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NEW GENERATION UNIT FOR PLASMA-ARC DEPOSITION OF COATINGS AND ATOMISATION OF CURRENT-CARRYING WIRE MATERIALS

V.M. Korzhyk, D.V., Strogonov, O.M. Burlachenko, O.V. Ganushchak, O.M. Voitenko

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

A plasma-arc unit of industrial type of up to 50 kW total power for deposition of functional coatings on critical parts and spheroidization of wire materials is presented. A feature of the unit is application of a system of water cooling of plasmatron internal components, modified design of the nozzle and cathode parts and reduction of plasmatron overall dimensions, ensuring a higher productivity of the process, widening of its application areas, improvement of mechanical and technological characteristics of the produced granules and coatings, etc. Presented is the microstructure and results of studying the granulometric composition of the dispersed phase, which are indicative of producing dense coatings with less than 1 % porosity, forming from granules of a spherical shape predominantly in a narrow particle size range of 20–100 μm.

KEYWORDS: plasma-arc atomization, current-carrying wire, coating deposition, spheroidization, granulometric composition, binding strength, density, sphericity

INTRODUCTION

The first studies of the process of plasma-arc spraying were performed in the 60s of the previous century. The impetus for this was the rapid development of aviation and missile technology, which required creation of new efficient methods of deposition of refractory coatings on heavy-duty parts of aviation and missile gas turbine engines (GTE) and liquid rocket engines (LRE). In 1961 the process of plasma-arc spraying using current-carrying wire-anode was patented in the USA [1]. Development of this process was due, primarily, to a number of problems, arising in spraying with powder materials by transferred-arc plasmatrons, in particular low erosion resistance of copper nozzles in the anode spot zone, low values of the efficiency factor (EF) of powder heating in the plasma jet, material utilization coefficient (MUC) on the level of 20–60 %, etc. [2, 3]. In the USSR this method has also become widely accepted. For instance in works [4–7] the authors used this technology to deposit coatings in IMET-108 unit (Baikov IMET of RAS) (Figure 1, *a*) and obtained spherical powers from refractory wire materials based on tungsten, molybdenum, niobium, etc. It should be noted that this process ensured a high productivity, which at the power of 20–25 kW was equal to 10–12 kg/h for tungsten wire. However, the above-mentioned process had the significant disadvantages of a wide granulometric composition of the sprayed particles in the range of 40–1000 μm, and a considerable degree of their oxidation as a result of a short length of the argon jet, which resulted in a low density of the applied coatings (porosity of 4–10 %), binding strength of 25–35 MPa, etc.

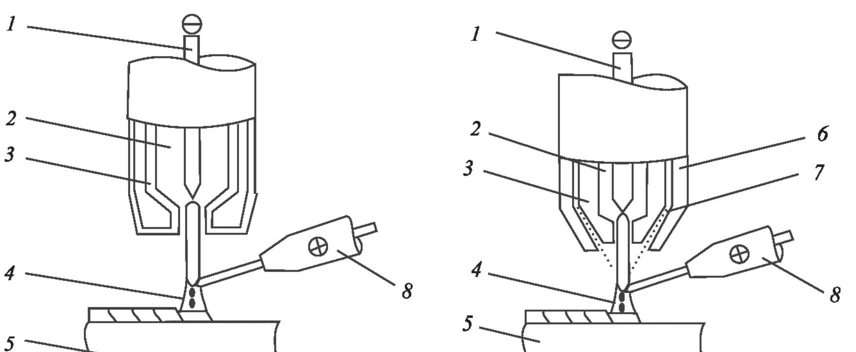

Figure 1. Main varieties of the process of plasma-arc spraying of current-carrying wire materials with (*a*) and without (*b*) use of accompanying gas flow, respectively: *1* — nonconsumable tungsten cathode; *2* — plasma forming gas injection; *3* — plasma forming nozzle; *4* — spaying particle plume; *5* — product; *6* — compressing nozzle; *7* — accompanying gas flow; *8* — consumable wire-anode

Further development of this method was design and manufacturing of serial units UN-126 and KT-088 (PWI, Ukraine) [8, 9] and PLAZER 30-PL-W (R&D PLAZER Center Ltd, Ukraine) [10], where the above-mentioned disadvantages were eliminated through application of an accompanying gas jet (Figure 1, *b*). The accompanying gas flow directed coaxially to the plasma one forms the configuration of the latter, promotes its compression, and, thus, reduces the opening angle of spraying particle plume, increases the outflow velocity and dynamic head of the plasma jet, which, in its turn, creates the conditions required for achieving the optimal granulometric and chemical compositions of the dispersed phase [11]. It leads to reduction of coating porosity to 1–4 %, increase of the coating binding strength to 40–60 MPa, etc. This technology has reached its maximum development abroad at the beginning of 2000s, and it became known as Plasma Transferred Wire Arc (PTWA) process. PTWA technology was patented in 2009, and it is used predominantly at reconditioning and improvement of wear resistance of inner surfaces (> 50 mm) of such engine elements, as cylinder blocks for Ford, Nissan, Volkswagen concerns, etc. The main scope of work on development of such equipment was performed in the USA (Flame Spray Industries), Germany (GTV), and Switzerland (Oerlikon). This method is characterized by high properties of the sprayed coating strength (up to 80 MPa), low porosity (1–2 %), productivity (on the level of 10 kg/h), etc. [12].

In addition to the coating sphere, this technology has received a boost with development of additive technologies of printing 3D products, and it is becoming widely accepted for manufacturing high-quality spherical granules, which are produced during the process of wire material atomization (Plasma Atomization Technology (PAT)) [13]. At present equipment is known [14, 15], which allows producing granules with the sphericity coefficient higher than 0.8 and more than 50 wt.% yield of 20–100 μm size fraction.

Note, however, that at present, the plasma-arc spraying and atomization method has several significant limitations on productivity, which in the general case is not more than 12 kg/h, and does not allow using compact wires of more than 2.0 mm diameter, and in the case of atomization of more than 1.6 mm flux-cored wires with refractory non-conductive components (WC, B_4C, etc.) it does not allow ensuring the processes of metallurgical interaction of the flux-cored wire sheath and core, resulting in formation of granules with a high degree of heterogeneity by chemical and phase composition. This is due to limited power of plasma-arc equipment, which is not higher than 30 kW (300 A and 100 V) for all the equipment models, as a result of application of gas cooling system.

Therefore, further advance of this plasma-arc spraying and atomization technology can consist in development of new plasmatron designs with water cooling and optimized geometry of the nozzle part and smaller overall dimensions, which will allow raising the current load from 300 to 500 A, improving the process productivity, increasing the plasma jet velocity characteristics, intensifying the processes of wire dispersion and of metallurgical interaction in melting of flux-cored wire components, etc.

DEVELOPMENT OF HIGHER POWER PLASMATRON FOR PLASMA-ARC ATOMIZATION AND DEPOSITION OF COATINGS FROM CURRENT-CARRYING WIRES

Proceeding from the results of earlier developments and gained experience of operation of serial versions of plasmatrons for plasma-arc spraying, a goal was set to develop a plasmatron of PLAZER 50-W model of a higher power (up to 50 kW) and with enhanced technological capabilities (both for producing spherical granules, and for coating deposition on the external and inner surfaces of ≥ 70 mm diameter).

Optimization of the plasmatron design consisted in the following:

● increase of the current load due to designing a system of water cooling of the nozzle part, cathode and anode assemblies. It allowed application of currents on the level of 400 to 500 A, compared to serial PLAZER 30-M plasmatron of PLASZER 30-PL-W unit [10], where this value cannot exceed 300 A, because of air cooling application. Moreover, a design with water cooling allows using helium or a mixture on its base as the plasma forming gas, which, in its turn intensifies the processes of heating, melting, dispersion and spheroidization of current-carrying compact and flux-cored wires;

● optimization of the gas-discharge chamber geometry due to a change in the ratios of the nozzle channel length (l_n) to its diameter (d_n) from 1.0 to 1.4, which provides a 15 % increase of the maximal velocity of the plasma jet outflow from 520 to 600 m/s, according to calculations using Computational Fluid Dynamics (CFD) software (Figure 2), and

● construction of a spherical section, which expands at the nozzle outlet (by the type of Laval nozzle [16]), and ensures a more homogeneous temperature and electric density of the plasma and length of the plasma jet, which, in its turn, intensifies the spheroidization processes and provides greater acceleration of the particles.

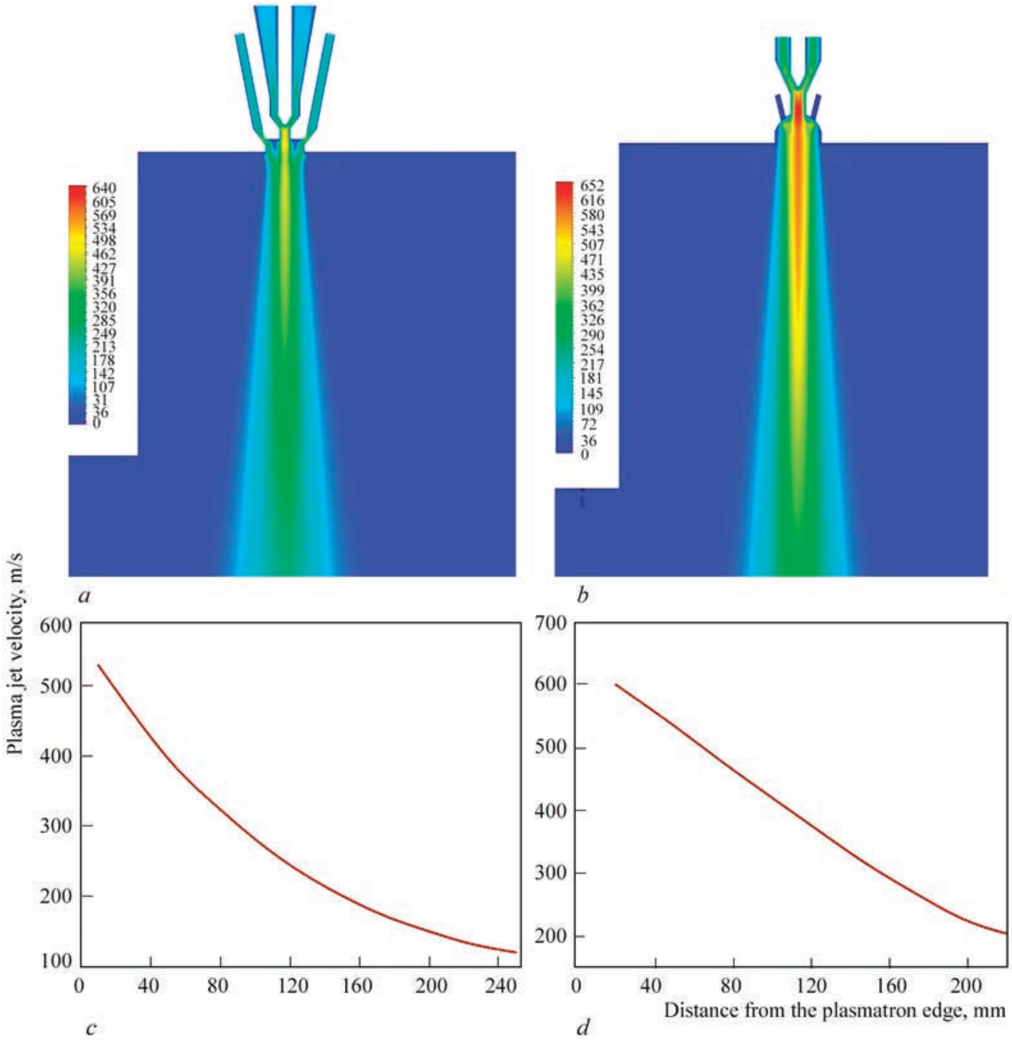

Figure 2. Visualization of the process of modeling velocity characteristics of the plasma jet (*a*, *b*) and dependencies of the plasma jet velocity on the distance from the plasmatron edge (*c*, *d*): *a*, *c* — serial PLAZER 30-W plasmatron; *b*, *d* — developed PLAZER 50-W plasmatron

An improved system of plasma jet blowing by an accompanying gas flow in the zone of atomization cone formation was also developed, which ensures laminar outflow of the accompanying gas flow (compared with the prototype, where the accompanying gas flow comes out through an annular gap with a predominantly turbulent nature of movement). It ensures greater extent of the high-velocity high-temperature zone of the plasma jet, reduction of the angle of opening of the atomization cone and achieving an optimal composition of the dispersed phase.

Appearance and design of the new PLAZER 50-W plasmatron (Figure 3) and its characteristics are given below.

Technical characteristics of serial PLAZER 30-W and developed PLAZER 50-W plasmatrons

	PLAZER 30-W	PLAZER 50-W
Maximal current, A	300	500
Maximal voltage, V	80	120
Accompanying gas flow rate, m^3/h	30–60	15–30
Plasma forming gas flow rate, m^3/h	13	13
Plasma forming gas type	Argon	Argon, helium and their mixtures
Nozzle diameter, mm	3	3
Overall dimensions L×W×H, mm	90×70×175	250×60×50
Weight, kg	1,5	1,5
Cooling type	Air	Water

As one can see from the technical characteristics, the developed PLAZER 50-W plasmatron has the following differences from plasmatron of the previous PLAZER 30-W modification: increase of the current load on the plasmatron internal parts from 300 to 500 A due to replacement of air cooling system by water cooling; more efficient cooling of the plasmatron cathode and nozzle assemblies, which allows application of helium and mixtures on its base as plasma forming gas, that greatly enhance the plasma arc power (due to voltage increase from 80 to 120 V) and

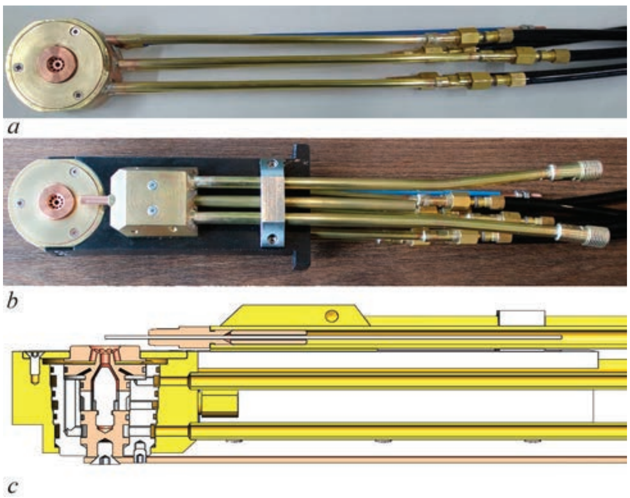

Figure 3. Appearance and computer 3D model of the developed PLAZER 50-W plasmatron for plasma-arc spraying: *a* — appearance; *b* — appearance as an assembly with the cathode unit and fastening to the manipulator; *c* — 3D model of gas-discharge chamber

increase the effectiveness of heating of consumable wire-anode; higher velocity of plasma jet outflow and greater extent of argon plasma zone at plasma jet compression by accompanying gas, the optimal effect of this being manifested at its lower flow rates (to 30 m^3/h).

Note that owing to its small overall dimensions (height dimension), the plasmatron can be used for spraying inner surfaces of more than 70 mm diameter and for spheroidization of current-carrying wires in atomization chambers (including small-sized ones).

INVESTIGATION OF GRANULOMETRIC COMPOSITION AND MICROSTRUCTURE OF COATINGS PRODUCED IN THE DEVELOPED PLASMATRON

Comparative studies were performed of granulometric composition of atomization products (spherical granules) at the following technological parameters of plasmatron of the previous modification and the developed one (Table 1).

Analysis of granulometric composition of atomization products (Figure 4) showed that at atomization with serial PLAZER 30-W plasmatron the main powder fraction (90 % of the total weight) is 63–250 μm particle size, and for PLAZER 50-W plasmatron it is 63–160 μm in the absence of 250–315 μm fraction, while the proportion of 160–200 μm fraction does not exceed 2 wt.% (for serial plasmatron this parameter is 20 %).

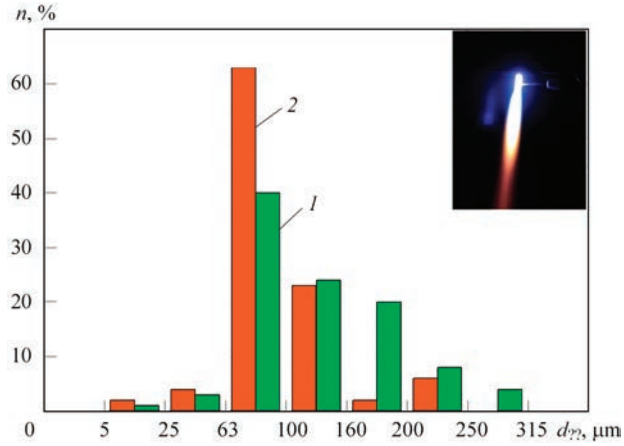

Figure 4. Size distribution of granules produced using the developed PLAZER 50-W plasmatron (*1*) and PLAZER 30-W plasmatron of previous modification (*2*)

The average size of spraying particles was calculated in accordance with the obtained data on size distribution of granules, produced with the use of serial PLAZER 30-W and developed PLAZER 50-W plasmatrons (Figure 4). These calculations showed that the developed design of the plasmatron gas-discharge chamber promotes lowering of this parameter from 134 to 99 μm, which, in its turn, should promote production of a more homogeneous, finely-dispersed lamellar structure of the coating.

These mode parameters were used to spray a coating from current-carrying compact wire from stainless steel of AISI 304 grade (d = 1.6 mm). Figure 5 gives a comparison of microstructure of coatings, sprayed in the serial and developed plasmatrons at the same atomization modes.

Microstructural analysis of the coating, sprayed in the developed plasmatron showed that in this case the coating is more homogeneous, with porosity close to 1 %. The coating structure has almost no round spherical unmelted particles, the lamelle thickness was reduced from 25 to 15 μm.

Studying the shape of dispersed phase particles showed that, on the whole, the granules are of a regular spherical shape (Figure 6), sphericity coefficient (S_{sph}) is equal to 0.75–0.85. Here, the proportion of irregularly shaped granules is not more than ~ 2 wt.%. It should be noted, however, that wire atomization and formation of a jet from overheated particles and their further solidification was performed in air and in water, where the processes of intensive chemical interaction of the wire material with oxygen, nitrogen

Table 1. Parameters of the mode of plasma-arc spraying of current-carrying AISI 304 wire of 1.6 mm diameter

Plasmatron model	Current, A	Arc voltage, V	Argon flow rate, l/min	Air flow rate, m^3/h	Cathode–anode distance, mm	Wire feed rate, m/min
PLAZER 30-W	235	80	50	48	10	10.0
PLAZER 50-W	–»–	85	–»–	30	–»–	10.5

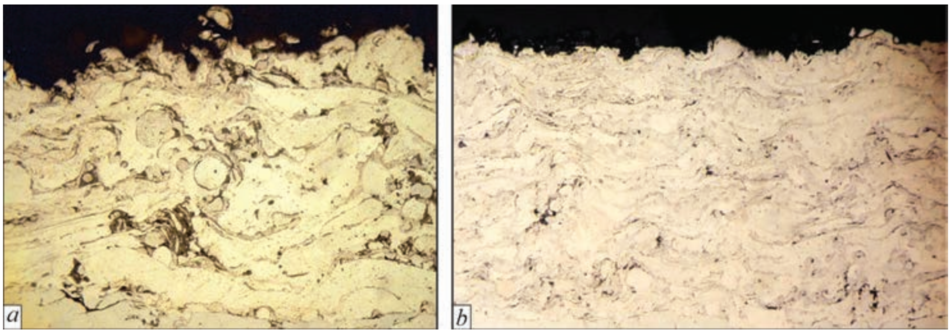

Figure 5. Microstructure of coating from AISI 304 stainless wire, sprayed with serial PLAZER 30-W plasmatron (*a*) and with developed PLAZER 50-W plasmatron (*b*)

and hydrogen are in place, which may lead to deterioration of the powder sphericity parameters. In work [17] it is reported that wire plasma-arc atomization in chambers with inert atmosphere allows producing powder, the sphericity coefficient of which may reach almost 0.90. Therefore, increase of particle sphericity parameters can be achieved due to creation of an inert atmosphere in the environment where the processes of powder atomization, dispersion and solidification take place.

Analyzing the above, the process of plasma-arc atomization of wire materials using PLAZER 50-W plasmatron can be regarded as an industrial process for producing spherical granules with up to 90 wt.% yield of 20–100 μm fraction, which satisfies the requirements to granulometric composition and sphericity coefficient for such processes of 3D printing as Selective Laser Melting (SLM), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), etc. On the whole, in this range of granulometric composition practically all the produced fractions can be used both as materials for the most wide spread 3D printing technologies, and for granule metallurgy. 20–80 μm fraction makes up 48 % of the total powder weight (SLM); 45–106 μm is equal to 64 % (SLS); 45–160 μm — 85 % (DMLS); 106–160 μm — 22 % (hot isostatic pressing (HIP)).

Obtained results were tested at spraying of the inner cylindrical surface (d_{in} = 95 mm) by current-carrying compact 1.6 mm wire of AISI 304 grade (Figure 7).

DEVELOPMENT OF NEW GENERATION INSTALLATION FOR PLASMA-ARC ATOMIZATION OF CURRENT-CARRYING WIRES

Application of the developed higher power plasmatron, which ensures wider technological capabilities of the process of plasma-arc atomization of current-carrying wires (wire spheroidization, producing spherical finely-dispersed granules, coating deposition not only on external, but also on inner surfaces of ≥ 70 mm diameter, etc.), requires intellectualization of processes of real-time control and monitoring of a large number of parameters including increase of the degree of automation of the technological process of plasma-arc atomization. A specialized system of unit control was developed for this purpose, which includes measuring, starting and control and signal instrumentation, use of a touch panel, programmable logic controller (PLC) and development of the respective software.

The software covers all the functions of control, adjustment, indication and emergency alarm signalling of the unit operation modes. PLC has the role of executive computing device, which performs correction of atomization process parameters based on the data received from the monitoring system, and corrects the equipment operation algorithms, changing the current, gas flow rate, wire feed rate, etc.

Figure 8, *c* shows the interface windows of the main control system (mobile control panel). They are divided into 5 main windows.

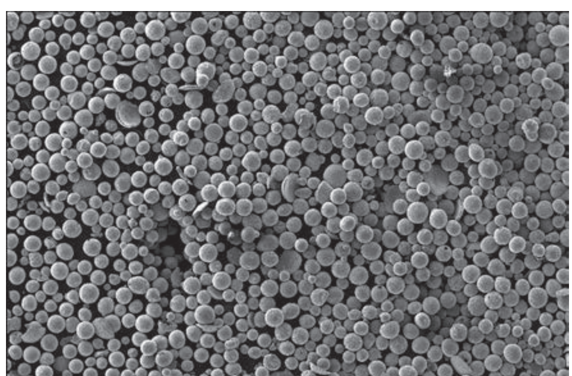

Figure 6. Morphology of granules from AISI 304 stainless steel of 20–100 μm fraction, produced at plasma-arc atomization of 1.6 mm wire

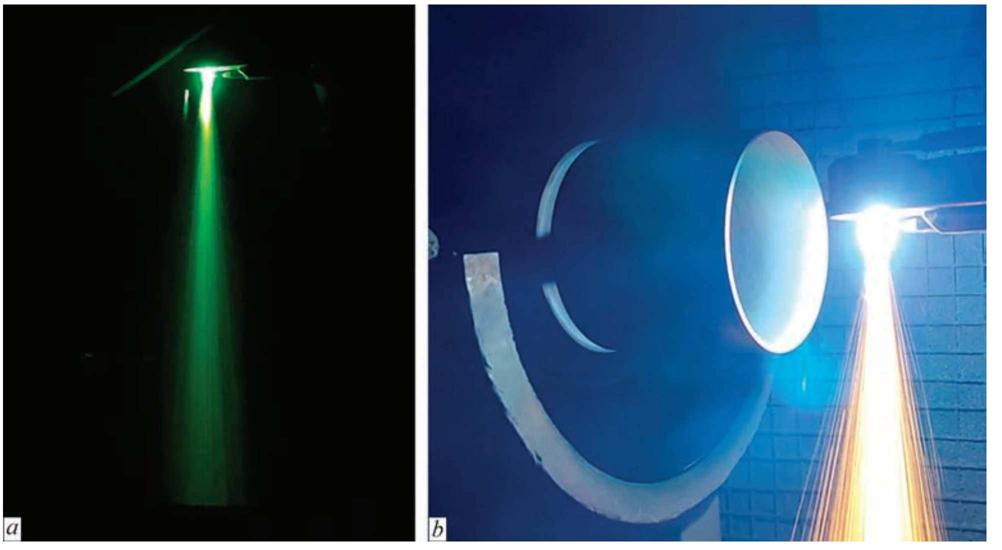

Figure 7. Appearance of two-phase particle-loaded jet (*a*) and process (*b*) of spraying the inner cylindrical surface (d_{in} = 95 mm) with current-carrying compact AISI 304 wire

AUTOMATIC CONTROL WINDOW (AUTO MODE)

Here, the operator assigns the minimum of the main technological parameters, control mode (external start/stop or local), and he can start the equipment. Automated software is fully responsible for controlling the technological process cycle. It runs the process according to pre-defined cyclogram algorithms. Indication and displaying of the main parameters of signal measurement system (current, voltage, gas flow rate and pressure, circuit temperatures, digital status of sensors, valves, etc.) is also given on the left.

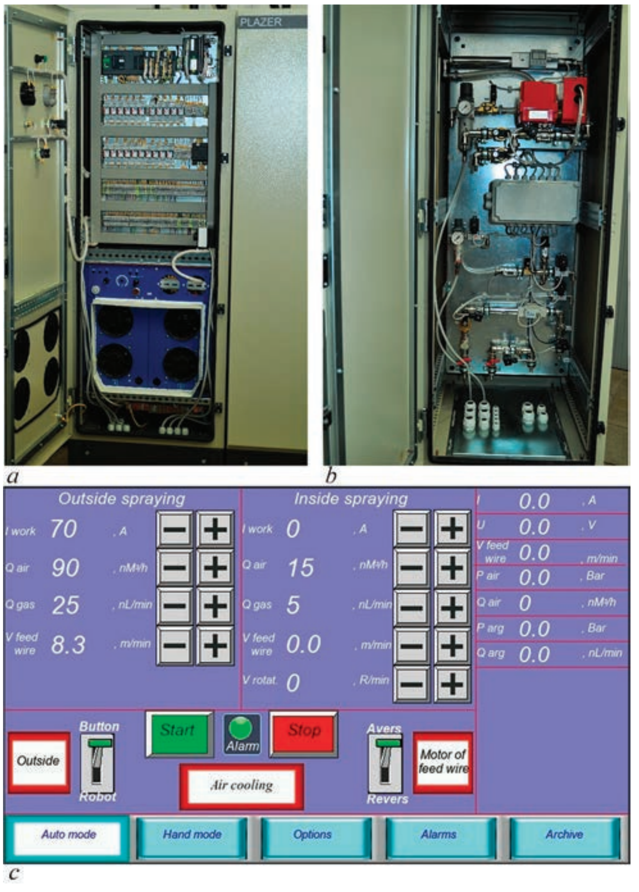

Figure 8. Appearance of the developed control cabinet for the process of plasma-arc spraying of current-carrying wires: *a*, *b* — electric part and gas preparation block, respectively; *c* — interface of the panel of entering the process technological parameters

MANUAL CONTROL MODE (HAND MODE)

This enables flexible control through direct impact of the operator on each assembly of the equipment, controlled by the operator himself. It is recommended to perform manual control only by qualified experts.

EQUIPMENT SETTINGS WINDOW (OPTIONS)

Here, it is possible to assign flexible settings of the equipment, such as signal boundaries, which trigger the emergency monitoring system, as well as starting, ending and transition values of technological parameters, temporary delays, response time during emergency shutdowns and other fine technological adjustments.

ALARM WINDOW (ALARMS)

This window is used for displaying messages in case of emergencies, which based on the last measured data, enable the operator understanding the cause of the emergency shutdown (it can be insufficient gas flow rate, gas pressure, too high or low current/voltage, equipment overheating, etc.). In case of elimination of the cause for the emergency, the technological process can be restarted.

DATA ARCHIVE WINDOW (ARCHIV)

In this window automatic recording and saving of equipment sensor readings will be performed. All the parameters are saved on the flash-card, and they can be exported to a PC for data storage and analysis.

Another distinctive feature of the above equipment is improved ergonomic design and unit control interface, adapted to the processes of plasma-arc spraying of external and inner surfaces and wire spheroidization (Figure 8, *c*). The developed pneumatic-hydraulic diagram (Figure 8, *b*), combined with an upgraded plasmatron design allows using helium and a mixture based on it as plasma forming gas. A possibility of feeding combustible gases into the accompanying gas flow is envisaged, in order to reduce the degree of particle oxidation for a certain range of materials (due to creation of a reducing atmosphere). To improve the process productivity, work on raising the current load in the above-mentioned equipment was performed, in order to increase its energy efficiency (at application of larger wire diameters (2–3 mm)). With this purpose, the thyrisor cooling assembly was upgraded (more powerful fans were selected and installed), which allows increasing the current regulation range from 380 to 500 A.

Production of the described new generation unit (Figure 9) was organized at R&D PLAZER Center Ltd. (Ukraine) under PLAZER 50-PL-W trademark. The above equipment was exported, including to China, to Zibo KNC Petroleum Equipment Co., Ltd, and it is used for protective coating deposition on critical parts of oil production equipment and on pipes of heating surfaces for waste incineration plants with application of compact and flux-cored wires of 1.6–2.4 mm diameter as spraying materials (including those with the core from refractory non-conductive materials).

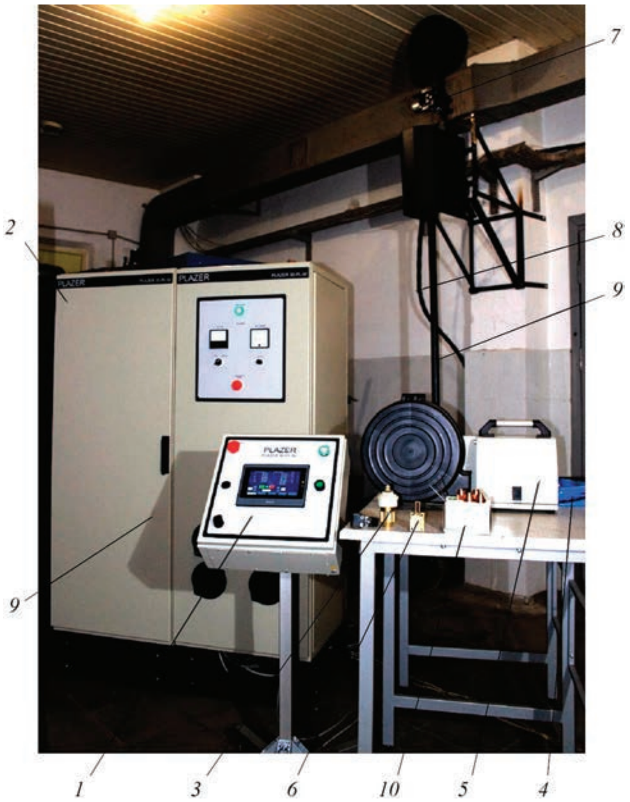

Figure 9. Main components of the unit for coating deposition by plasma-arc spraying of current-carrying wires: *1* — control system with programmable controller and touch panel; *2* — specialized inverter power source; *3* — plasmatron block for spraying of external surfaces with air cooling; *4* — cable-hose pack of the plasmatron for spraying of outer surfaces; *5* — system of fire feed for spraying of external surfaces; *6* — head for spraying of external and inner surfaces with water cooling; *7* — system of wire feed for spraying of inner surfaces; *8* — cable-hose pack of the plasmatron for spraying of inner surfaces; *9* —spare part kit

Specification of PLAZER 50-PL-W installation

Consumed power, kW	Not more than 50
Voltage of 50 Hz three-phase AC mains, V	380^{+19}_{-38}
Open-circuit voltage, V	160
Range of working current adjustment, A	100–500
Range of working voltage adjustment, V	30–100
Longest duty cycle, %	100
Air flow rate at 0.6 MPa pressure, Nm^3/h	15–60
Argon or helium flow rate at 0.1 MPa pressure, Nm^3/h	1–3
Wire feed rate, m/min	2–15
Plasmatron cooling	Water
Plasmatron nozzle and cathode life, h (machine time)	Not less than 100
Water pressure at cooling, MPa	0.3–0.5
Cooling water flow rate, Nm^3/h	0.4–0.6
Diameter of the used wire materials, mm	1.0–2.4
Control type	Automated
Controller type	PLC

CONCLUSIONS

1. A new generation unit for plasma-arc coating deposition and current-carrying wire material atomization was developed. Its features are application of a plasmatron with higher current load and consumable wire heating efficiency, improved weight and dimensional characteristics and intelligent system of automatic control and monitoring of a larger number of technological parameters in real time. Its serial production was organized at R&D PLAZER Center Ltd enterprise (Ukraine).

2. Compared to previous analogs, the developed unit allows: improvement of atomization process productivity from 12 to 16–18 kg/h; using both compact and flux-cored wires of up to 2.4 mm diameter for spraying (including those with a core from refractory non-conductive materials; producing high-quality coatings with less than 1 % porosity; and spheroidized granules with the main finely-dispersed fraction of 20–160 μm.

3. The range of the main parts, on which protective coatings are deposited using the developed unit, includes plungers, rods, pistons of various pumps, rotors, turbine shafts, drill well rods, parts of hydraulic and power equipment, shafts and other parts of ship engines and other ship equipment, parts of chemical equipment, large-sized components of railway equip-

ment (axles, crankshafts, rods and sleeves of locomotive diesel engines) and many other products.

4. Reduction of plasmatron overall dimensions with simultaneous increase of the efficiency of sprayed wire heating in the developed unit promotes expansion of its applications, in particular allows using it both for spraying the external and inner surfaces of more than 70 mm diameter (cylinder blocks, pipe inner surfaces, etc.), and for plasma-arc spheroidization of wires in atomization chambers (including small-sized ones) to produce spherical granules of finely-dispersed fractions with the sphericity coefficient of 0.75–0.85, which meet the requirements to materials for such methods of 3D printing as SLM, SLS, EBM, DMLS and granule metallurgy (HIP).

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ORCID

V.M. Korzhyk: 0000-0001-9106-8593,
D.V., Strogonov: 0000-0003-4194-764X,
O.M. Burlachenko: 0000-0003-2277-4202,
O.V. Ganushchak: 0000-0003-4392-6682,
O.M. Voitenko: 0000-0003-4946-6517

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

V.M. Korzhyk
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: vnkorzhyk@gmail.com

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