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PROMISING DIRECTIONS OF WORKS IN THE FIELD OF WELDING AND RELATED TECHNOLOGIES AT SSPA «POWDER METALLURGY»

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The paper presents the promising directions and obtained results in the field of welding and related technologies, pursued in Belarus at SSPA «Powder Metallurgy», including friction stir welding, additive technologies, flame spraying of powder materials and electrospark coatings. Comprehensive development of works in the field of additive technologies is achieved by application of equipment, which ensures polymer and metal 3D-printing, production of metal powders and additional compaction operations. Alongside research performance, this equipment is used for product manufacturing. A unit with a system of recording the welding mode parameters was developed for conducting experimental studies and practical application of friction stir welding. Computer modeling programs (Deform, Sysweld, Ansys, etc.) are used during performance of investigations and development of technological processes and tool designs. Tool manufacture is performed in experimental production, in particular by the methods of powder metallurgy and additive technologies. New scientific and practical results were obtained on development of processes and equipment for flame deposition of coatings from powder materials on parts of various functional purposes, using high power jets (up to 125 kW). Investigations were performed and equipment was developed for forming thick-layer (up to 5000–7000 μm) electrospark coatings with application of electrode-anode vibration of 22 kHz frequency. 18 Ref., 8 Figures.

Keywords: *friction stir welding, additive technologies, flame spraying, computer modeling, tool manufacture, equipment for electrospark coating deposition*

Research area devoted to study of high-energy processes of surface treatment and forming powder coatings has been developing at SSPA of the NAS of Belarus (SSPA PM) for the last twenty years [1–3]. Search works have been performed to study the influence of pulse-periodic laser impact on metal powder particles, as well as on these particles and metal surface, on which they were located [4]. These studies resulted in development (2005) together with the Institute of Physics of the NAS of Belarus of a promising sample of powder laser stereolithography unit [4, 5], which can be regarded [5, 6] as an analog of modern metallurgical 3D-printer. 3D-printing in this analog was based on selective laser sintering, as it was then believed, of metal powder particles. The developed analog of metallurgical 3D-printer, the characteristics of which are given below, allowed shifting the focus of the performed above-mentioned research towards studying the processes of producing advanced samples of porous permeable materials, primarily, for medical purposes (Figure 1). Results of these studies showed [7, 8] that there exist such modes of pulse-periodic laser radiation, at which permanent joints can form, both between the metal powder particles, and between these particles and metal base in the contact zones. The main mechanism of such joint formation is liquid-phase sintering.

Service parameters of the analog of metallurgical 3D-printer

Solid-state laser	P = 150 W; λ = 1064 nm, microprocessor control and monitoring system
Layer deposition system	Adjustable microprocessor regulation system
Working print area, mm	250×250×100
Minimum construction zone, μm	x = 100; y = 100; z =20
Repeatability, μm	x = 20; y = 20; z =20
Loading system	Manual
Powder collection and recovery system	Manual
Consumable materials	Titanium alloys, nonferrous metal alloys

It should be noted that not only selective laser fusion used at 3D-printing by individual types of metallurgical 3D-printers can be considered as a variety of processes related to welding. Also regarded as such [6, 9, 10] can be the following processes used at 3D-printing: Fused Deposition Modeling, or as they are also called, Fused Filament Fabrication. They are based on model layer-by-layer deposition of molten polymer filament. Alongside them, the processes of Direct Metal Deposition, based on direct layer-by-layer deposition of metal molten under the impact of laser radiation or electric current, as well as Electron Beam Melting, based on layer-by-layer selective electron beam penetration of the powder layer, should be also considered as a variety of processes related to welding.

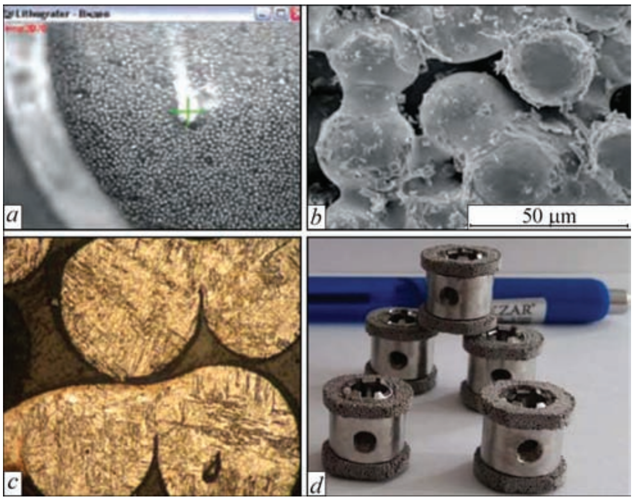

Figure 1. Process of pulse-periodic laser impact followed by the monitoring system of 3D-printer analog (*a*), produced structure of porous material (*b*) and particle contact (*c*) of a spinal fusion implant (*d*)

Additive technologies, which appeared in the second half of 1980s in the form of rapid prototyping, using laser systems of selective photopolymerization, by the end of the first decade of XXIst century became the basis of the forming sixth wave of innovations, together with nanoelectronics, optoinformatics, photonics, artificial intelligence systems, as well as CALS technologies, which determines the present and future development of science and technology all over the world [6, 11]. Starting from 2015, SSPA PM has conducted purpose-oriented activities for establishing our own additive manufacturing. Here, we take into consideration not only the earlier obtained practical experience, related to development and manufacture of an analog of metallurgical 3D-printer, as well as producing in it promising, primarily, for medical applications, porous permeable materials, but also the acquired experience of our own production of metal powders with spherical shape of particles, using the processes of melting and gas atomization of metal melts [1, 3]. At present, additive manufacturing organized at SSPA PM is based on the following process equipment:

- assembled in France metallurgical 3D-printer ProX DMP 300 of 3D-Systems International Company (Headquarters in the USA), in which the process of 3D printing is performed by layer-by-layer selective laser fusion of metal powders;
- manufactured in China vacuum-induction unit JT-QWH-25KG;
- manufactured by Ultimaker B.V. Company (The Netherlands) 3D-printer Ultimaker 3 Extended, in which the process of 3D-printing is performed by layer-by-layer deposition of molten polymer filament;
- manufactured by GOM Company (Germany) 3D-scanner ATOS Triple Scan 16M.

Characteristics of the above process equipment are given below.

Service parameters of 3D-printer ProX DMP 300

Fiber laser	P = 500 W, λ = 1070 nm, microprocessor control and monitoring system
Layer deposition system	Adjustable microprocessor regulation system
Working print area, mm	250×250×300
Minimum construction zone, μm	x = 100; y = 100; z =20
Repeatability, μm	x = 20; y = 20; z =20
Loading system	Automatic pneumomechanical with microprocessor control system
Powder collection and recovery system	Automatic pneumomechanical with microprocessor control system
Consumable materials	Stainless steel, tool steel, nonferrous metal alloys, high-temperature alloys, aluminium and titanium oxides, metal ceramics

Service parameters of vacuum induction unit JT-QWH-25KG

Maximum load, kg	25 (for steel)
Power of induction medium-frequency heater, kW	100 (at 4 KHz frequency)
Maximum temperature, °C	
in dispensing crucible	≤2200
in melting crucible	≤1850
Vacuum working pressure, Pa	≤0.66
Maximum pressure in spray chamber, MPa	6
Gases used for spraying	Ar, N_2

Service parameters of 3D-printer Ultimaker 3 Extended

Printing technology	Fused deposition modeling (FDM)
Number of extruders	2
Working print area, mm	215×215×315 (for one extruder) 197×215×315 (for two extruders)
Consumable materials	ABS, PLA, PVA, HIPS, WATSON, nylon, polycarbonate

Performance of 3D-scanner ATOS Triple Scan 16M

Number of surface points from selected zone captured in one scan	Up to 16 MP
Scan field parameters in the selected zone, mm	320×240×200
	535×400×320
Scanning accuracy in the selected zone for the scan field, mm:	
320×240×200	Not worse than 7 μm
535×400×320	Not worse than 19 μm

Work on development of technologies of producing both promising for mechanical engineering and medicine samples of products (Figure 2, *a*, *b*) from titanium and high-temperature metal alloys by 3D-printing, and of powders proper (Figure 2, *d*) from high-temperature alloys is performed in additive production. It is planned to use these powders as consumable material not only for metal 3D-printing, but also for traditional flame and plasma surfacing.

It should be also noted that studying the structure (Figure 2, *c*) of promising for mechanical engineering samples of products produced by 3D-printing in metallurgical 3D-printer ProX DMP 300 leads to the conclusion that the main mechanism of pulse-periodic laser fusion is microwelding, at which a molten pool can form, its dimensions exceeding the diameter of the initial powder particles several times.

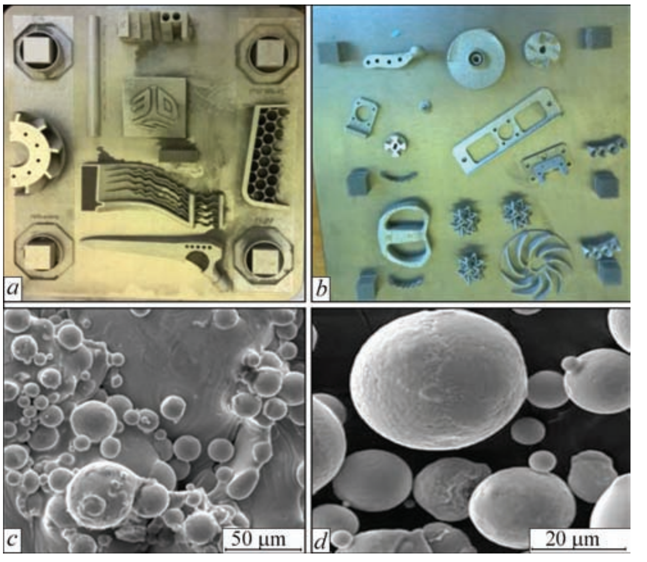

Figure 2. Test (*a*) and advanced (*b*) samples of products, their structure (*c*) and proposed powders for 3D-printing (*d*)

Work on mastering the production of domestic medical implants (Figure 3, *a, b*) and endoprostheses (Figure 3, *c, d*), the most accurately allowing for anatomical features of the patients, is also performed in additive production for the needs of Belarus health care.

In addition to perspective improvement of the developed additive technologies, it is also planned to develop and improve in additive production the technologies based on 3D-scanner application, both for automated quality control as to accuracy of product manufacturing, and reengineering. At development and improvement of reengineering technologies, it is planned to focus on eventual lowering of the cost of products manufactured in additive production. Within the framework of development of this production, it is also planned to develop and improve the technologies of rapid prototyping and producing molten polymer filament using the processes of model layer-by-layer deposition, as well as improve the already available at SSPA PM technologies of heat treatment and hot isostatic pressing of powder materials, including the technologies of laser and electroerosion cutting. Application of the above technologies in additive production will promote greater effectiveness of its functioning and at the same time improvement of physicomechanical and strength properties of the manufactured products.

Friction stir welding (FSW) has been one of the most dynamically developing areas in the field of welding over the last decades.

Starting from 1991, after patenting of this solid-phase friction welding process (Friction Stir Welding — FSW) by The Welding Institute (TWI), research in this field has been intensively conducted, and equipment and tools have been developed. Technical and economic advantages of this process enable its active introduction into production, ousting the traditional fusion welding methods. The main FSW advantages include:

• high stability of weld quality, strength and endurance of welded joints (impact toughness, ultimate strength, bend angle, cyclic strength and some other parameters) in absence of distortions or thermal deformations, without pores, inclusions or cracks;

• shortening of production cycle by 50–70 %, compared to regular welding processes, for instance, arc welding;

• possibility of welding parts from dissimilar materials, unweldable by the traditional methods;

• possibility of automation and application of real-time in-process quality control (with availability of special fixtures and tools it can be performed in standard metal-cutting equipment) in all-purpose milling machines and CNC machines, as well as with application of robotic systems;

• low energy consumption (2.5 % of energy consumed in laser welding; 10 % of energy consumed in arc welding);

• fast payback due to low energy consumption and no need for consumable materials, or for envisaging the sanitary and ecological measures;

• high welding hygiene, as there is no hot metal spatter, evolution of harmful substances (welding aerosols and gases), no ultraviolet radiation, or electromagnetic fields.

The following should be regarded as the process disadvantages:

• need for large capital expenditures for introduction of sophisticated modern high-tech equipment with maximum complex automation and robotization;

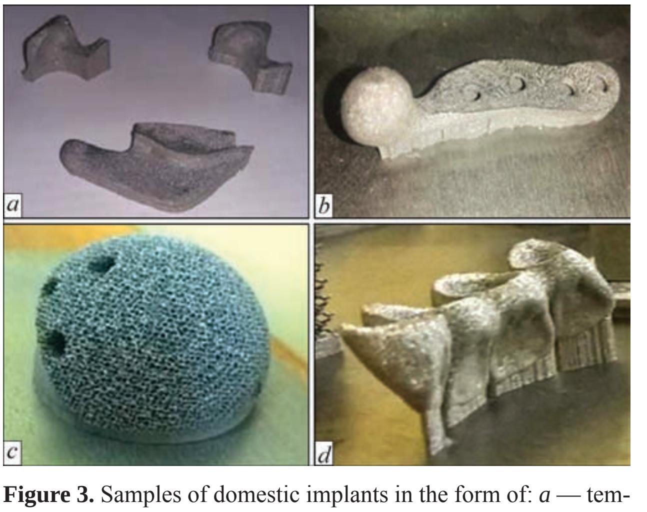

Figure 3. Samples of domestic implants in the form of: *a* — temporomandibular joint; *b* — mandibular miniplate; endoprotheses in the form of: *c* — hip cup; *d* — dental crown

Figure 4. Examples of tools produced by the methods of powder metallurgy and 3D-printing

• need for specialized fixtures for basing and rigid fastening of parts before welding, which is several times greater than in fusion welding;

• need to apply runoff tabs or multiple complication of the structure design.

Successful application of FSW requires an integrated approach, including performance of research, development of technology, equipment, tools and their manufacture. Starting from 2014, SSPA PM has conducted investigations of FSW processes, developed and manufactured the tools. Technologies of welding similar and dissimilar aluminium, iron and copper based alloys 0.5 to 10 mm thick are studied and developed, and work on 3D-surfacing is performed.

In order to conduct experimental studies and for practical application of FSW, a laboratory set-up with system of programmable automatic control (CNC) of the technological process and system of recording the welding mode parameters was developed.

Investigation and development of technologies and tool designs are performed with application of computer modeling programs (Deform, Sysweld, Ansys, etc.).

Pilot production manufactures tools by the methods of powder metallurgy and 3D-printing. Tools from tool steels for welding aluminium alloys of 0.3 to 10 mm thickness, and from hard alloys and WRe for welding materials from 0.8 to 6.0 mm thick are currently produced. The manufactured tools are shown in Figure 4.

Work is in progress on development and setting up manufacturing of FSW equipment in the Republic of Belarus. One of the directions of work in the field of welding and related technologies, which was further developed at SSPA PM in scientific and practical terms, is the technology of flame spraying of coatings.

Flame spraying of coatings from self-fluxing alloys, developed by Wall Colmony Corporation (USA) in 1945, is still widely applied at surface strengthening of parts for various purposes, usually, of small overall dimensions, for instance, exhaust valves, levers and pushers of the gas-distributing mechanism of internal combustion engines, and parts of various machines. With increase of overall dimensions, and product weight, respectively, the amount of heat, evolving at operation of the currently available standard machines is insufficient for coating deposition.

Taking into account the disadvantages of the available methods, we developed a new process — continuous flame spraying of coatings from self-fluxing nickel alloys (CFSC) and equipment for its performance. In this process preheating of the sprayed surface of the part up to the required temperature, deposition of a layer of coating material, heating it and part surface up to the coating material melting temperature — surface melting, is performed without interruptions between the operations, by one high-power gas-flame spraying system TENA-GNpm (Figure 5).

Figure 5. TENA-GNpm system

An important feature of TENA-GNpm system is ensuring safe operation at coating deposition, that is achieved due to an ingenious system of gas mixing and gas nozzles. Used as the combustible gas is synthetic gas MAF to TU 38.102.1267–89 (methylacetylene-allen fraction), production of which is carried out in the Republic of Belarus. Work on gas-flame spraying of coatings is performed at its flow rate from 1.0 up to 3.5 m^3/h (maximum thermal power of the flame is more than 100 kW). Wide ranges of regulation of power of TENA-GNpm system allow deposition of coatings on parts of various dimensions and weight with the efficiency from 1 up to 8 kg/h [12].

Amorphous flame coatings are currently applied for reconditioning and strengthening of various parts: crankshaft main and connecting rods, camshaft bearing journals, crankshafts and eccentric refrigeration shafts that allowed their service life to be extended 1.3 to 1.6 times, compared to new uncoated parts. Deposition of amorphized coating on cast iron piston rings allowed their wear resistance to be increased 1.6 to 2.5 times, compared to electroplating chromium. Here, lowering of friction coefficient 1.5 to 1.6 times and reduction of sleeve wear 1.4 to 2.4 times is observed [13].

We developed a new process of powder flame spraying and TPpm-18 unit for spray deposition of high-quality coatings from a wide range of materials, including metal alloys, oxide ceramics, amorphous materials, special composites, etc. The unit is fitted with a new system of gas mixing and special multinozzle tips, ensuring safe operation (without backfire) at a high power (up to 100 kW and more). An important distinctive feature of TENA-Ppm18 unit is its fitting with air nozzles, forming the combustion chamber (about 15 mm diameter, length from 25 to 120 mm), as well as air ring distributor mounted on air nozzle, that allowed concentrating (compressing) the two-phase jet along the axis, raising its pressure and temperature, increasing the length of the jet high-temperature zone more than 3 times, and effective efficiency of powder heating, and lowering the thermal impact on the product.

The new process was used for repair of worn working surface of flexographic printing drum (1250–1600 mm diameter, 250–350 mm width) by spraying the coating layer with powder of amorphous alloy BKhM [14]. Spraying distance was equal to 250 mm, time of spraying 0.6 mm coating was 90 mi, powder consumption was 11200 g; and efficiency was 7.5 kg/h.

Unit operating mode

Powder	BKhM
Particle size, μm	20–40
Flow rate, g/min, kg/h	100 (7.5)
Gas pressure, MPa	
Air	0.4
MAF	0.2
O_2	0.6
Gas flow rate, m^3/h:	
Air	27.6
MAF	3.3
O_2	8.25
Power *N*, kW	81.36

Service tests showed that amorphous coating of the drum working surface with BKhM powder, when working three-shifts, ensures normal operation of the drum (without traces of wear) for two years at a high quality of printing. Flame spraying of a coating from BKhM amorphous material was also used for strengthening of the aluminium housing of Wankel engine. For comparison, Figure 6 shows the processes of spray deposition of an amorphous coating with BKhM powder by TPpm-18 unit on the drum of flexographic printing machine and of WC–12Co coating by Jet Kote supersonic spraying machine of Deloro Company on a shaft. One can see from Figure 6 that the jets are similar in both the processes. Hardness of amorphous coating deposited by TENA-TPpm-18 unit is equal to *HRC* 70–74, and that of WC–12Co coating deposited by Jet Kote equipment, is *HRC* 62–68. Spraying efficiency in the first case is three times higher than in the second.

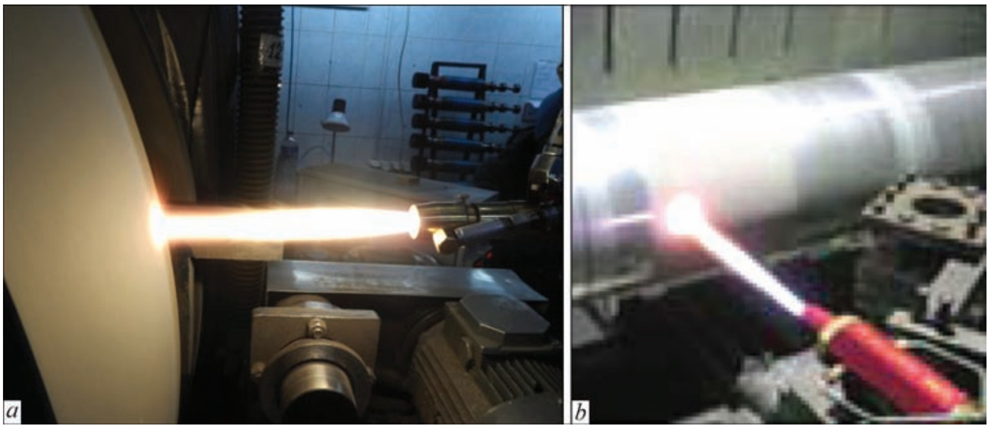

Figure 6. Spraying processes: *a* — amorphous coating deposition with BKhM powder by TPpm-18 unit; *b* — WC–12Co coating deposition by Jet Kote unit of Deloro Company

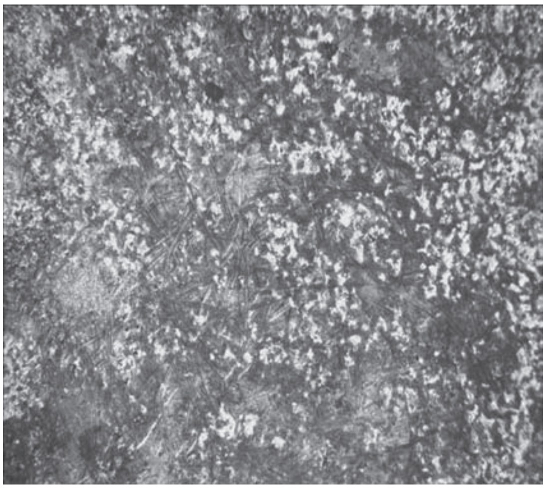

Figure 7. Coating formed at 22 kHz frequency of anode oscillations (×20)

A new technology of gas-flame spraying of thick-layered (2–4 mm) coatings from nanostructured ferritic powders with a special complex of properties, in particular, ensuring wide-range microwave absorption, was developed, and process equipment for its implementation was manufactured [15]. The essence of the proposed technology consists in that the powdered ferromagnetic material with particle sizes of (–53.0+5.0) μm is fed into the jet of gas-flame sprayer TENA-Ppm, moving at a speed of 300–750 m/s, the energy of which is used to transport and deposit the powder particles on substrates fixed in the mandrel. Flow rate of MAF combustible gas during unit operation is 3500 l/h, and that of oxygen is 8750 l/h. The process and equipment were transferred to the customer under a contract.

Saving energy resources and reducing labor consumption in production are in the first place in the activity of each mechanical engineering or repair enterprise. Under these conditions, methods with application of concentrated energy flows, which include electrospark alloying (ESA), are used for restoration of service properties of parts of machines and mechanisms lost in operation, improvement of service properties, and extension of service life. ESA method allows coating deposition on the treated surface by a compact electrode from any current-conducting material, and is characterized by low energy consumption. The formed spark coatings feature high strength of adhesion with base material. One of the drawbacks of the method, however, is the small thickness of the applied coating (up to 300–500 μm), that limits its application [16, 17].

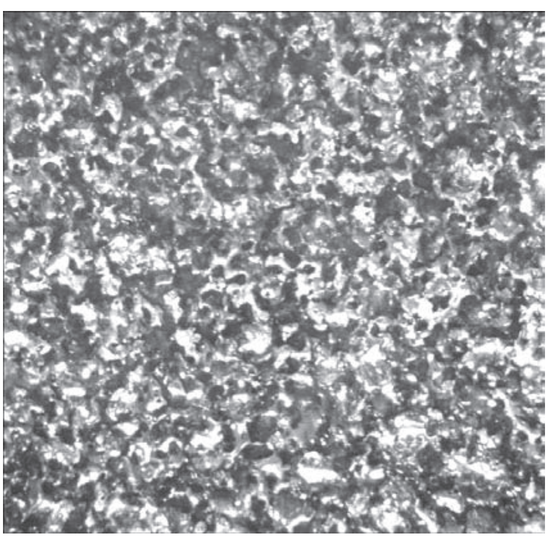

Figure 8. Coating produced at 600 Hz frequency of anode oscillations (×20)

The problem of increasing the thickness of spark coatings is being solved now. Thick-layer coatings of higher continuity were obtained at Federal State Budgetary Institution «All-Russian Scientific-Research Technological Institute of Repair and Maintenance of Machine and Tractor Park» (FGBNU GOSNITI, Russia) by the method of application of alternating cycles of deposition of coarse coatings with great roughness of surface profile and surface melting cycles for leveling the surface profile with reduction of the height of these irregularities by not less than 50 %. Here, surface melting of profile unevenness was performed with application of electrode materials with higher heat conductivity and erosion resistance relative to electrode material, forming the coating. Thick-layer coatings were formed in modes of low-frequency electrospark alloying with maximum frequency of alloying electrode vibration of 600 Hz [18].

SSPA PM performed a package of research work with application of experimental equipment for high-frequency electrospark alloying with the purpose of determination of the influence of ultrasonic impact (USI) on the process of forming electrospark coatings of greater thickness and continuity. Proceeding from the results of earlier studies, it was found that ultrasonic impact with 20.4–23.6 kHz frequency applied before the start and after the end of the main electrospark treatment actively influences the increase of the coating mass and thickness. Increase of coating mass in the first case is three times greater, and in the second case it is two times greater than in the case, when additional USI is not applied [19].

Investigations were performed with application of Alier-55 unit and ultrasonic device developed in the Sector of Electrophysical Coatings of SSU IWPC, consisting of a generator, power unit and ultrasonic piezoelectric converter.

The following energy modes of Alier-55 unit were selected for experimental studies: coatings were deposited with pulse energy of 4.3 J and their repetition rate of 100 Hz; surface melting of the coating was conducted by a combined method — working pulses with 10 J energy and 50 Hz repetition rate were obtained from Alier-55 unit, and the frequency of oscillations of electrode-anode of 20.4–23.6 kHz was set by ultrasonic device generator. Periodical contact of «surface melted» electrode with the deposited coarse coating layer performed at ultrasonic frequency of 20.4–23.6 kHz, resulted in high dispersion of protrusions of the coating coarse layer with displacement of dispersed particles to the relief depressions, ensuring leveling of the coating and increase of its continuity up to 85–90 % and of the thickness up to 5000 μm.

Figure 7 shows the topography of cathode surface (steel 45) after treatment with electrode-anode from titanium-tungsten-cobalt alloy T15K6 with vibroexciter frequency of 22 kHz. The formed coating has the structure with element size up to 10 μm. The coating after treatment by electrode-anode with vibroexciter frequency of 600 Hz, is shown in Figure 8. The formed coating has the structure with element size up to 100 μm.

Thus, it is experimentally established that application of ultrasonic converter with vibration frequency of electrode-anode of 22 kHz in surface melting operations allows performance of meting and refinement of the material of coating protrusions to values by an order of magnitude smaller than at application of vibroexciter with standard vibration frequency of 600 Hz. Here, more complete movement of molten material of the protrusions into the depressions occurs, and coating continuity is increased.

It is determined that energy modes of Alier-55 unit of 4.3 and 10 J power ensuring the liquid-drop nature of mass transfer and melting of profile irregularities, as well as ultrasonic impact with the frequency of 20.4–23.6 kHz, during coating deposition and melting of the tops of the protrusions, create thermodynamic phenomena, similar to local annealing as to the nature of their impact on cathode material.

This promotes reduction of the values of tensile (residual) stresses, arising in the coating alloyed layer during electrospark alloying, and shifts the brittle fracture threshold of the material, thus creating favourable conditions for monotonic and continuous growth of the thickness of electrospark coatings up to values greater by an order of magnitude that at application of standard ESA techniques.

Investigation results are currently used to develop equipment for forming thick-layer (up to 5000–7000 μm) electrospark coatings with application of electrode-anode vibration of 20.4–23.6 kHz frequency.

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