. Model of 3D-printer PLAZER 3D PW for the development of new plasma technologies for manufacturing volumetric products: *a* – general view; *b* – three-axis plasmatron positioner

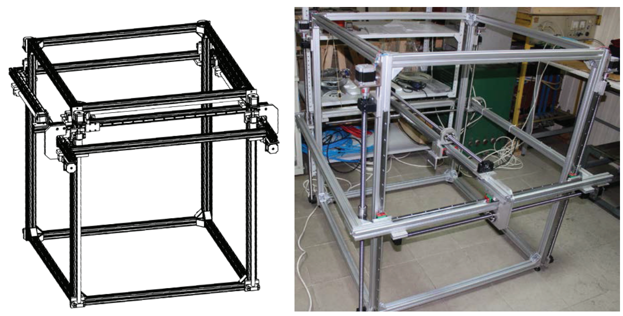


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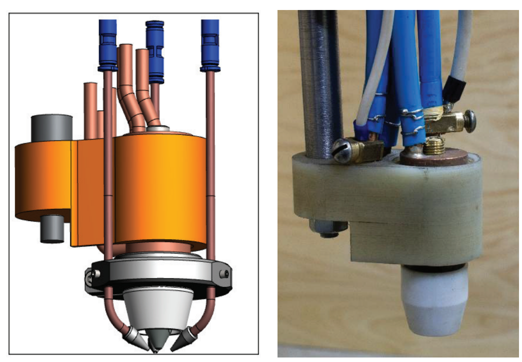
Fig. 15. Three-axis positioner of PLAZER 3D PW installation: *a* – computer 3D-model; *b* – external view



a *b*

Fig. 16. Plazmatron for 3D printing of PLAZER 3D PW installation: *a* – computer 3D-model; *b* – external view

a *b*

Fig. 17. The PLAZER 3D PW installation: *a* – manipulator with a plasmatron and a powder doser-feeder; *b* – view of power supply and control unit with the open front panel

Table 5

Comparison of the main technical and economic indicators of SLM-technologies of 3D printing of metal products with the developed additive plasma-arc technology

Indicators	Metal parts 3D-printing technologies			
	SLM (LENS company)	SLM (POM company)	SLM (AeroMet company)	Additive plasma-arc technology (3D-printer PLAZER 3D PW)
Equipment characteristics	Laser Nd:YAG, power of 1 kW	Laser CO_2, power of 2 kW	Laser CO_2, power of 14 kW	Based on welding 2–20 kW
Yield of building-up metal, (cm^3/hr)	8	8	160	>500–5000
Possibility of multi-axis (degrees of freedom) machining	3 axes	3 axes	3 axes	4–5 axes
Maximum dimensions of the grown parts	100 mm	200 mm	350 mm	900 mm and more
Type of material used for 3D printing	Metal powder	Metal powder	Metal powder	Metal and alloy powders, composition materials powders, powder mixes. Wire – solid and flux-cored
Material Utilization Rate, %	Near 40 %	Near 40 %	Near 70 %	More than 90 %
Application areas	Manufacture and repair of small expensive complex shape parts	Manufacture and repair of small expensive complex shape parts	Manufacture and repair of small expensive complex shape parts	Manufacture and repair of medium- and large-sized three-dimensional parts of different purpose
Approximate cost of major items of equipment	Laser: $80.000...$120.000 per 1 kW of power			Welding equipment: $ 1000...$ 5000 per 1 kW of power

It should be noted that the mechanical strength of products obtained with additive plasma arc welding technology is predominantly 90...95 % of the strength of the cast metal, which is not always achieved in the SLM process.

5. The results of studies of the current state of additive welding technologies for the production of volumetric products

As the analysis of literature sources has shown, the quality of volumetric products obtained with the help of plasma technologies is higher than the quality of similar products obtained by means of additive arc welding processes (for example, WAAM) [12]. However, it is inferior to the quality of products obtained by selective laser melting, in terms of accuracy of geometric dimensions and surface roughness. This problem can be solved by combining the technology of plasma surfacing with CNC milling. The formation of an accurate geometric shape of the product and finish machining are carried out using a single software and control system. As described above, this approach has been successfully implemented in 3D printing processes using arc welding technology. It should be noted that in the overwhelming majority of cases, three-dimensional parts obtained by selective laser melting are also subject to sizing and finishing. Therefore, the difference in costs for the final machining of volumetric parts made by additive plasma cladding and the SLM method is not significant for the cost index.

Based on the equipment developed in PWI (Fig. 14–17), the development of a line of 3D printers for the printing of three-dimensional metal products of complex shape with increased dimensions of the working zone for the movement of the surfacing heads and, accordingly, the growing products (from more than 900 mm – up to several meters) is currently being carried out. In this case, it is envisaged to use not only plasma or microplasma powder overlaying, but also combinations of plasma and electric arc welding heads and hybrid processes in such equipment (for example, plasma-MIG welding technology with a current-carrying wire [31]). The prospect of such equipment is based on the advantages and high efficiency of plasma technologies in the welding of aluminum and other difficult-to-weld alloys [32]. The use of hybrid equipment is very promising for the manufacture of large-sized three-dimensional parts with increased productivity and mechanical characteristics.

The advantages of arc plasma compared to conventional electric arc are a higher temperature, degree of energy concentration, and a smaller width of the heating source [33]. Accordingly, plasma surfacing allows additive growth of narrower layers with lower heating of the product during its growth. In addition, for the additional minimization of the thermal effect, the use of non-transferred arc plasmatrons is possible. At the same time, the performance of plasma technologies is not inferior to the electric arc technology. Consequently, for the additive manufacturing of three-dimensional metal parts, the use of plasma welding (cladding) technologies makes it possible to reduce these drawbacks of arc welding.

The PWI has many years of experience in using plasma technologies to produce welded joints and welded metal layers (for example, [33–35]). This experience shows that such technologies are able to provide a new level of 3D printing indices and properties of the obtained products in comparison with the considered arc welding methods (WAAM, MX3D, GMAW, GTAW, etc.). There are the following advantages of welding (cladding) plasma-arc technologies:

– plasma arc torch inner temperature may reach 30000 °C that is five or six times more than in the ordinary electric arc, that's why plasma can melt almost any refractory material for the three-dimensional parts layer-by-layer building-up;

– cylindrical shape of the arc (in contrast to the conventional conic shape);

– arc pressure on the metal is 6–10 times higher than that of the ordinary arc;

– possibility to maintain the arc at low currents (0.2–50 A) in microplasma welding modes;

– minimal heating of the previously deposited layers during the parts formation; heat penetration into the base metal is mainly less than 5 %;

– no metal spattering during the layers building-up; extremely low metal mixing;

– possibility to regulate the thicknesses within a wide range (from 0.5 to 5.0 mm) and widths (1.5–50.0 mm) of the deposited metal layer during the three-dimensional parts additive building-up;

– possibility to regulate the gas environment composition (reducing/inert/oxidizing) during the additive building-up of layers in the part formation;

– higher efficiency and performance of the process (2–3 times and more);

– possibility to use a wide range of consumable materials (powders of metals and alloys, composite materials, solid and flux-cored wires, etc.);

– possibility to change the metal composition during the parts formation; obtaining the parts with a gradient structure.

6. Discussion of the results of studies of the current state of additive welding technologies for the production of volumetric products

The analysis of the current state of the modern industry in the use of arc welding technologies has confirmed their prospects for the manufacturing of large-sized three-dimensional parts from low-carbon, high-strength, alloyed steels, nickel, aluminum, titanium and other alloys. The production of lightweight hollow and bimetallic volumetric products, as well as long-length building structures is also promising.

The use of additive welding arc technology makes it possible to achieve significant savings of costly alloys in the manufacture of three-dimensional structures. For example, the ratio of the weight of the consumed material to the weight of the finished complex shape part with stiffeners made of titanium alloy Ti-6Al-4V for the Wire-Arc Additive Manufacturing technology is 1.1. For traditional production (cutting of sheet billets, welding, machining), this figure is 4.9. By mechanical properties, the resulting printed products are close, and in some respects superior to the given alloy in a cast state after thermomechanical processing (hot isostatic pressing, forging).

The main disadvantages of arc welding processes for 3D printing of metal products are:

– significant size of the heat-affected zone (HAZ);

– rather large dimensions of the buildup layer;

– increased residual stresses;

– restrictions on the composition and types of filler materials.

To reduce (or eliminate) the negative impact of these disadvantages, it is advisable to use the plasma arc technology.

The promising nature of this approach is related to:

– higher temperature in the plasma arc flame;

– its smaller dimensions and arc pressure on the molten metal;

– minimizing the heating of previously deposited layers and less penetration of the deposited metal into the main one;

– the possibility of adjusting within a wide range of thickness (from 0.5 to 5.0 mm) and width (1.5...50.0 mm) of the deposited metal layer;

– the possibility of using a wider range of consumables (powders of metals, alloys, composite materials, powder mixtures, solid and flux-cored wires);

– the possibility of forming products with a gradient structure.

Additive plasma arc technologies of 3D printing of volumetric metal products in comparison with the widely used selective laser melting (SLM) process differ as follows:

– higher yield of the grown metal (by 1–2 orders) at a lower unit cost of the equipment (3–10 times);

– no restrictions on the maximum size of the grown parts when the mechanical strength of the products reaches 90...95 % of the strength of the cast metal.

To solve the problem of lower (compared with the SLM-technology) accuracy of geometric dimensions and roughness of the surface of volumetric products obtained by welding technologies, it is advisable to combine these technologies with CNC milling.

7. Conclusions

1. The analysis of the current state of 3D technologies for the production of volumetric metal products showed the following. For the production of precise parts of small dimensions, it is advisable to use laser technologies (for example, SLM). For the production of large-sized parts, it is advisable to use welding technologies (for example, WAAM, PTA). Among the additive welding technologies, the plasma arc welding ones are the most promising. In them, high (5...50 kg/h and more) capacity is combined with the possibility of obtaining sufficiently thin (1.5...5.0 mm) walls with a relatively small overheating. The use of additive plasma-arc printing makes it possible to increase the accuracy of manufacturing and the quality of the surface of volumetric metal products in comparison with other arc welding methods.

2. The main advantages of additive welding technologies for the production of three-dimensional metal structures of complex shape in comparison with SLM-technologies are:

– increase in the process productivity by 1–2 orders with the same power consumption; 3–10 times reduction in the cost of equipment;

– the possibility of increasing the overall dimensions of the created parts by a factor of 10–100 or more times;

– expansion of the range of used consumables (powders, wires, composite materials);

– increase in the utilization factor of consumables by 20–50 %.

– about 20 times reduction of the equipment cost.

The main drawbacks of additive welding technologies for the production of three-dimensional metal structures are quite large dimensions of the heat-affected zone and the build-up layer. This leads to the emergence of undesirable temperature gradients, the accumulation of residual stresses and, as a result, a decrease in performance. One of the methods for eliminating these drawbacks is to increase the thermal locality of the energy source. For example, the use of non-transferred arc plasma.

3. Additive welding technologies allow achieving approximately 5-fold savings of materials in combination with an increase in the quality (for example, strength and density) of the resulting metal parts, compared to traditional methods of mechanical manufacture.

4. To date, in the manufacture of industrial equipment for 3D printing of metal products, two main approaches are used: without concomitant machining and with it. In the first case, anthropomorphic robots are widely used for the implementation of welding technologies. In the case of plasma arc welding technology, it is advisable to use 3D portal positioners that enable the use of concomitant machining.

5. In Ukraine, a sample of industrial 3D printer PLAZER 3D PW is developed for manufacturing volumetric metal products up to 900×900×900 mm. It is based on additive technologies of powder microplasma (welding current up to 50 A) and plasma (welding current up to 120 A) cladding. The experiments carried out with the help of this sample confirmed the prospects of using additive plasma-arc technologies. In particular, it has been established that the utilization factor of the consumable material is increased by 25–40 % compared to the wire electric arc surfacing.

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