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PLASMA-ARC TECHNOLOGIES OF ADDITIVE SURFACING (3D PRINTING) OF SPATIAL METAL PRODUCTS: APPLICATION EXPERIENCE AND NEW OPPORTUNITIES

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ABSTRACT

The growing relevance of 3D printing of finished metal products in recent years is predetermined by the reduction of costs for manufacturing, machining, changing the standard sizes and nomenclature of parts, the possibility of manufacturing solid parts with complex internal geometry. One of the most promising 3D printing processes, which provides a wide range of productivity (0.02–25 kg/h and more) with the possibility of surfacing a wall with a thickness of 2-20 mm, is additive plasma-arc surfacing (APAS) with wires and powder materials. The work examines the state-of-the-art of research on additive manufacturing of metal parts from steels and alloys, determines the state and prospects for the development of APAS. It is shown that APAS allows performing 3D printing using a wide range of filler materials, in particular, compact and composite (powder) wires, powders of light alloys and refractory metals, composite powders and mechanical mixtures of powders of alloys, metal ceramics, carbides, borides, etc. New opportunities for the application of APAS include development of technologies for growing products from materials with gradient functional properties, from dissimilar materials, with accompanying modification of the deposited metal by additional treatment, improving the properties of the deposited metal due to the use of hybrid processes. The state of innovative developments of APAS technologies and equipment carried out at the PWI of the NAS of Ukraine, and their industrial implementation is highlighted.

KEYWORDS: additive manufacturing, 3D printing, plasma-arc surfacing, steel, nickel, aluminium, titanium alloys, structure, mechanical properties, gradient functional properties, equipment

INTRODUCTION, AIM AND TASKS OF WORK

In recent years, there has been a qualitative leap in the approach to the use of 3D printing processes, associated with the transition from the creation of prototype models, according to which metal products were fabricated, to the direct printing of such products from various metals and alloys [1]. Modern AM — Additive Manufacturing is an innovative manufacturing process that offers the manufacture of products with advanced surface geometry of the required size with a surface that requires a minimal mechanical treatment, directly from CAD models, which leads to shortening in manufacturing time, a reduction in the volume of wastes and final cost. For example, the cost of additive surfacing of titanium parts of aircraft engineering is twice as low as the cost of their production from forged billets [2]. Another important area of application of additive manufacturing is military affairs. Thus, due to the extreme flexibility and the possibility of adaptation to the solution of a wide range of industrial problems, the additive growing of parts is becoming more and more relevant in the modern world.

In modern additive manufacturing, two main approaches are predominantly used to obtain a finished metal product [1, 2]: layer-by-layer selective melting of powder and direct layer-by-layer growing of a part wall from the material in the form of powder or wire. For the processes of selective powder melting, laser (SLM) or electron beam (EBSM) energy is used. Both of these processes provide the formation of parts according to the dimensions specified in the models. After 3D printing by these methods, in most cases, mechanical treatment of a part surface is not used. However, these methods have a number of significant disadvantages, namely: dimensions of parts that can be printed are limited by the dimensions of the installations for printing by these methods (the working field is not more than 800×800×800 mm); complex expensive equipment; the need in using powders of the correct spherical shape of tiny sizes (5–15 μm), which are expensive and explosive and fire-hazardous; the need in using several times more powder than the volume of a finished part; when growing a part with gradient differences in mechanical properties, when gradually using powders of different chemical composition, their mixing occurs outside the fusion zone, which causes the need in rejecting the powder that remains in the installation after the printing is finished.

Often in production it becomes necessary to form a billet from a certain material with mechanical treatment after growing. In such a case, it is advisable to use additive growing with the help of electric arc melting of the material supplied into the welding pool, namely [3]: argon-arc surfacing with a nonconsumable electrode (TIG) with a filler wire; surfacing using consumable electrode, including submerged-arc surfacing (SAS), shielded-gas consumable electrode (MIG/MAG process and, as a variant, cold metal transfer CMT), as well as additive plasma-arc surfacing (APAS) by powders or filler wires.

Plasma-arc surfacing is the most promising from the point of view of growth productivity, increase in material utilization rate, quality of the deposited metal, and the possibility of reducing the process of mechanical treatment of a billet due to the maximum approximation to the real dimensions of a part [4]. The APAS process can be implemented in the current range of 3–450 A. At the same time, the welding/surfacing process at currents of up to 50 A has received a separate name — microplasma welding/surfacing [5].

A significant contribution to the development of 3D printing of metal materials using constricted arc energy and powder materials and filler wires was made by scientists of the PWI and Paton IMSW [3–5].

Among the additive technologies that use surfacing methods, the processes DED-W/ WAAM/3DMP (Wire Direct Energy Deposition/Wire Arc Additive Manufacturing/3D Metal Print), or WAAM — additive surfacing using metal wire have become most widespread, which include arc processes using a nonconsumable and consumable electrode, as well as processes with a short circuit of the arc gap (of CMT type — Cold Metal Transfer) [3]. CMT is a modified version of welding using consumable electrode in a shielding gas based on the mechanism of the controlled metal transfer mode into the welding pool by using pulsed current and reciprocating wire movement.

Among the arc CMT methods, the process of additive technologies has a number of indisputable advantages. One of the most important is the system of reverse wire feed, synchronized with a high-speed digital control, which determines the arc length, short circuit phase and heat transfer into the welding zone [6]. This process provides minimal spattering of metal, relative stability of weld formation, reduced heat transfer to the treatment zone. However, the CMT process in terms of using in additive technologies has its disadvantages: relatively low productivity due to the use of small diameters of wires and presence of significant inner defects (pores, inclusions).

The use of APAS provides a number of advantages from both a technological and economic point of view. These include high productivity, wide range regulation of heat transfer to the base and deposited materials and, as a result, control of the penetration depth and width, structure, composition and properties of the material being formed. APAS with the use of direct current of reverse polarity or alternating current provides cleaning of the surface of the previous layer from contaminations due to the effect of cathode atomization, sufficient wetting and spreading of liquid metal at a minimal heating of the surface. At the same time, manufacturing of layered materials with a favorable structure without inner defects is provided. In addition, the compared simplicity and low cost of the equipment for plasma surfacing should provide the interest of manufacturers for using in additive technologies [3, 7].

The abovementioned predetermined the powerful potential of application and development of APAS technologies. Such advantages and wider technological capabilities of APAS over WAAM methods should be noted [3, 8]:

- wide adjustment of the productivity of 3D printing (0.02–25 kg/h) and the degree of detailing volumetric elements (widths from 2.0–2.5 to 10–20 mm) by implementing the process both in the mode of microplasma surfacing with a low-ampere plasma-arc (at currents of 5–35 A), as well as at currents of 50–450 A and higher (depending on the capacity of the power source);
- a wide range of adjustment of the input energy, heating zone and penetration depth of previously deposited layers by means of APAS using a direct or tangential plasma-arc;
- 3D printing at direct current of direct and reverse polarity, alternating current, including the implementation of the process of cathodic cleaning and destruction of oxide films, when surfacing light metals and alloys with refractory oxide films on their surface;
- 3D printing using one to four filler wires, including a conductive filler wire with preheating;
- use of compact and composite (flux-cored) wires, powders of light alloys and refractory metals, composite powders and mechanical mixtures of powders of alloys, metal ceramics, carbides, borides, etc. for 3D printing as a filler material;
- implementation of the 3D printing process using an filler that does not move together with the plasmatron during deposition of a layer (metal grit, foil, thin bands of metal), which is applied alternately af-

Table 1. Comparison of basic technical and economical indicators of different technologies of additive surfacing (3D printing) of volumetric metal products

Number	Technology	Average value of width of single deposited layer, mm	Average sizes of roughnesses of free surface of manufactured products, mm	Deviation of geometric sizes of a product, mm	Productivity of manufacturing of a 3D product, kg/h	Specific losses of electric power, kW/kg	Characteristics of strength (% from the tensile strength of initial filler material)	Characteristics of ductility (% from the parameter of elongation of initial filler material)
1	WAAM (arc additive surfacing using current conducting consumable MIG/MAG wire)	4.0–6.5	0.5–2.0	0.5–1.5	0.3–15.0	6–18	0.80–0.90	0.85
2	WAAM (arc additive argon-arc surfacing using consumable electrode with the feed of neutral filler TIG wire)	6.0–8.0	0.5–1.0	0.5–1.0	1.0–4.8	7–15	0.50–0.80	0.85
3	WAAM (CMT)	2.0–4.0	0.3–0.6	0.2–0.8	0.5–7.0	5–10	0.80–0.90	0.75–0.80
4	Microplasma layer-by-layer powder surfacing	1.6–3.2	0.1–0.5	0.1–0.5	0.01–0.3	4–8	0.9–0.95	0.85–0.90
5	Microplasma layer-by-layer wire surfacing	2.0–3.5	0.2–0.8	0.2–0.8	0.02–0.4	5–10	0.9–0.95	0.85–0.90
6	Plasma layer-by-layer wire surfacing	3.0–4.0	0.5–1.0	0.2–0.8	0.2–10.0	5–12	0.9–0.96	0.85–0.90

ter deposition of each layer (a process similar to the methods of "lamination" or selective melting);

● possibility of launching a plasma-arc without adding wire or powder, which allows preheating of the base or deposited layers before additive surfacing.

A comparison of basic technical and economic indicators of additive surfacing processes using a free arc with the processes using a constricted (plasma) arc also confirms the advantages of additive plasma-arc technologies (Table 1) [3–8].

The aim of the work is to analyze the state-of-the-art of scientific research, technological developments and practical experience of additive manufacturing of metal products from various types of alloys and composite materials; identification of the potential of application and development of additive technologies of plasma-arc surfacing, in which a plasma-arc is used as a heating source; identification of new opportunities and promising directions for their further development and application.

To achieve this aim, the following tasks were solved in the work:

1. Analysis of the state of scientific research and practical experience of APAS of volumetric products from various types of alloys.

2. Identification of new possibilities of plasma-arc technologies in additive manufacturing, including when applying hybrid and combined methods of 3D-printing.

3. Description of the developments of new equipment for the implementation of APAS technologies in additive manufacturing.

1. APPLICATION OF APAS TECHNOLOGIES (3D PRINTING) OF SPATIAL METAL PRODUCTS

1.1 APAS OF VOLUMETRIC PRODUCTS FROM STEELS AND IRON- AND NICKEL-BASED ALLOYS

A number of problems arise during additive manufacturing of 3D objects from steels, iron-, and nickel-based alloys, related to their overheating during the surfacing process. For example, during CMT printing of a wall made of 2Cr13 steel, a small number of pores without cracks in different layers was observed, which indicates a high level of densening [6]. The precipitated microstructure consisted of martensite and ferrite together with the (Fe, Cr)$_{23}$C$_6$ phase, which is precipitated on α-Fe grain boundaries. However, due to overheating, the content of martensite gradually increased from the 5th to the 25th layers, despite a partial decomposition of metastable martensite into stable ferrite due to the diffusion of carbon atoms. The hardness changed slightly from the 5th to the 15th layers and then increased rapidly from the 20th to the 25th layers; the fracture process transformed from ductile (1st–10th layers) to mixed (15th–20th layers) and, finally, to brittle fracture (25th layer). Thus, in order to adjust the 3D printing process with a stable formation of the product structure, it is

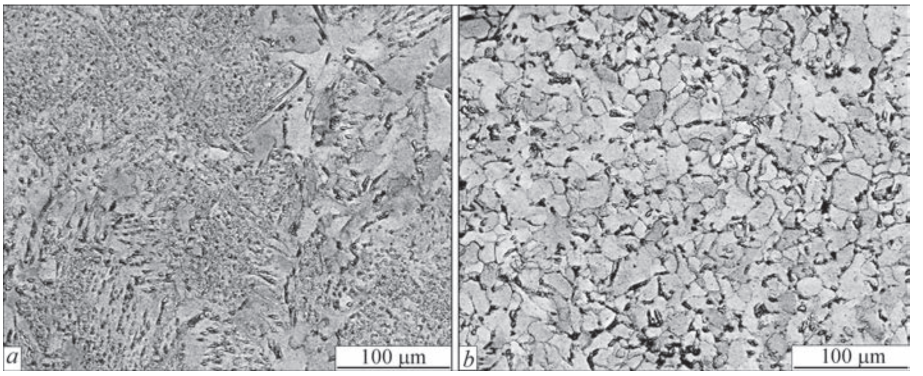

Figure 1. Microstructure of spatial product of the type "thin wall" manufactured by additive microplasma surfacing with the feed of neutral filler wire Sv-08G2S: *a* — upper layer; *b* — middle of the wall (electron microprobe analysis in CamScan-4 analyzer

necessary to change the technological approach. One of the promising options here is APAS.

Thus, the APAS process is proposed to produce parts with an increased wear resistance from intermetallic alloys, for example, iron aluminide. In [9] it is shown that it is possible to manufacture parts from an iron-nickel-aluminium intermetallic compound using this method. In [10], it is proposed to use plasma-arc 3DPMD technology for the additive manufacturing of wear-resistant functional layers of wear surfaces and the body of the tool from alloys based on nickel Ni 625 and iron-based PS Fe-hard D. Plasma-arc surfacing using wires (up to 120 A) and microplasma surfacing with powder materials (at a current of up to 50 A) for the manufacture of products from carbon and stainless steels is proposed in [11]. The study of the peculiarities of the manufacturing processes of steel spatial primitives of the type "wall", "glass", "cone" and "hemisphere" showed that the deviations from the nominal size during their manufacture do not exceed ± 0.5 mm, the porosity lies within 1–2 %, and the mechanical strength is about 90–95 % of the strength of cast metal. The structure of the deposited material is fine-grained and uniform, mixing of layers is extremely low.

The analysis of the microstructures of the specimen of additive microplasma surfacing using the filler wire Sv-08G2S (of 1.2 mm diameter), performed at the PWI of the NASU, showed the absence of cracks and pores and that the structure is homogeneous and uniform similar to the structure of specimens deposited by the microplasma method using filler powder. The walls are characterized by a density that corresponds to a cast structure, with grains of small sizes, without dendrites. Porosity, inclusions and microcracks are absent. Discontinuity between the contacting layers along the fusion line is absent; the size of the heat-affected-zone of the build-up layer is ~2 mm. The microstructure of the deposited material is equiaxial, the grain has approximately the same sizes in all directions (15–20 μm) with clearly visible boundaries and a eutectic component between them (Figure 1). These are grains of ferrite (light grains) and pearlite (dark regions). The multilayer structure of the deposited volumetric specimen is not revealed, mixing of the deposited layers is extremely low, the formation of oxides is not observed.

In the case of the WAAM process using MAG surfacing with Sv-08G2S wire (1.2 mm diameter), the microstructure of the deposited metal is represented with ferrite and pearlite grains (Figure 2). The difference of this structure from the analogues produced by microplasma surfacing using the same wire is the coarser grain size, as well as the presence of primary crystals in the form of dendrites and eutectics. Dendrites appear in the form of tree-like formations with clear axes of individual branches. The interlayers of

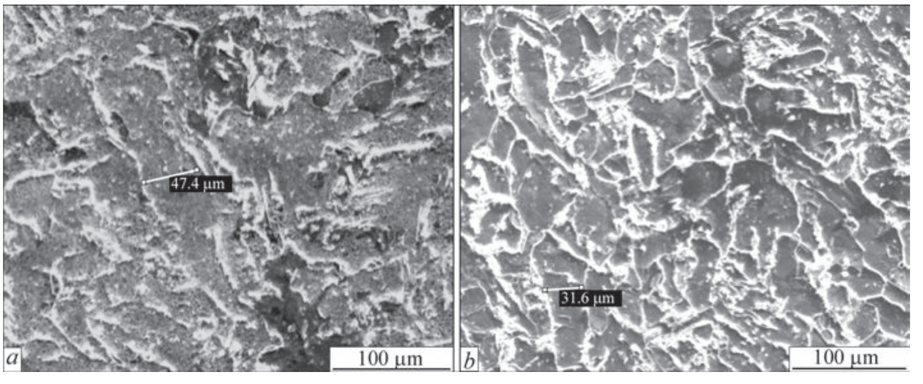

Figure 2. Microstructure of spatial product of the type "thin wall" manufactured by the WAAM (MAG) method using the wire Sv-08G2S: *a* — upper layer; *b* — middle wall of electron microprobe analysis in CamScan-4 analyzer

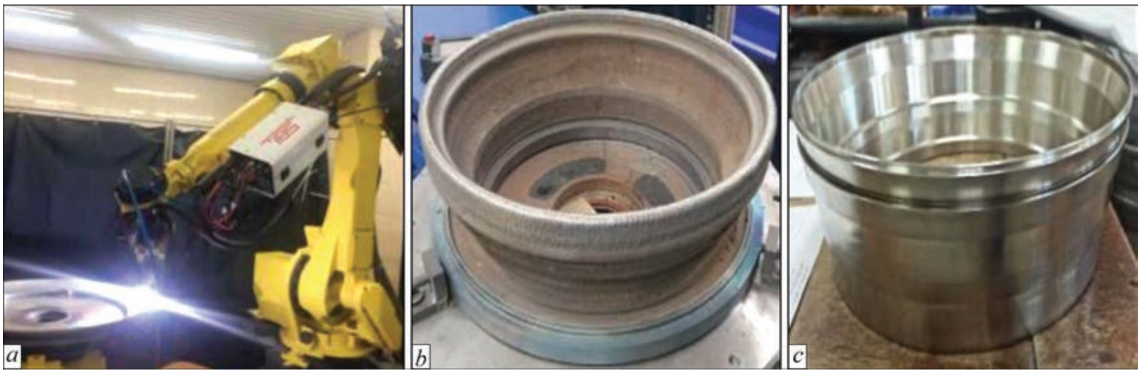

Figure 3. APAS process (3D printing) of a billet of nickel heat-resistant EI 868 (KhN60VT) alloy (*a*), billet of a part after 3D printing (*b*), finished part after machining (*c*) [14]

another phase, which is a part of the eutectic, are revealed between the primary crystals. It can be said, that the eutectic structurally degenerates, it appears in small quantities as a result of nonequilibrium crystallization. Its formation is facilitated by the slowed down cooling compared to microplasma surfacing. The distance between the branches of dendrites of the main ferrite phase during such cooling is quite large, so the eutectic has a coarse structure. There is no formation of oxides, but large sizes of wave-like ridges on the surface can be noted.

The difference between the specimens produced by additive MAG surfacing and the specimens produced by microplasma technology is primarily contained in the tendency of increasing the granularity and sizes of HAZ with an almost unchanged content of silicon and manganese. This can be explained by higher input energies and, accordingly, a higher intensity of heating of the built-up layers during MAG surfacing.

In [12], the principle possibility of using plasma-arc (microplasma) with a pulsed current for 3D printing of steel volumetric metal products with sufficient geometric detailing was also confirmed. At the same time, the grains of the deposited layers change their structure from a relatively small grain size near the substrate to a very coarse structure with a large grain size near the apex of a product. At the same time, as a material for 3D printing, the possibility of using steel shot with a size of about 1 mm is shown. However, in the case of using such a filler material by the method of microplasma surfacing, the productivity is low (of about 50 g/h) in the case of control of product temperature and cooling after each layer during a certain waiting time [12]. Such an approach allows adjusting the grain size and hardness of printed volumetric steel products.

For the additive manufacturing of components with a complex geometry from carbon and alloy steels, APAS applying wire and powder filler materials is also used in the manufacture of tools with complex contour surfaces for transverse rolling [13].

The successful experience of APAS of critical products of the hot duct of aircraft engines with the use of a filler wire from the nickel heat-resistant EI 868 (KhN-60VT) alloy has also been gained (Figure 3) [14].

To provide an optimal combination of a quantity and morphology of strengthening phases of the alloy and a favorable combination of ductility and heat resistance characteristics, the heat treatment was carried out at T = 1200 °C. The macrostructure of the specified products, specimens before and after heat treatment is layered, typical for multilayer surfacing with a clear distribution of layers (Figure 4, *a*, *b*) [14]. The

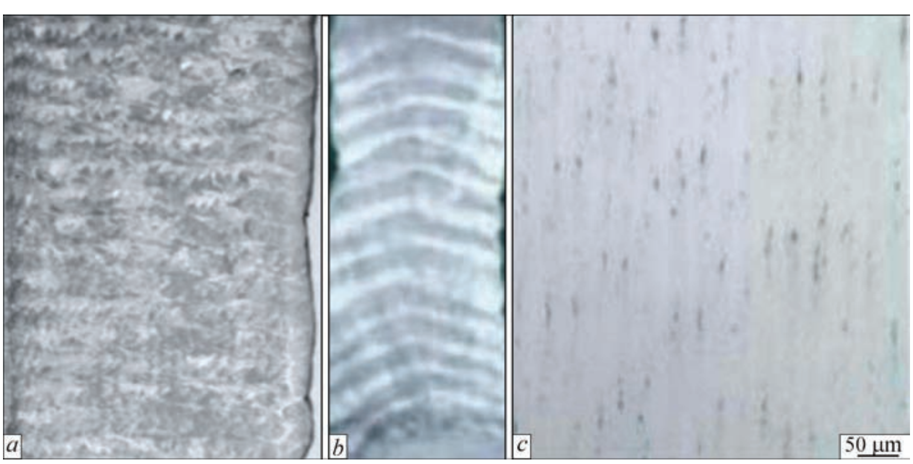

Figure 4. Macro- (*a*, *b*) and microstructures (*c*) of the material of volumetric products of nickel heat-resistant EI 868 (KhN60VT) alloy produced by additive plasma-arc surfacing: *a* — longitudinal direction; *b*, *c* — transverse direction [14]

Figure 5. APAS process of three-dimensional structure of the type "wall" with the use of filler wire from aluminium alloy

microstructure after heat treatment at a magnification of ×200 is shown in Figure 4, *c*. During the analysis of the microstructure of the specimens after heat treatment, the presence of a dendritic structure with elongated grains in the direction of heat removal in the process of layer-by-layer growing (across the layers) was found (Figure 4, *c*). In the microstructure, the fusion lines are invisible and the structure is homogeneous with mutual germination of grains between the layers. The microstructure corresponds to the normal heat-treated state of the EI868 (KhN60VT) alloy, overheating was not detected.

Mechanical tests of the specimens from the indicated heat-resistant nickel EI 868 (KhN60VT) alloy, carried out at $T = 900$ °C, are at the level of values of forgings established by the norms of technical conditions (Table 2).

Thus, the material of volumetric products from the EI868 (KhN60VT) alloy produced by the APAS method meets the requirements of the technical documentation for the manufacture of stator parts of aircraft engines.

1.2. APAS OF VOLUMETRIC PRODUCTS FROM ALUMINIUM ALLOYS

For 3D printing of volumetric products from aluminium alloys, APAS has a number of advantages over other arc methods. In addition to high productivity and ability to regulate heat transfer to the material being deposited, this technology helps to overcome the problem of defects arising as a result of oxide refractory films on the surface of aluminium alloys. APAS at direct current of reverse polarity or alternating current provides cleaning of the surface of the previous layer from contaminations due to the effect of cathodic atomization, increased wetting and spreading of liquid metal with minimal heating of the surface, allows providing sufficient detailing of volumetric elements with minimal wall thickness (Figure 5).

Table 2. Mechanial properties of specimens from nickel heat-resistant EI 868(KhN60VT) alloy made by APAS [14]

Method of manufacturing specimens for mechanical tests	Mechanical properties		
	σ_t, MPa	$\sigma_{0,2}$, MPa	δ, %
Specimens produced by APAS	Longitudinal direction		
	349	471	48.1
	341	482	59.0
	345	477	53.6
	Transverse direction		
	326	432	64.0
	306	526	66.3
	316	479	65.2
Forging according to TU 27.1001190414-038:2007	> 220	> 450	> 50

In [15, 16], the results of studies of the structure and mechanical properties of 3D specimens produced by additive surfacing of AlMg5 aluminium alloy wire using direct current microplasma technology and the CMT method are given. It was found that these two 3D printing methods are characterized by the same defects as traditional metallurgical processes (Figure 6).

It was found that magnesium is encountered in the form of eutectic veins with a fine differentiation, i.e., with a strong branching and small sizes of Al + Mg eutectic inclusions or compact inclusions with rounded borders. The size of the strengthening phases in the specimens from the indicated AlMg5 alloy, produced by additive microplasma surfacing, is smaller than in the specimens grown by the CMT method, which made it possible in this case to provide higher values of mechanical properties for the microplasma technology (Table 3).

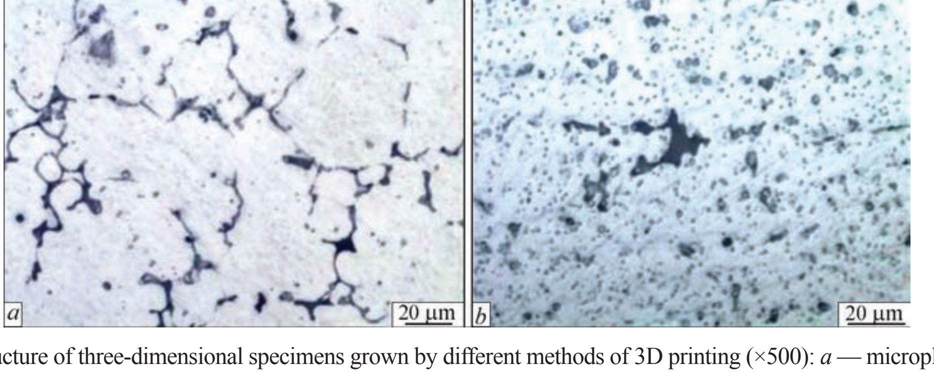

Figure 6. Microstructure of three-dimensional specimens grown by different methods of 3D printing (×500): *a* — microplasma; *b* — CMT

The results of mechanical tests confirmed that the methods of microplasma and CMT additive surfacing correspond to GOST 17232–99 and EN ISO 18273 standards for aluminium AlMg5 alloy. At the same time, for this alloy, the APAS technology showed a slightly higher level of mechanical properties than for 3D printing using the CMT method.

A comparison of the structure and mechanical characteristics of volumetric products manufactured by APAS of the wire from 5A06 alloy and arc MIG surfacing using a similar consumable electrode shows a significantly lower degree of anisotropy of the structure and mechanical characteristics for plasma-arc technology [13]. For the MIG method, the average values of the tensile and yield strength of the specimens in the direction perpendicular to the orientation of the texture are 251 and 101 MPa. The same indices in the direction parallel to the orientation of the texture are 239 and 90 MPa. The average indices of relative elongation in the direction parallel and perpendicular to the orientation of the texture are 37 and 34 %, respectively. In APAS of 5A06 alloy, the average values of the tensile and yield strength of the specimens in the direction perpendicular to the texture orientation are 295 and 150 MPa. The same indices in the direction parallel to the orientation of the texture are 290 and 145 MPa. In general, the strength indices of the specimens produced by APAS of 5A06 wire are at the level of 0.92–0.94 of the strength of the sheet metal 5A06.

Table 3. Mechanial properties of volumetric materials from AMg5 alloy produced using different technologies [15, 16]

Method of 3D printing	Mechanical properties		
	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %
Microplasma additive surfacing	274	154	25.2
CMT additive surfacing	261	124.5	13.7
Norms for AlMg5 alloy according to GOST 17232–99	>270	>120	>13.0
Norms according to EN ISO 18273	250	120	9

The possibility of manufacturing complex-profile cylindrical parts of the “car wheel disc” type, which operate under the conditions of increased dynamic and impact loads, and the “adapter”, APAS wire from aluminium-magnesium 1580 alloy, which is deformable, with additions of scandium at direct current of reverse polarity (Figures 7, 8) [17].

Figure 9 shows the macrostructure of layers of the upper (Figure 9, *a*) and lower (Figure 9, *b*) parts of the wall made of aluminium-magnesium 1580 alloy, produced by APAS at direct current of reverse polarity (Table 4) [17]. There are regions of increased growth of

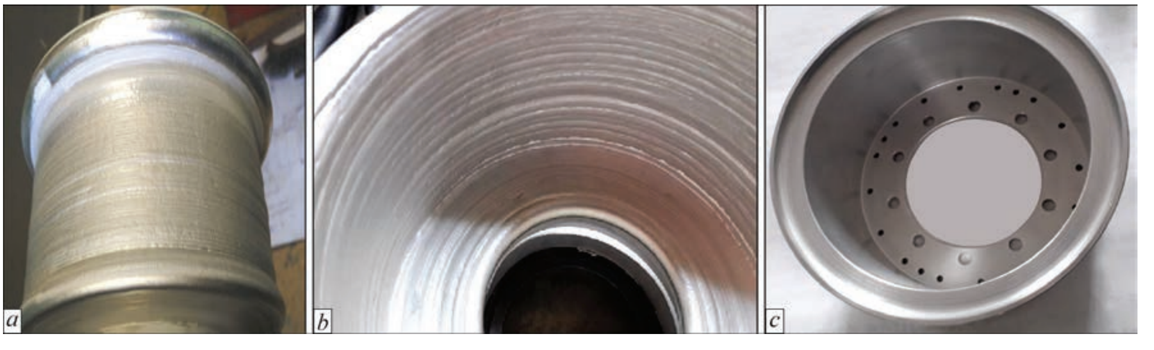

Figure 7. Disc of a car wheel of aluminium-magnesium 1580 alloy, made by APAS at direct current of reverse polarity [17]: appearance of outer surface (*a*) and inner cavity (*b*) after 3D printing; appearance after machining (*c*)

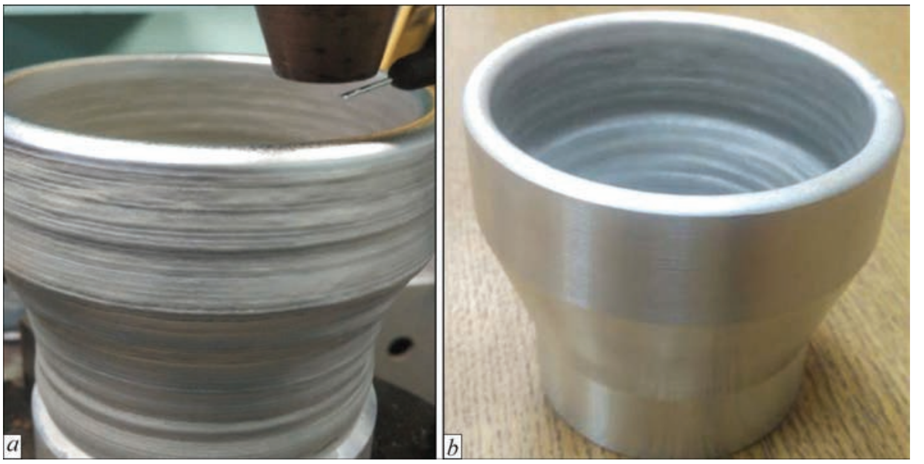

Figure 8. Transition piece of 1580 aluminium-magnesium alloy, made by APAS at direct current of reverse polarity [17]: outer appearance after 3D printing (*a*) and after machining (*b*)

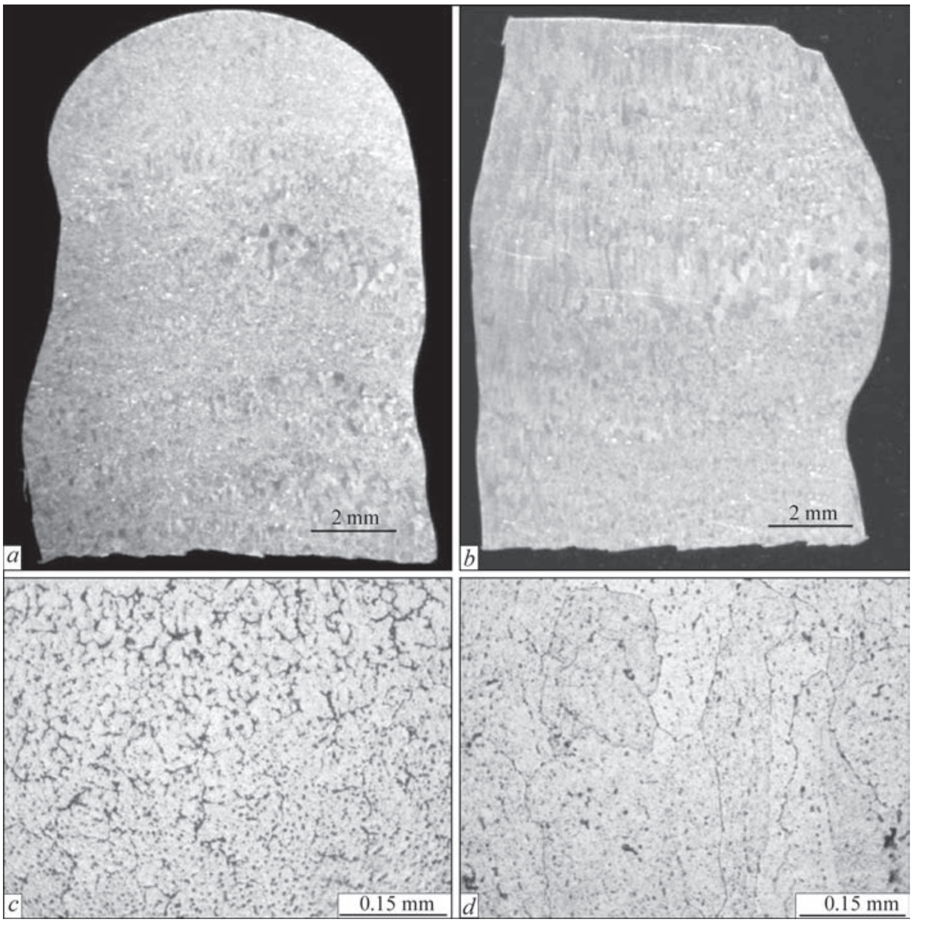

Figure 9. Macro- (*a*, *b*) and microstructures (*c*, *d*) of different zones of volumetric elements from 1580 aluminium-magnesium alloy made by APAS at direct current of reverse polarity [17]: *a*, *c* — upper part; *b*, *d* — lower part

dendrites on the macrosections, and mainly in the lower part of the surfacing. In the upper part of the surfacing, they are less pronounced, which is explained by a decrease in the effect of thermal cycling and reheating of the metal as the wall grows. There are also differences in the microstructure of the upper (Figure 9, *c*) and lower (Figure 9, *d*) parts of the wall at different magnification. The structure represents an aluminium-magnesium solid solution with individual particles of the primary β-phase (Al_3Mg_2) on the grain boundaries, where clusters of primary intermetallics are also encountered $A1_3$(Sc, Ti), $A1_3$(Sc, Cr), $A1_3$Sc. The microstructure of the upper part of the surfacing (Figure 4, *a*) is more finely dispersed with a larger volume fraction of β-phase precipitation along the grain boundaries — up to 2.5 %. The differences in the microstructure of the lower and upper parts of the surfacing (Figure 9, *c*, *d*) once again indicate that the metal heating cycles of the previous layers, which are associated with repeated surfacing, lead to the effect of increased directed growth of dendrites, which is the more intensive, the more often it is repeated.

Therefore, APAS of deformable aluminium-magnesium alloys provides the relative stability of the structural and phase composition of the material of the previous layers under the influence of subsequent thermal cycles in the course of forming a billet. The values of the tensile strength of the surfacings are at the level of the properties of the cast material, inferior to the deformed one; the ductility of the deposited metal significantly exceeds both the ductility of castings — by 2–3 times, and the ductility of annealed rolled semi-finished products — by 1.5 times.

When using APAS on multipolar asymmetric current with the filler wire ER2319 made of high-strength

Table 4. Mechanial properties of aluminium 1580 alloy produced using different deposited materials [17]

Material and specimen state		σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	φ, %
1580 alloy, APAS	Surfacing 1	294	192	24.5	33.5
	Surfacing 2	296	193	25.0	27.0
P-1580 alloy, cast	Cast rod	312	183	9.1	–
P-1580 alloy, rolling	Hot formed	369	266	16	–
	Cold formed	453	429	5	–
P-1580 alloy, rolling + annealing	Annealed	390	277	14	–

hard-to-weld AlCu6MnZrTi alloy, prone to hot cracking during welding, the tensile strength of a volumetric specimen produced from the deposited metal is 258 MPa, or 63 %, which is 0.63 of the strength of a sheet material of the aluminium-copper 2219 alloy in the state of complete heat treatment [18]. Conducting the heat treatment of such printed material by quenching and artificial aging allows increasing the strength of the metal of a part to 0.8–0.85 of the strength of a massive billet treated in the process of manufacturing and heat-treated. When using the TIG process for 3D printing of this alloy, the average tensile strength is 237 MPa, which is only 57 % of this value for the sheet material from 2319 alloy.

By optimizing the APAS technological modes at alternating (multipolar) current, it is possible to form volumetric products from high-strength aluminium alloys of the Al–Cu–Li (AA2319) system, which also belong to the hard-to-weld class [19]. The structure and properties of the material produced by APAS of this alloy are influenced by the value of the constricted arc current and the wire feed speed, the ratio of direct/reverse current pulses, and the heating temperature of the previous deposited layers. At the same time, any shielding gas atmosphere, composition of the plasma-forming mixture, consumption of working gases and plasma flow rate have a rather significant effect on the reduction of porosity in the deposited layers of this alloy. Thus, during APAS of AA2319 alloy, a high-quality wall was produced at a plasma-arc current of 120 A (frequency of 50 Hz, balance 50 %), deposition rate of 140 mm/min, wire feed rate of 0.9 m/min, when using a mixture of Ar/He15/N0.015 gases, the flow rate of shielding gas is 15 l/min and plasma-forming gas is 0.3 l/min, as well as at a preliminary heating of the substrate to a temperature of 200 °C (Figure 10).

1.3. APAS OF VOLUMETRIC PRODUCTS FROM TITANIUM ALLOYS

The APAS process using both wires and powders is one of the most promising for the production of volumetric titanium parts, including in such industries as aerospace, automotive, shipbuilding and marine engineering [20]. Compared to laser and electron beam additive technologies, it becomes possible to manufacture parts from different materials. The main advantage of this group of technologies is the possibility of 3D printing of large-sized structures at significantly lower consumption of materials and investments [21]. Even without solving the problem of maximum productivity when using APAS technologies, the rate of growing the volume of titanium alloys reaches 170 cm^3/h and higher. Such productivity cannot be provided by most beam methods [22].

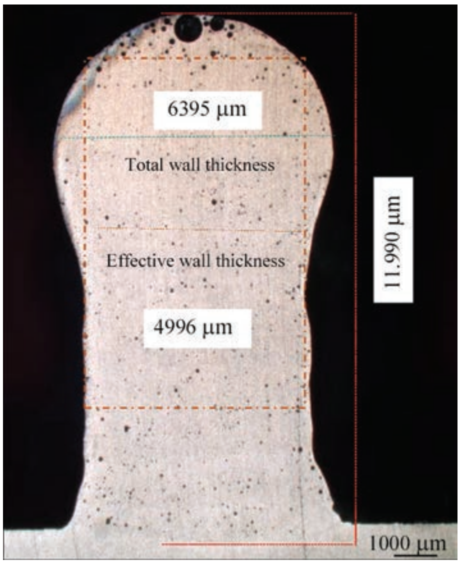

Figure 10. Result of high-quality APAS at alternating current of volumetric element in the form of a multilayered wall from AA2319 alloy of the Al–Cu–Li system [19]

The main technological difficulty of APAS of volumetric products from titanium alloys is the reliable provision of effective gas shielding of both the welding pool as well as regions of parts that can be heated to temperatures above 300 °C. Such heated regions intensively absorb gases from the surrounding atmosphere. To eliminate this, local gas shielding with the help of various devices and systems, as well as

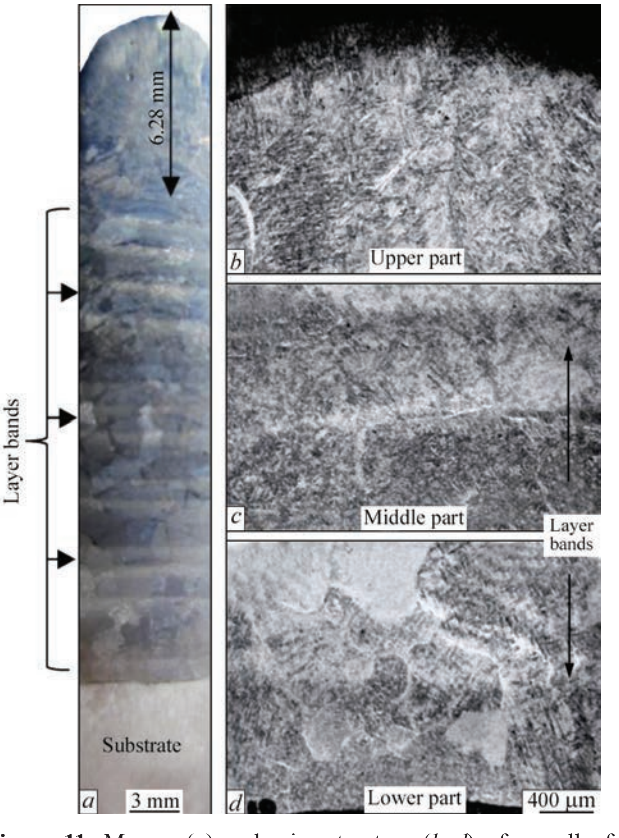

Figure 11. Macro- (*a*) and microstructure (*b*–*d*) of a wall of Ti–6A1–4V alloy, produced by APAS: *b* — upper region; *c* — middle region; *d* — lower region

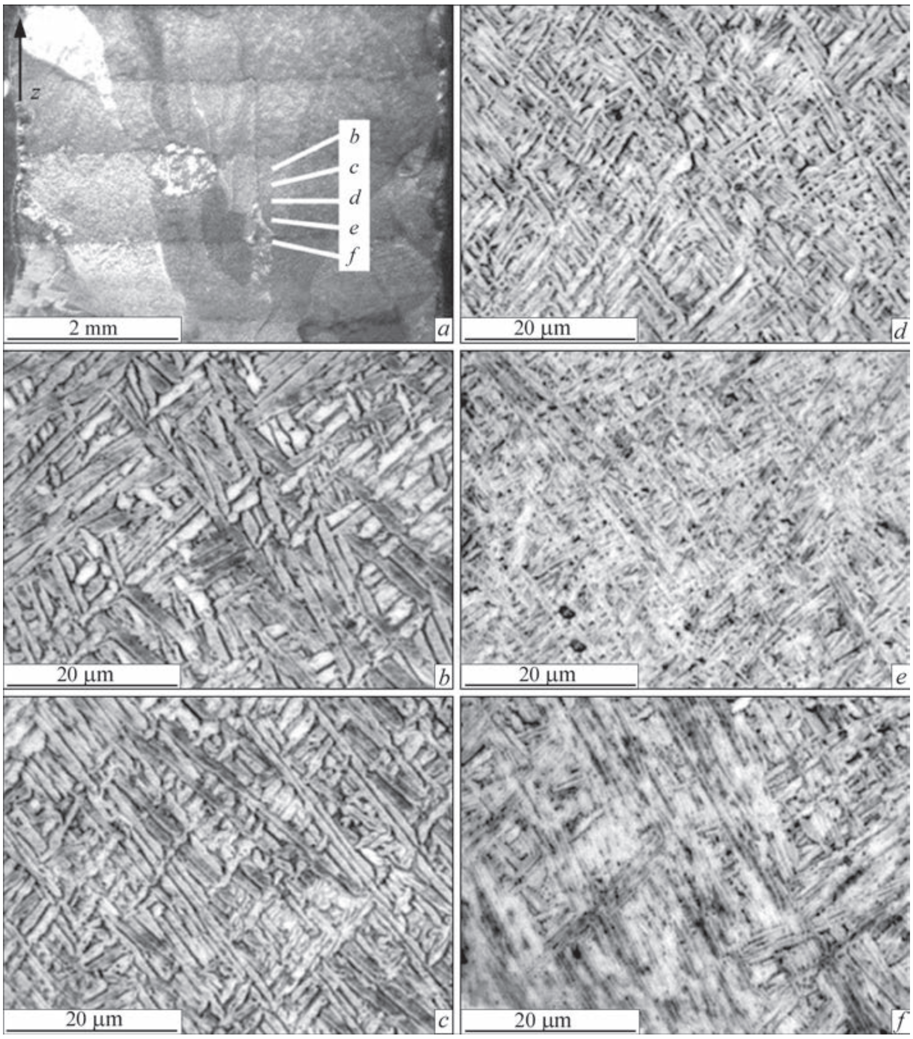

Figure 12. Structures of layer zones of a spatial element of the type "wall" of up to 17.4 mm width, made by APAS with the use of the wire from Ti–6A1–4V alloy: *a* — macrostructure of deposited wall; b–*f* — microstructure of places, mentioned in *a*

3D printing in a controlled atmosphere are used. The most effective solution to the problem of gas shielding is the creation of a special chamber with an argon atmosphere. However, creating such a chamber requires some investment. There is also a limitation of the dimensions of the grown three-dimensional parts by the dimensions of this chamber.

The application of local gas shielding in APAS also allows achieving excellent results and satisfactory mechanical characteristics of printed products from titanium alloys. Thus, when using a pulsed direct current of a plasma-arc power source and a filler wire made of Ti–6Al–4V alloy with a diameter of 1 mm in local gas shielding, spatial defect-free structures with a thickness of 4 mm or more from this alloy with excellent mechanical characteristics can be created [23].

In the process of 3D printing, a coarser-grained structure is formed in the lower layers, and in the layers located above, the size of β-phase grains, martensite and Widmanstatten elements decreases (Figure 11). The similar structures were previously found in the processes of 3D printing of this alloy using laser radiation [24], as well as WAAM process using a consumable electrode [25]. At the same time, the average yield strength (YS) and ultimate tensile strength (UTS) reach 909 and 988 MPa, respectively, and the elongation reaches about 7.5 %. Such indices exceed the requirements of the standards for this alloy produced by cast technologies, and are also higher than in materials of a similar composition after thermal deformation treatment (forging). This provides grounds for the successful use of such material in the aerospace industry.

The work [26] describes the APAS 3D printing process of Ti–6Al–4V alloy wires, which is aimed at the production of large aerospace components. The technology made it possible to produce direct walls of up to 17.4 mm thick, which provided the maximum wall width after mechanical treatment of 15.9 mm and in this case surpassed the competing processes. The coefficient of using Ti–6Al–4V material was on average 93 %, and the maximum productivity of 3D printing was 1.8 kg/h. During deposition, in the layers facing the substrate, coarse columnar grains were formed, which, upon cooling, turned into a structure

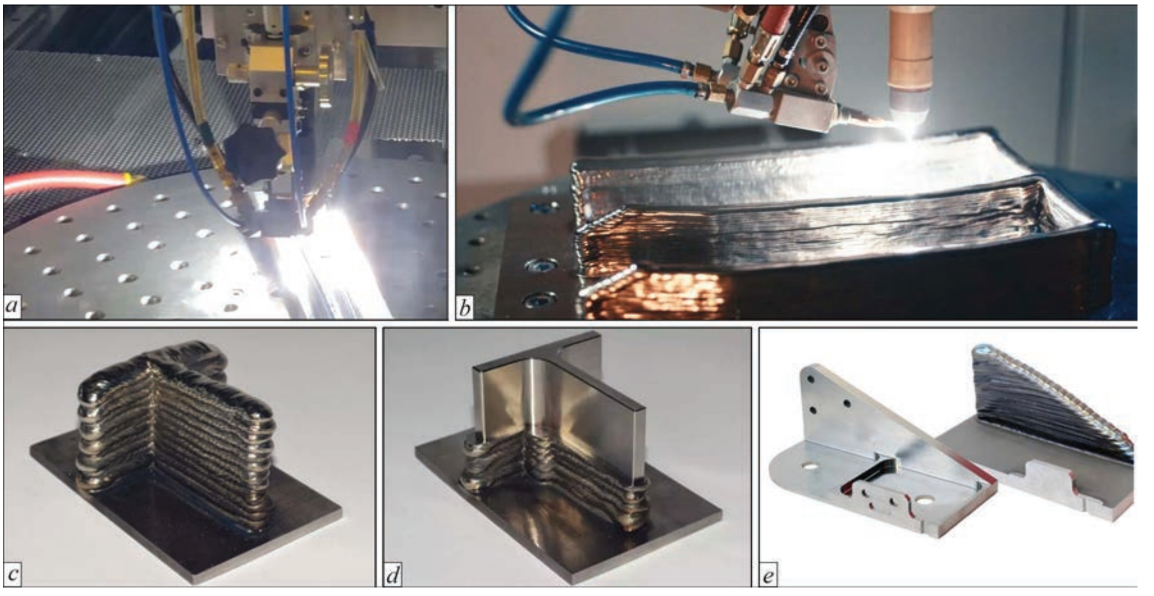

Figure 13. 3D printing process of aircraft parts of titanium alloys using APAS technology in a controlled medium (*a*, *b*) in Camarc Additive LLC Company, USA and examples of printed parts before and after machining (*c*–*e*)

of Widmanstatten lamellae (Figure 12). In the deposited layers, bands were found, which had a repeating basket weave microstructure with variable dimensions. It is possible to see an increase in the size of Widmanstatten elements. The average microhardness was 387 *HV*, which is 12 % higher than that of a substrate made of the material of a similar composition.

At present time, some practical experience has been accumulated in the production of aircraft parts from titanium alloys using APAS technology in a controlled environment. As examples of the successful application of this technology in the aerospace industry, it is possible to cite the results obtained by the Companies Camarc Additive LLC, USA (Figure 13) and Norsk Titanium, the Netherlands (Figure 14). Since 2017, the latter has been producing aircraft parts using high-tech industrial machines for 3D printing. The parts, printed by the Norsk Company using the APAS method with titanium alloy filler wires were approved at the federal level for commercial aircrafts Boeing, USA. The technologies used here are not only by 75 % more efficient than conventional forging, but also reduce costs for the manufacture of titanium products by 50–75 % and require fewer resources. Currently, Norsk is joined by a number of other companies in the issue of 3D printing aerospace products, including the British Company Renishaw and Stratasys.

One of the main problems that arise in the APAS 3D printing process, as in practically all additive technologies, is the formation of significant residual stresses in the volumetric structure, which are manifested in the distortion (deformation) of printed elements [27]. To control the influence of heat accumulation on the mass transfer of the filler metal, the wall formation and arc stability during 3D printing of spatial products from titanium alloys under the conditions of local gas shielding, an infrared pyrometer was used to measure the temperature between passes [28]. The arc stability and metal transfer were monitored using a high-speed chamber. Such an approach makes it possible to optimize APAS modes and minimize the residual stresses.

For the manufacture of thin-walled Ti6Al4V structures, an innovative APAS wire process with forced interpass cooling using a compressed CO_2 was proposed [29]. It was shown that forced interpass cooling not only improves surfacing properties, but also contributes to geometric repeatability and improved production efficiency by reducing the time between layers application.

2. ALLOYING, SYNTHESIS OF NEW ALLOYS, MANUFACTURING VOLUMETRIC PRODUCTS FROM COMPOSITE AND GRADIENT MATERIALS IN PRODUCTION USING APAS TECHNOLOGIES

Additive arc technologies, such as CMT, use a single filler wire, while APAS technology allows feeding multiple wires. Thus, an increase in the produc-

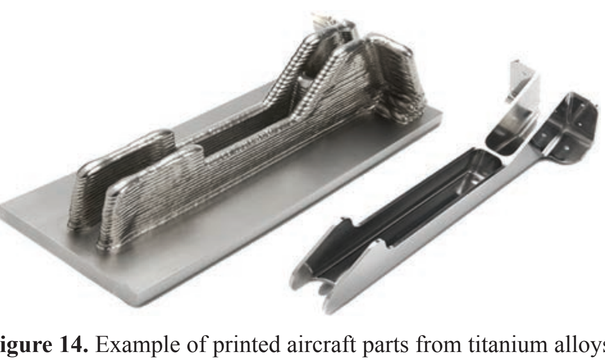

Figure 14. Example of printed aircraft parts from titanium alloys before and after machining, produced by APAS in the controlled medium in the Norsk Titanium Company, Netherlands

Table 5. Combination of different types of steel wires in the technology of double-wire APAS [30]

Materials, produced as a result of 3D printing	Grades of steel wires which were combined in the combinations of a multiwire APAS	
	Material A	Material B
Combination 1	G3Si1	G 19 9 L Si
Combination 2	G 18 L Nb	G 19 9 L Si
Combination 3	G3Si1	G Mn4Ni2CrMo

tivity of using the energy potential of this process is achieved by increasing the number of filler wires. When implementing a multiwire APAS, in this case, an increase in the productivity of the 3D printing process is achieved, which is proportional to a number of filler wires, or a higher stability of the surfacing process and the quality of the deposited material. However, the most promising result of multiwire APAS is the alloying of a volumetric material in the process of 3D printing. Alloying can be local (change in the chemical composition of certain areas of the printed material) or full, which is the synthesis of new alloys in the process of 3D printing of a volumetric product.

German researchers have gained a positive experience in a simultaneous use of two or more filler wires of different chemical composition [30]. Thus, by changing the rate and diameter of filler wires, it is possible to adjust the chemical composition of certain elements in the deposited metal. Double-wire APAS with a combination of different types of low-alloy ferritic steel wires, as well as wires of austenitic steels containing Ni, Cr, Mo, Nb (Table 5) confirmed the possibility of a smooth change in the chemical composition of the printed material during the 3D printing process and the control of the chemical composition by controlling the arrangement of low and high ductility phases to avoid the negative influence of intermetallic phases (Figure 15) [30].

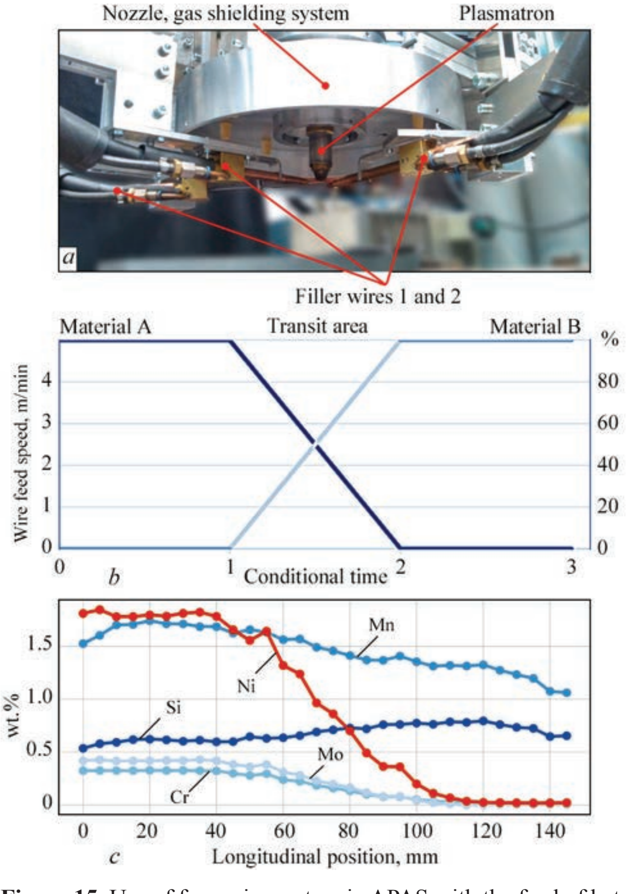

Figure 15. Use of four-wire system in APAS with the feed of heterogeneous wires (*a*, *b*) and change of chemical composition over the volume of specimen, produced on the data of combination No. 3 of heterogenenous wires feed (Table 5) (*c*) [30]

In argon-arc surfacing using a nonconsumable electrode, also the possibility of adjusting the chemical composition of the deposited metal was confirmed by combining the feed of heterogeneous wires from aluminium 2319 (A1–Cu) and 5087 (Al–Mg) alloys (Figure 16). Thus, spatial products were manufactured from the high-strength 2024 (Al–Cu–Mg) alloy synthesized in the 3D printing process [31]. The regulation of the feed rate of each wire was obtained by the chemical composition of the printed material and its properties, which allowed achieving an optimal combination of physical and mechanical properties of manufactured spatial products (Figure 17) [31].

Namely this possibility of performing additive growing of parts from aluminium wires of different chemical composition was also confirmed when using a multipolar asymmetric current as a heating source using a constricted arc. In APAS with the use of a filler wire, a finer structure of the deposited metal is formed compared to the conventional argon-arc surfacing with a tungsten electrode, which improves the strength indices of parts deposited by APAS by 10–15 % compared to similar indices of parts produced by argon-arc surfacing.

The use of APAS technologies, in which the formation of spatial products can be carried out with simultaneous feeding of different types of powder

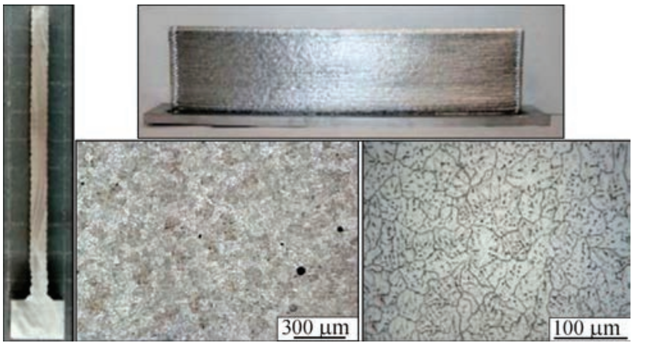

Figure 16. Appearance and microstructure of a product of the type "wall" from synthesized high-strength 2024 (Al–Cu–Mg) alloy produced by additive surfacing with the feed of two heterogeneous types of 2319 (A1–Cu) and 5087 (Al–Mg) aluminium alloys [31]

materials into the plasma-arc (for example, powders of structural, wear-resistant, heat-resistant alloys, carbides, borides, silicides, etc.) opens up the possibilities of creating new volumetric materials with a unique combination of functional properties. Such materials are extremely promising for the production of parts and tools of a new generation, in which, for example, a certain part of the volume provides the specified strength indices, and the other — increased wear resistance, corrosion resistance, heat resistance, special magnetic and electrophysical properties.

Such materials can include:

- metal-ceramic composites of a permanent composition;
- gradient materials (of a variable chemical composition over the volume of a product);
- multilayer materials and their combination with gradient materials.

The examples of such technological developments, produced at the PWI, are mentioned in Figures 18, 19.

Figure 18 shows the process of manufacturing a cylindrical billet of a tool for metal treatment with the use of powder APAS, in which powder of wear-resistant FeNiCrBSH alloy and tungsten carbide WC was supplied from two powder dispensers. Applying automated control of powder feed parameters, the regulation of WC content can be reached in the range of 0–50 rpm % in the surface layers and achieving the hardness of up to 68–70 *HRC*.

Figure 19 shows an example of APAS of the composition of a titanium alloy and a spherical tungsten carbide (Ti–6A1–4V + WC) applying the hybrid additive technology “plasma surfacing with the use of a filler wire — plasma-powder surfacing”. This technology allows surfacing a volumetric multilayer material of a gradient type (with a layer thickness of about 2 mm) and varying the hardness over the volume from *HRC* 32 for the lower layers of titanium alloy to *HRC* ≥ 56 to the surface layers.

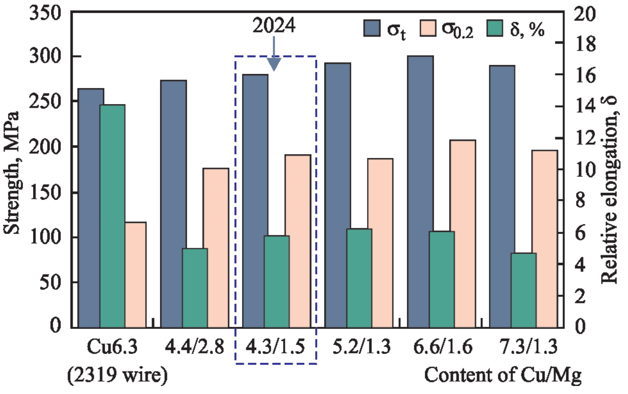

Figure 17. Optimization of physicomechanical properties of volumetric products manufactured by a double-wire APAS with the feed of heterogeneous wires of 2319 (A1–Cu) and 5087 (Al–Mg) aluminium alloys [31]

4. DIRECTIONS OF EQUIPMENT DEVELOPMENT FOR THE IMPLEMENTATION OF TECHNOLOGICAL CAPABILITIES OF APAS IN ADDITIVE MANUFACTURING

In the creation and the use of equipment for the implementation of 3D printing processes by the APAS method, both directly product manufacturing companies as well as specialized companies that traditionally deal with welding technologies are involved. Thus, the Norsk Company has created 3D printing machines like MERKE IV RPD for the Rapid Plasma Deposition (RPD) process. The specialized Company Camarc Additive’s, USA has developed APAS processes for steels, niobium, titanium and aluminium alloys, for which it has created PAAWS (Plasma-arc Additive Wire System), the equipment of which offers four axes of movement (*X*, *Y*, *Z* and rotation) together with a table for printing with a liquid cooling. Printing in

Figure 18. Process of manufacturing a cylindrical billet of the tool for metal treatment by APAS of powders of wear-resistant FeNiCrBSH alloy and tungsten carbide WC (*a*, *b*) and microstructure of a product in different zones (*c*)

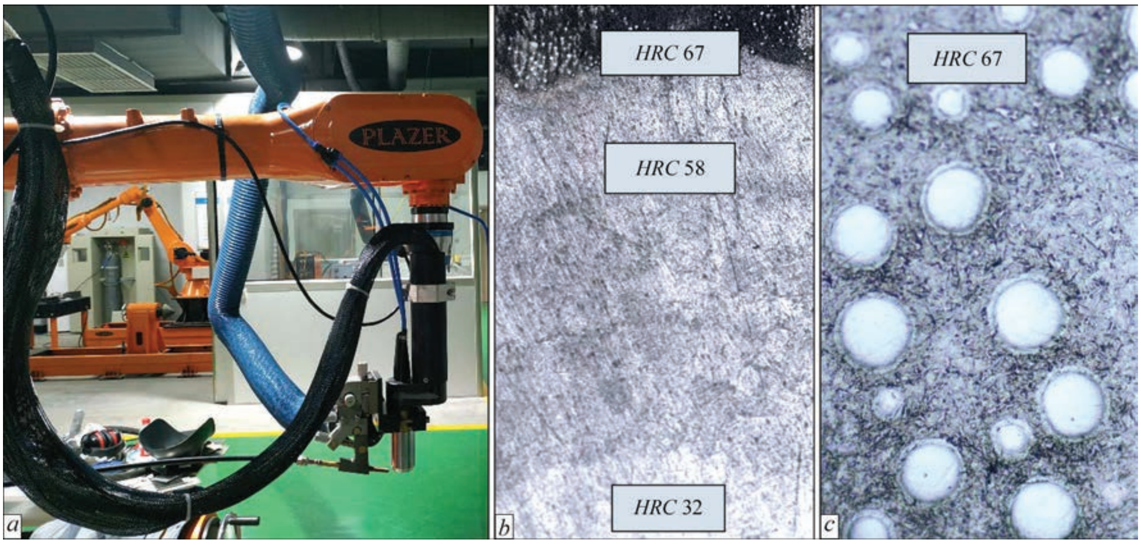

Figure 19. System for implementation of hybrid additive technology of "plasma surfacing using filler wire – plasma-powder surfacing" (*a*) and structure of the deposited multilayered wall Ti–6Al–4V + WC (*b*) Ch50, and upper deposited layer (*c*), Ch200

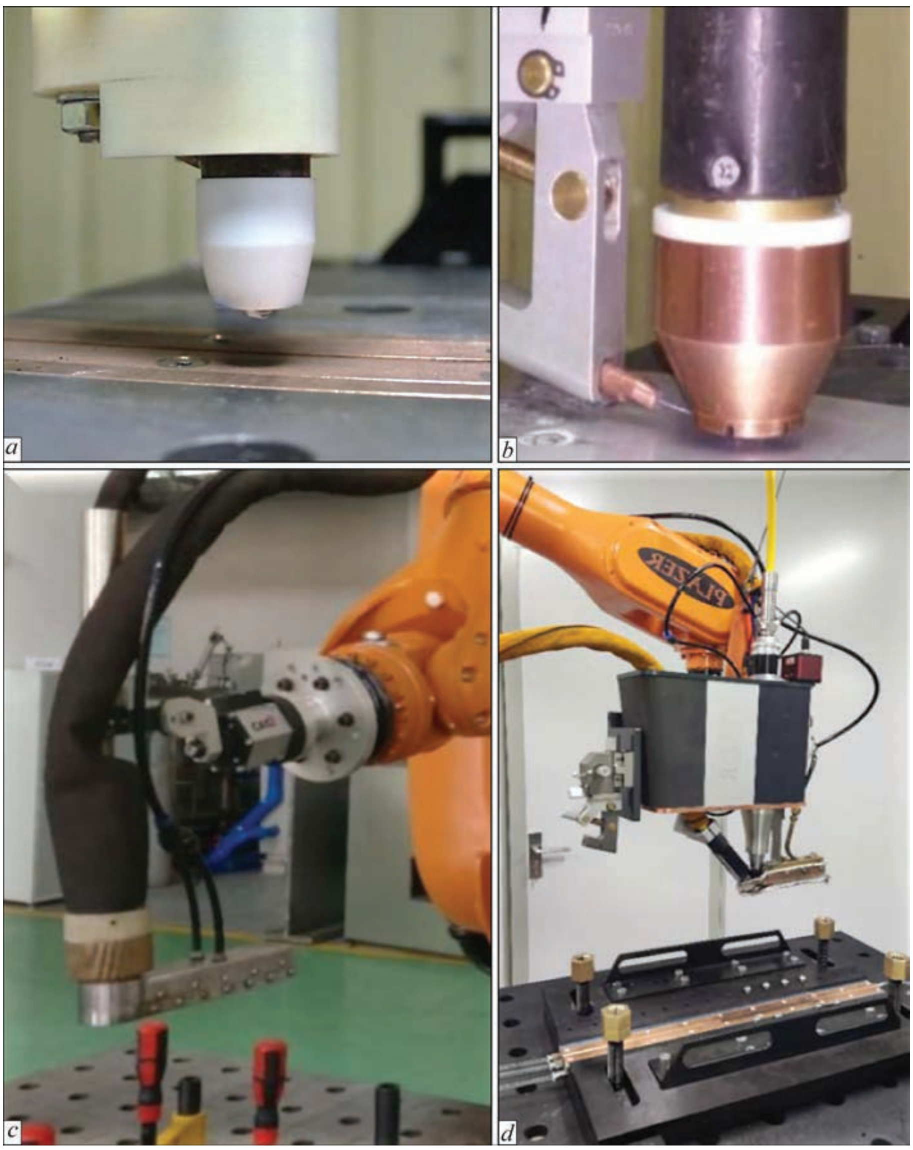

Figure 20. Appearance of plasmatrons designed at the PWI for using in additive manufacturing

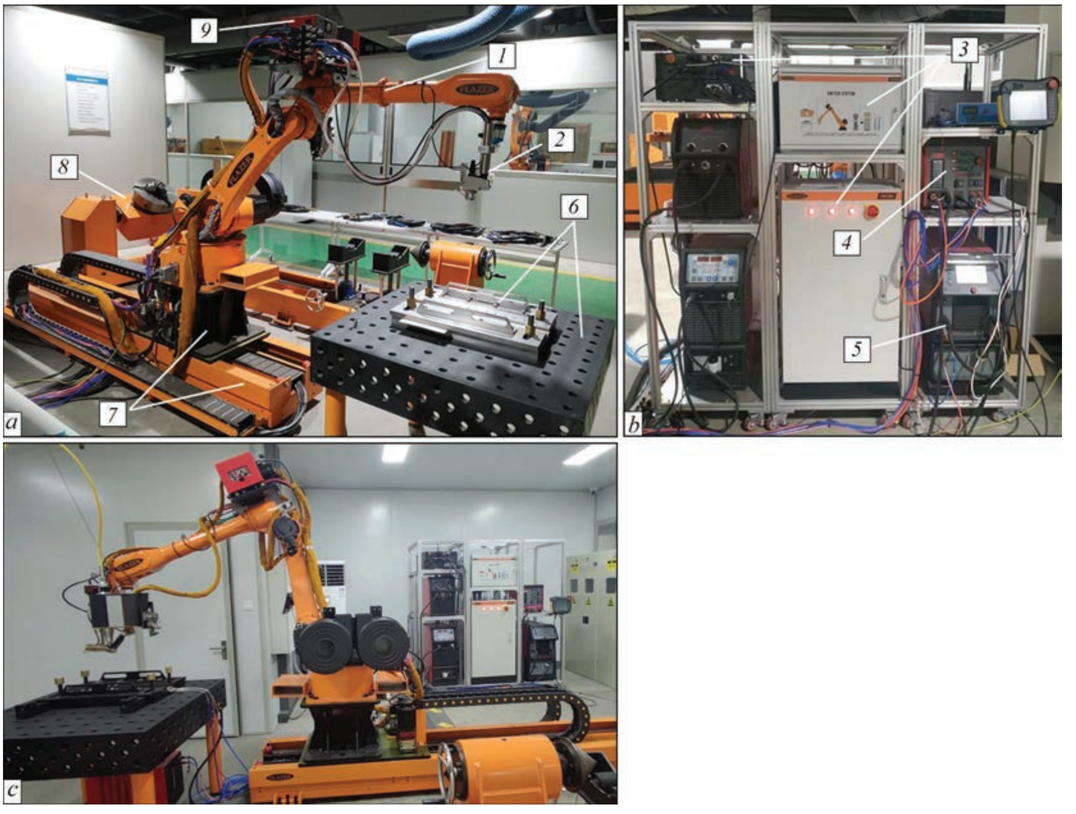

Figure 21. General appearance of the robotic complex of equipment for single- and multiwire APAS, powder APAS and hybrid process of "APAS with the use of plasma-arc and arc with consumable electrode" (*a*), stand with the power sources of a robot, plasmatron, cabinet for adaptation of robot commands and smart automatic system of equipment monitoring (*b*) and robotic complex for implementation of additive laser-plasma (laser-microplasma) surfacing (*c*) [32]: *1* — anthropomorphic robot; *2* — plasmatron; *3* — smart control system of robotic welding process: *4* — plasma module; *5* — plasma-arc power source; *6* — table for surfacing with technological equipment; *7* — system for linear movement of robot by rails; *8* — two-axial rotator-manipulator; *9* — mechanism for feeding filler wire

a working field of 1000×10000×600 mm can be carried out in a closed chamber with a controlled inert atmosphere with a real-time process control. Another well-known manufacturer of 3D printing machines is SBI Company, Austria, whose equipment is designed for the manufacture of products from titanium and aluminium alloys, austenitic and chrome-nickel steels, copper, bronze, etc.) on a direct current of direct polarity or on an alternating current.

At the PWI, in the direction of the development of APAS processes, the main attention is paid to the development of technologies and equipment that allow expanding the technological capabilities of additive manufacturing, increasing the quality of the deposited material, synthesizing new materials with a unique set of properties.

The differences between such technologies lie in the plasma-arc parameters, namely:

APAS is carried out by a plasma-arc of an alternating asymmetric current with a frequency of 150 Hz at currents from 3 A (in the mode of microplasma additive surfacing) to 320 A (in the mode of high-performance additive surfacing with wires of increased diameters or multiwire surfacing) with an accuracy of stabilizing the welding current amplitude up to ± 1 A for joining materials with a refractory oxide film on the surface (for 3D printing of products from aluminium, magnesium and other light alloys, including such high-strength aluminium alloys that are difficult-to-weld — Al–Cu–Li, Al–Mg–Li, A1–Cu–Mg–Li, Al–Zn–Mg, Al–Zn–Mg–Cu, etc.);

APAS is carried out by a plasma-arc of direct current of direct polarity from 3 A (in the mode of microplasma additive surfacing) to 450 A (in the mode of high-performance additive surfacing with wires of increased diameters or multiwire surfacing) with the superimposition of current modulation with a frequency of up to 2000 Hz (for 3D-printing of alloy and high-strength steels, titanium and nickel alloys, copper, refractory metals, etc.).

These technologies have the following opportunities:

- independent selection of the waveform of alternating current in the half-periods of the passage of the current of direct and reverse polarity;
- the use of pulsed supply of plasma-forming gas (argon) at a set frequency and the difference in consumption of plasma-forming gas, as well as the use of pulsed supply of a filler wire;
- in welding at direct current, the application of the welding wire preheating with an alternating asym-

Figure 22. General appearance of an area with three robotic complexes for 3D printing of large-sized and cylindrical shells and lengthy complex-profile structures of aluminium and titanium alloys with the use of additive plasma-arc technologies

metric current, as well as modulation of the welding current to improve the mixing of the metal pool to be deposited.

For the realization of APAS technologies at the PWI, a variety of local gas shielding systems and a series of plasmatrons and corresponding installations have been developed, for example for:

● additive microplasma powder surfacing and surfacing with filler wires for work on asymmetric alternating and direct current in the current range of 3–35 A (Figure 20, *a*);

● powder APAS and APAS with filler wires for work on asymmetric alternating and direct current for work in the range of currents 50–320 (450 A) (Figure 20, *b*);

● for the realization of the hybrid additive process "plasma surfacing with a filler wire – plasma-powder surfacing" (Figure 18, *a*);

● to implement the hybrid additive process "plasma surfacing using a plasma-arc and an arc with a consumable electrode" (Figure 20, *c*);

● for the implementation of additive laser-plasma (laser-microplasma) surfacing (Figure 20, *d*).

The described processes are used at the Paton Research Institute of Welding Technologies in Zhejiang Province, China in two robotic complexes equipped with a smart automatic control and monitoring system (Figure 21). The mentioned complexes implement 3D printing processes of large-sized parts and bodies of rotation of up to 3000 mm long, up to 600 mm in diameter, 600 mm wide and 1000 mm high. The total weight of a volumetric part reaches up to 1000 kg [32].

At present, the works started on the creation of a technological area at the PWI, which includes three robotic complexes that use the plasma-arc 3D printing technologies described above (Figure 22) and allow manufacturing:

● large-sized (diameter from 100–200 mm to 2–3 m and height of up to several meters and higher) cylindrical shells made of aluminium alloys with elements and inner stiffeners of a complex shape;

● lengthy (up to 4–12 m) structures with a complex profile, including aluminium and titanium alloys and box structures with inner stiffeners.

CONCLUSIONS

1. The potential and advantages of APAS compared to widespread conventional arc WAAM methods, including CMT technology, were revealed and substantiated, namely:

● wide adjustment of 3D printing productivity (0.02–25 kg/h) and a degree of detailing of volumetric elements (from 2.5 to 10–20 mm width) by implementing the process both in the mode of microplasma surfacing with a low-ampere plasma-arc (at currents of 5–35 A) as well as at currents of 50–450 A and higher;

● a wide range of adjustment of input energy, heating zone and penetration depth of previous deposited layers by means of APAS with the use of direct or contacting plasma-arc;

● 3D printing at direct current of direct and reverse polarity, alternating current, including the implementation of the process of cathodic cleaning and destruction of oxide films during surfacing of light metals and alloys with refractory oxide films on their surface;

● 3D printing using powder or wire, including one to four filler wires, with a current-conducting filler wire with preheating;

● implementation of hybrid 3D printing technology — combination of a plasma-arc with an arc or laser heating source;

● implementation of 3D printing process using an additive that does not move together with plasmatron during layer surfacing (metal grit, foil, thin bands of metal) and applied alternately after surfacing of each layer (analogue of lamination);

● the possibility of using plasma-arc without the addition of wire or powder, which allows performing a preheating of the base or deposited layers before additive surfacing.

2. The possibilities of using APAS technologies for manufacture of volumetric products from structural, alloyed and high-strength steels, heat-resistant nickel alloys, aluminium high-strength alloys, titanium alloys with physical and mechanical characteristics that contain mostly 90 % or higher of the indices of similar materials produced by conventional metallurgical methods were confirmed, which in a number of cases meet the requirements of the standards for such materials after thermomechanical treatment.

3. New possibilities of using APAS are shown, in which the formation of spatial products can be carried out with a simultaneous feeding of different types of heterogeneous wires of powder materials (for example, powders of structural, wear-resistant, heat-resistant alloys, carbides, borides, silicides, etc.) or with the simultaneous feeding of wire and powder (granules) into the plasma-arc. This allows carrying out local or volumetric alloying of the material of a volumetric product, performing 3D printing simultaneously with the synthesis of new alloys, creating new materials with a unique combination of functional properties (metal-ceramic composites of a permanent composition, gradient materials of a variable chemical composition over the volume of a product, multilayer materials and their combination with gradient materials). Such materials are promising for the production of critical parts and tools of the new generation, in which, for example, a certain part of the volume provides the specified strength indices, and the other — increased wear resistance, corrosion resistance, heat resistance, special magnetic and electrophysical properties.

4. At the PWI of the NASU, a number of innovative APAS technologies were developed and corresponding original equipment for 3D-printing of large-sized products from aluminium and titanium alloys were created, including for the implementation of:

● additive microplasma powder surfacing and surfacing using filler wires for work on asymmetric alternating and direct current in the range of currents of 3–35 A;

● powder APAS and APAS using filler wires for work on asymmetric alternating and direct current for work in the range of currents of 50–320 (450 A);

● hybrid additive process “plasma surfacing using a filler wire – plasma-powder surfacing”;

● hybrid additive process “plasma surfacing using a plasma-arc and an arc with a consumable electrode”;

● additive laser-plasma (laser-microplasma) surfacing.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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