DOI: http://dx.doi.org/10.15407/tpwj2018.11–12.01

ADVANCED STUDIES AND DEVELOPMENTS OF THE E.O. PATON ELECTRIC WELDING INSTITUTE IN THE FIELD OF WELDING AND RELATED TECHNOLOGIES

Academician B.E. PATON
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazimir Malevich Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

A number of recent new developments of the E.O. Paton Electric Welding Institute is presented, namely the technologies and equipment for welding with applying the highly-concentrated power sources: plasma, laser and electron ones. Technologies were developed for welding of pipes, thick titanium, aluminium-lithium alloys, high-strength steels. The vapor-phase technologies were developed for producing nanostructured materials for welding composite materials and intermetallics. Technologies and equipment for underwater welding and cutting, new electron beam tool for welding in open space were developed. To increase the life and safety of the weld, the postweld treatment was suggested by using the high-density electric pulses and high-frequency mechanical peening. To control the quality of welded structures, the designed digital equipment, based on high-sensitive solid-body converters and an industrial robot with a technical vision system for products of intricate geometry were developed. The new method was developed for growing refractory metal single crystals. New equipment is presented for welding of live tissues. 28 Ref., 2 Tables, 25 Figures.

Keywords: *plasma, laser, electron beam and resistance welding, titanium, aluminium-lithium alloys, strength, quality control, surfacing, single crystals, welding of live tissues*

Welding and related technologies are now constantly and stably progressing. With their applying the industrially developed countries of the world produce over a half of their gross national product. Having a confidential advancing, the welding entered all the spheres of the mankind life. It is widely used not only in the industry and construction, but also in manufacture of home appliance, sports equipment, in creation of art masterpieces and even in medicine. All this allows the world's welding community to state that the present welding technologies not only take part in the material production of different products, but also have a significant influence on the improvement of quality of people life and promote the continuous progress of the nowadays society.

Analysis of tendencies in development of a global market of welding equipment shows that the technologies of welding will be further widened in future. The demand for energy-saving welding technologies, which are based on application of the highly-concentrated energy: plasma, laser, electron beam, as well of hybrid power sources, will significantly grow. Automation and robotization of the welding processes will continue its widening and become useful in those cases where they are mostly effective.

The application of new designs will allow updating the welded structures, and decrease in their metal consumption will provide applying of steels and alloys of the higher strength. But it is not necessary to forget the requirements for safety, life and quality of the welded structures.

The challenging are the studies and developments of the Electric Welding Institute, carried out during the recent years with account for the tendencies in the development of present directions of the welding science and technology.

Plasma, as a highly-concentrated power source, finds ever more application in welding and related technologies. A number of developments were made at the Institute with its application, giving good results. The developed technology of high-speed plasma welding of alloys of up to 12 mm thickness per one pass and welding equipment: welding plasmatrons of unique design, plasma module, control system by means of a programmed logic controller with a feasibility of integration with a welding robot, allowed increasing the technological and technical-economic characteristics of the thick metal welding process. The equipment provides the feasibility of operation with variable-polarity pulses of current at a preset wave shape, at a smooth control and discrete control of duration of pulses and pauses between them within the wide range, as well as the feasibility of operation at direct and pulsed current of a straight and reverse polarity. In comparison with the traditional process of arc TIG welding, the weld, produced by the plasma welding, has by 40 % smaller width and mass of metal being deposited, and also more fine-dispersed and homogeneous structure of the fusion zone. More-over, the value of energy input is decreased by 2.5–3.0 times, and zone of weakening — by 1.5 times.

The significant achievement of the recent years is the development of a hybrid plasma-arc welding [1, 2]. The combination of two welding power sources provides the higher base metal penetration. The technology of welding steels and aluminium alloys of 5–12 mm thickness has been developed which allows increasing the welding speed by 25–40 % and decreasing the consumption of welding wire by 40 %, as compared with a pulsed-arc consumable electrode welding. To realize this technology, the plasmatron of a unique design (Figure 1) and basic technological processes were developed.

To provide the high physicomechanical properties of aluminium alloy welds is possible by the developed technology for the spot plasma welding at a pulse of a special shape and stabilization of its length and equipment for its realization. In comparison with the pressure spot resistance welding, this technology can be used at a single-sided access to the site of welding. The cathode cleaning of aluminium alloy surfaces welded; high efficiency and lower power consumption allow its integration into the robotic welding lines.

With application of plasma power sources the high-efficient process of a supersonic plasma spraying of coatings from powders of metal, alloys, ceramic materials and their mixtures was developed at the Institute. For its realization the equipment of a new generation has been designed (Figure 2), which envisages the feasibility of a separate feeding of components of inexpensive plasma-forming gas on air base

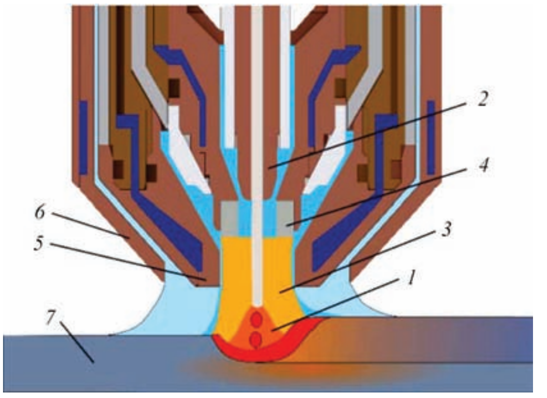

Figure 1. Scheme of hybrid welding plasmatron: *1* — consumable electrode arc; *2* — consumable electrode nozzle; *3* — non-transferred constricted arc; *4* — plasmatron tubular electrode; *5* — plasma-forming nozzle; *6* — protective nozzle; *7* — specimen being welded

(air and additions of methane or propane in amount of 5–10 %). The plasmatron, generating the supersonic jet, increases the kinetic energy of particles being sprayed by 9–16 times, and, as a consequence, provides the significant increase in all the service properties of coatings. In particular, the adhesion strength is 1.5–2.0 times increased as compared with coatings, which were produced by a plasma spraying at subsonic modes.

Traditionally at the Institute, the investigations and developments are continued by using the laser and electron beam power sources. On the basis of modern fiber disc and diode high-safety lasers the technology and automatic equipment have been developed for the laser welding of high-strength and stainless steels, aluminium and titanium alloys, which are used

Figure 2. Equipment for high-efficient supersonic plasma spraying

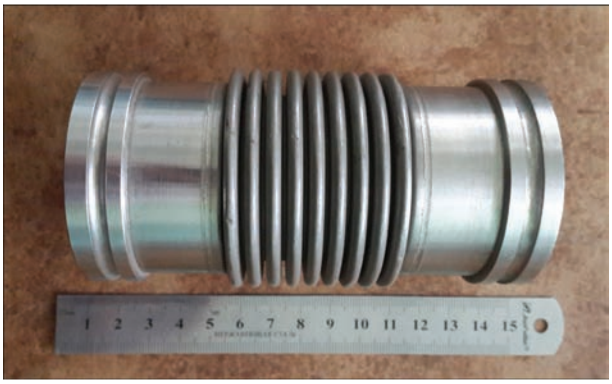

Figure 3. Multilayer bellow, made of tubes, welded by laser radiator

for manufacture of a large spectrum of products. For example, they are used for welding of thin-walled various-diameter pipes of stainless steels for manufacture of multilayer bellows (Figure 3). The designed high-power laser welding equipment is successfully applied in railway car, automobile and ship building, and for site works in these industries the semiautomatic manual laser tool of up to 2 kW power has been designed (Figure 4).

At the Ukrainian and foreign enterprises of aircraft and rocket construction the developments of the Institute in the field of laser welding, in particular for welding of dissimilar metals, stringer panels, nozzles of liquid-propellant rocket engines, aerospace control surface elements, thin-walled hull structures and other elements of flying vehicles passed the industrial trials.

The Electric Welding Institute occupies one of the leading positions in the world in design and manufacture of equipment for the electron beam welding. Its products are exported to many countries of the world. Thus, the equipment for electron beam welding (EBW) has been designed and manufactured at

Figure 4. Semi-automatic manual laser tool

Figure 5. Typical medium-sized chamber with a mobile gun and wheeled-out table

the Institute, which can be divided conditionally into several types by the chambers dimensions, namely «small» (0.26–5.7 m^3), «medium» (19–42 m^3) and «large» (80–100 m^3) (Figure 5). Coming from a definite task of the Customer the chamber type is defined and the appropriate technology of welding is developed [3]. The chambers have the mechanical equipment with a mobile electron beam welding gun on a precision multiaxial mechanism of movement. This mechanism with a digital programmed control provides a controlled linear movement of the gun along three Cartesian coordinates of axes, as well the gun rotation by 0–90° in plane *Z–X* (from vertical orientation to horizontal one). The rotation of a part welded is provided by the precision welding manipulators with horizontal and vertical axes of rotation. The most technological flexibility is provided by the manipulator with an inclined axis of rotation, which performs the electron beam welding, for example, of intricate concentric sections of aircraft engines (Figure 6) or aircraft components with a variable geometry.

Depending on a definite application the chamber is completed with high-voltage invertor power sourc-

Figure 6. Welded billet of aircraft engine section of titanium alloy VT-6

Figure 7. Manual electron beam gun with a high-voltage connector

es of 15, 30 and 60 kW capacity and the system of secondary-emission electron visualization RASTR, which forms the welding zone image both before, during and after finishing of welding. The EBW equipment has a sophisticated system of control, allowing the user communication with equipment through Windows — oriented graphical interface [4].

The Institute has a successful large experience in design and manufacture of electron beam equipment and technologies for the space purpose. The works were carried out for design of the new generation of an electron beam welding tool for making site and repair-restoration works in the open space (Figure 7). The tool is equipped with a triode electron beam gun of up to 25 kW capacity, separated from the high-voltage power source. Such design solution and application of a flexible high-voltage cable with a compact high-voltage connector for supply allowed decreasing greatly the dimensions and mass of the tool, as well as increasing its manoeuvrability for realizing the technological processes. The service life of continuous operation and safety of the tool was also increased. There is a possibility to obtain a sharply focused beam of ≤0.6 mm diameter. The gun weight is 3 kg. The tool

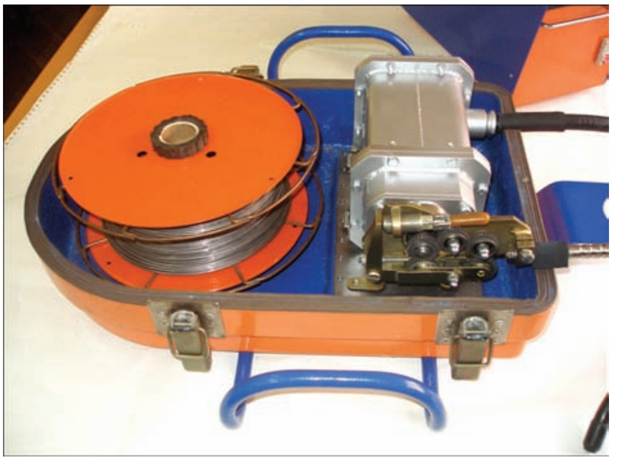

Figure 8. Semi-automatic machine for underwater welding and cutting by flux-cored wire at up to 200 m depth

can operate in manual and automatic modes with use of the robotic equipment or manipulators.

Traditionally, the Institute pays a lot of attention to the pipe subject. Over the recent years the investigations were carried out and technologies and equipment were developed for the press magnetically-impelled arc butt welding (MIAB) of position welds of high-strength steel pipes with wall thickness of up to 10 mm and diameter of up to 200 mm. The physical principle of MIAB welding process is characterized by that the arc is moved in the gap between pipe edges being welded under the effect of external magnetic field, generated by the magnetic systems. The welded joint is formed under pressure and simultaneous plastic deformation of pipe edges. The dominating factor, which makes joint, is the presence of a melt layer at the beginning of the upsetting period.

Table 1 presents the mechanical properties of welded joints of pipes of different sizes and steel grades. They meet the requirements of the International standards for gas pipelines. The developed technologies and equipment found the wide application in industry, providing the quality welding both in field and stationary conditions.

The underwater welding is one of the directions of studies and developments of the Institute, where our scientists made important scientific-technical

Таблиця 1. Mechanical properties of pipe welded joints

Steel grade	Pipe size, mm	Base metal, σ_t, MPa	Welded joint, σ_t, MPa	Base metal, KCV_{+20}, J/cm^2	Welded joint, KCV_{+20}, J/cm^2	Base metal KCV_{-20}, J/cm^2	Welded joint KCV_{-20}, J/cm^2	Welded joint KCV_{-40}, J/cm^2
09G2S	42 (δ = 5)	460–478 469	453–478 465	57–5 58	59.0–78.1 68.5	57.8–58.0 57.9	64.0–74.5 69.3	–
35	89 (δ = 10)	538–565 551	528–554 541	56–64 60	52–965 70	–	–	–
01Star520	191 (δ = 7)	638–665 651	618–674 656	116–154 135	87–152 119	–	–	–
STRG410	60.5 (δ = 5.5)	452–464 458	450–462 456	90–98 94	86–92 89	102–104 98	87–94 91	88–94 92

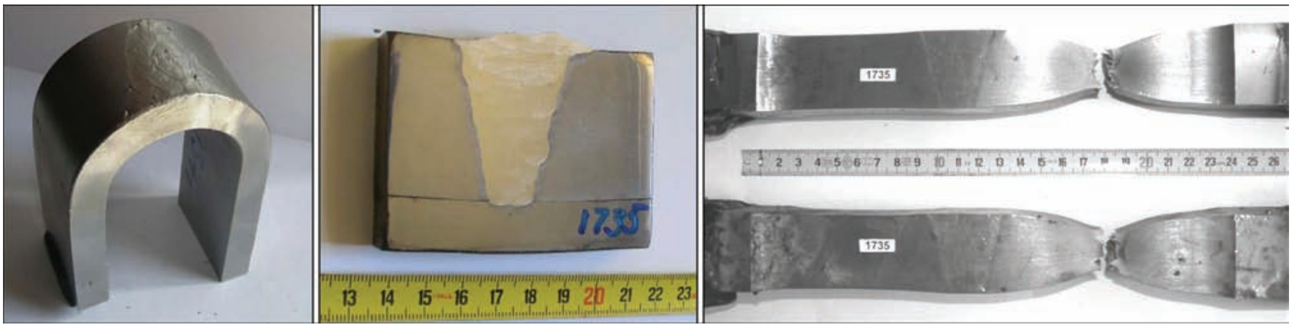

Figure 9. Microsection and specimens after mechanical tests (metal thickness is 40 mm)

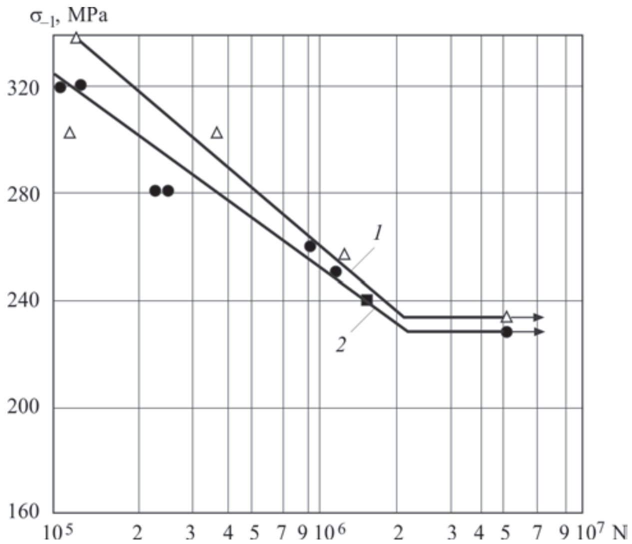

Figure 10. Fattigue strength at alternating-sign bending: *1* — underwater welding; *2* — welding in air

Table 2. Mechanical properties of weld metal, produced under water (ANSI/AWSD3.6, class A)

Material	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ψ, %	KCV_{-20}, J/см^2
Electrodes	≥460	≥600	≥29	≥47	≥100
Flux-cored wire	≥350	≥550	≥30	≥60	≥80
Steel X60	435	580	18	–	60

achievements, in particular in the field of welding materials. The carried out theoretical and experimental studies of peculiarities of arc burning under the water and conditions of guarantee of the continuous arc process at different hydrostatic pressure allowed developing the new flux-cored wires and electrodes for the so-called wet welding of low-carbon, low-alloy steels and those of the higher strength [5].

For the arc cutting of steels and alloys under water at the depth of up to 200 m the electrodes and flux-cored wire, as well as the new type of the semi-automatic machine, which feeding mechanism, located under water beside the diver-welder, were developed (Figure 8). The carried out investigations of mechanical properties of weld metals (Figure 9), the results of which are given in Table 2, proved the high quality of works made by the proposed technology of the underwater welding, because the metal structures safely operate by dozens of years. Studies of results of strength values of welded joints at a cyclic load showed that they are not inferior to joints made under the normal conditions (Figure 10).

Titanium is one of the basic nowadays structural materials, which are used in many branches of industry in manufacture of critical structures. By starting from the development of the technology of welding of a sheet titanium of small thickness at the beginning of the 50 s of the last century the Institute is continuously and comprehensively dealing with studies of the titanium welding problems. Thus, at the Institute the technology of welding the titanium products with medium and large thicknesses by tungsten electrode into

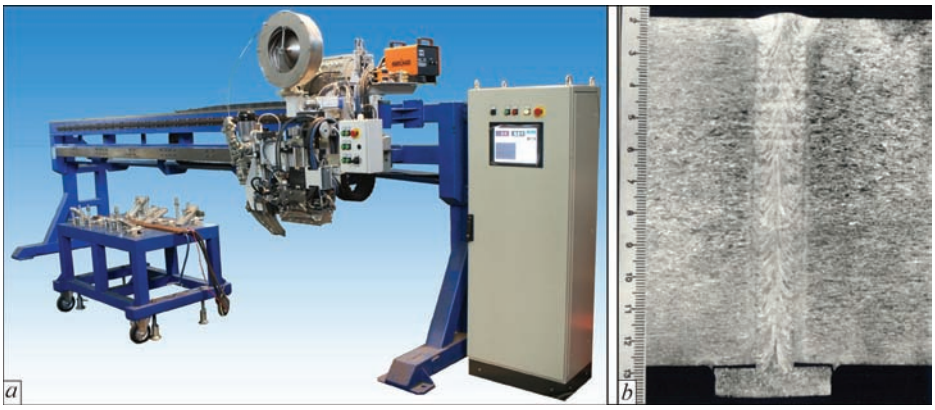

Figure 11. Welding equipment UD 682 for welding and surfacing of parts of up to 110 mm thickness and up to 4 m length (a) and macrosection of welded joints (*b*)

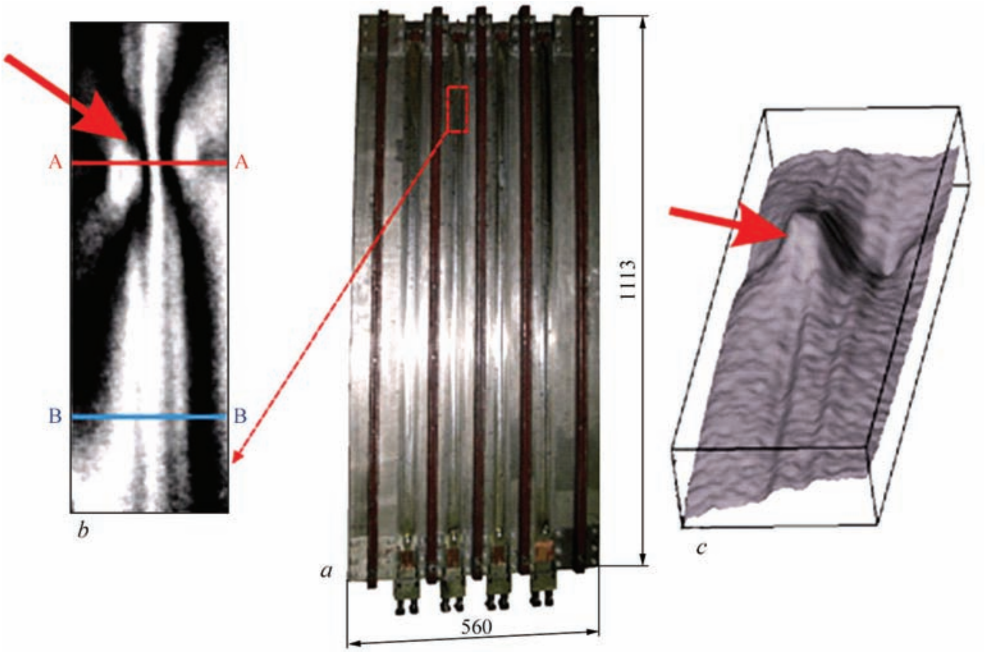

Figure 12. Nondestructive quality testing of stringer panel of alloy VT-20 by electron shearography method: *a* — panel in mechanical fixture after welding; *b* — pattern of interference fringes in the examined region; *c* — three-dimensional pattern of deformed surface

a narrow gap was successfully developed. This technology is distinguished by such advantages as a low consumption of welding wire, small width of weld and heat-affected zone, decrease in angular deformations and residual welding stresses. To guarantee the fusion of side walls with weld, the controllable variable magnetic field was used. The installation UD 682 was designed (Figure 11) for welding and surfacing of joints of up to 110 mm thickness and length of up to 4 m. By using this equipment the titanium alloys PT3V, VT6, VT20 of various thickness were welded. The investigations of welded joints confirmed their high quality. The strength level of welded joints of titanium VT6 in applying the welding filler titanium wire SPT2 is 95 % of the base metal strength, and the impact toughness *KCU* of weld metal is 85 J/cm^2. Content of gas impurities in weld metal is at the level of their content in filler wire, which proves the high quality of the gas shielding.

The titanium alloys found wide spreading in the manufacture of structures in aircraft and aerospace industries. At the Institute a complex of investigations was carried out for the development of technology of the deformation-free welding of stringer panels of high-strength titanium alloy VT-20 with a guarantee of their high precision and strength at cyclic loads. It was proved that the making of high-penetration welds by the argon arc nonconsumable electrode welding over the layer of activating flux with applying the preliminary elastic deformation and high-frequency mechanical peening of welds guarantees the higher values of fatigue life of these panels as compared with electron beam and argon arc nonconsumable electrode welding with an immersed arc. Applying before welding the preliminary elastic deformation of a sheet and stiffeners at the level of $(0.3–0.4)\sigma_y$ provides relieving the welding deformations and creates the necessary conditions for making the welding process in the automatic mode. It was found, that the effective method of nondestructive testing of panel welds quality is the electron shearography. Figure 12 shows the result of this testing of panel in tension state directly after panel welding. At the general background of deformation of the test region a local distortion is observed, that indicates the defective zone. This is also confirmed by the three-dimensional pattern of the deformed surface. X-ray control confirmed the presence of pores clustering in the anomalous zone. The developed technologies of deformation-free welding and nondestructive testing were recommended for industrial manufacture of the aircraft panels.

One of the main requirements to the structural materials for the aerospace engineering is a specific strength. The aluminium-lithium alloys of different systems of alloying, which have a low density and higher specific strength meet this requirement. However, the application of these alloys in welded structures was limited by the insufficient study of their weldability. At the Electric Welding Institute a complex of works was carried out for investigation of weldability of the aluminium-lithium alloys. As a result, the effective methods of welding, filler material, modified by scandium, were suggested. The effect of welding methods on strength and crack resistance of

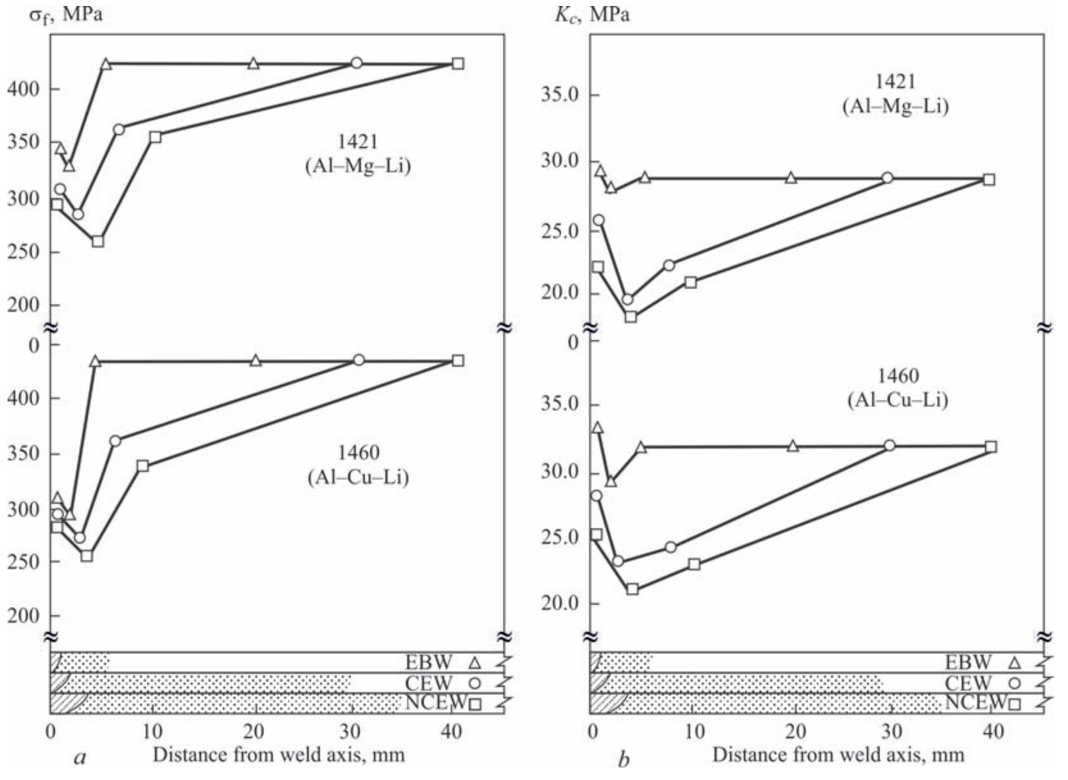

Figure 13. Effect of methods of welding by electron beam (EBW), consumable (CEW) and non-consumable electrodes (NCEW) on fracture strength σ_f (*a*) and crack resistance K_c (*b*) of different zones of joints of aluminium-lithium alloys 1421 and 1460

different zones of joints, made of aluminium-lithium alloys, was investigated (Figure 13).

To solve the problems of geometric and technological adaptation during robotic welding of critical structures (Figure 14), the specialized systems of technical vision were developed at the Institute [10–11]. The welding robots with technical vision systems find automatically a joint and correct in a real time scale the trajectory and welding mode parameters for compensation of errors in assembly and mounting of semi-products. Thus, they perform the welding operations completely in the automatic mode. The technical vision systems, developed at the Institute, are successfully applied with robots of such well-known manufacturers as ABB, FANUC, KUKA.

Figure 14. Welding robot with a technical vision system [7]

Composite materials and intermetallics find the more demands in many branches of industry, construction, medicine, etc. due to their unique properties. However, their application is restricted by a lack of reliable technologies of producing the permanent joints of structures of dissimilar or new nanostructured materials. The application of traditional methods of welding and brazing do not guarantee the strength characteristics in practice.

To solve this problem, the vapor-phase technologies were developed at the Institute for producing nanostructured materials (NM) with a large-length boundaries of grains, close to materials welded by the chemical composition [8, 9]. Figure 15 presents structures of some produced nanomaterials on the base of single-phase and heterophase systems. The nanostructured materials have a high plasticity during heating and a low energy of activation of diffusion mobility of alloys. The application of such NM as intermediate layers in the form of foils (Figure 15, *a*) solves the problem of welding of alloys, based on intermetallics and composites [10, 11]. Figure 15, *b* presents structure of joints, made of alloys, based on intermetallics γ-Ti–Al and high-temperature alloy based on nickel (Figure 15, *c*). The high reaction ability of the nanolayer foils and

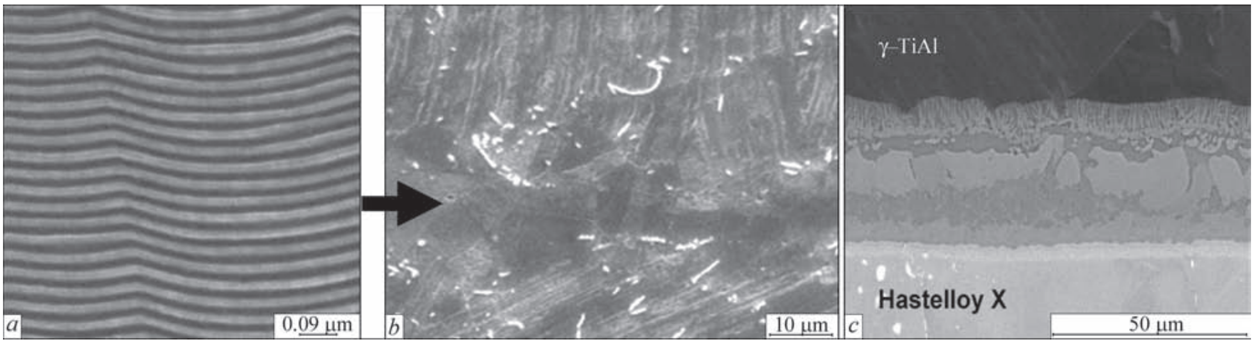

Figure 15. Structure of nanolayer foil and welded joints by applying of nanostructured materials: *a* — microstructure of cross-section of the nanolayer foil from layers of titanium (*dark*) and aluminium (*light*); *b* — microstructure of joining zone of alloy on γ-Ti-Al base; *c* — microstructure of joining zone of alloy on γ-Ti-Al base and high-temperature Ni

their superplasticity during heating under conditions of external loading give opportunity to realize the reaction brazing processes for a short-time heating of the joining zone at a low pressure. This technological scheme can be used for repair works under conditions of a local heating of the joint zone at a restricted access to power sources and possibility of applying the intensive radiation beams, for example, in the space conditions.

Today, in the production of metal structures many advanced materials are used, but steel is the main structural material. At the Institute, a complex of investigations was carried out to determine the optimum parameters of welding of high-strength steels 10G2FB, microalloyed by vanadium and niobium, as well as steels 12GN2MFAYu, 12GN3MFAYuDR [12, 13]. It was found, that the probability of cold crack formation in welded joints of high-strength steels can be reduced to minimum, if to apply the technology of welding, which provides cooling of joints at the rate $w_{6/5}$ of not more than 10 °C/s, content of diffusive hydrogen in deposited metal of not more than 4 cm^3/100 g and level of residual stresses in steel joints of less than 0,5 of yield limit. Owing to these investigations the reliable and efficient technologies of welding of high-strength low-carbon alloyed steels with yield limit of 1000 MPa and higher were developed. They were used in manufacture of metal roofing structures of NSC «Olimpiysky» in Kiev, modern high-capacity tanks for oil storage and other objects.

Reliability is one of the most important qualities, which is characteristic for the present advanced welded structures. To guarantee it, many advanced technologies, developed at the Institute of Electric Welding, were directed. It should be noted among them the technological processes of electrodynamic treatment (EDT) and high-frequency mechanical peening (HMP).

The new technological process, which is used after producing the welded joints, is the electrodynamic treatment by pulses of high-density electric current. It promotes the increase in toughness and refinement of the metal structure, allows decreasing greatly the residual stresses (Figure 16, *a*) and increasing the fatigue resistance (Figure 16, *b*) of welded joints. The designed equipment allows removing the residual welding distortions in thin-walled structure elements (Figure 17). The developed technology and equipment provided the treatment of critical welded joints of ship hull and aircraft structures, which contributes to increase in their life and reliability [14, 15].

The studies, carried out at the Institute, proved that the effective decrease in intensity of corrosion-fatigue fracture of welded joints of steel metal structures is guaranteed by applying the technology of high-frequency mechanical peening [16–18]. Influence of in-

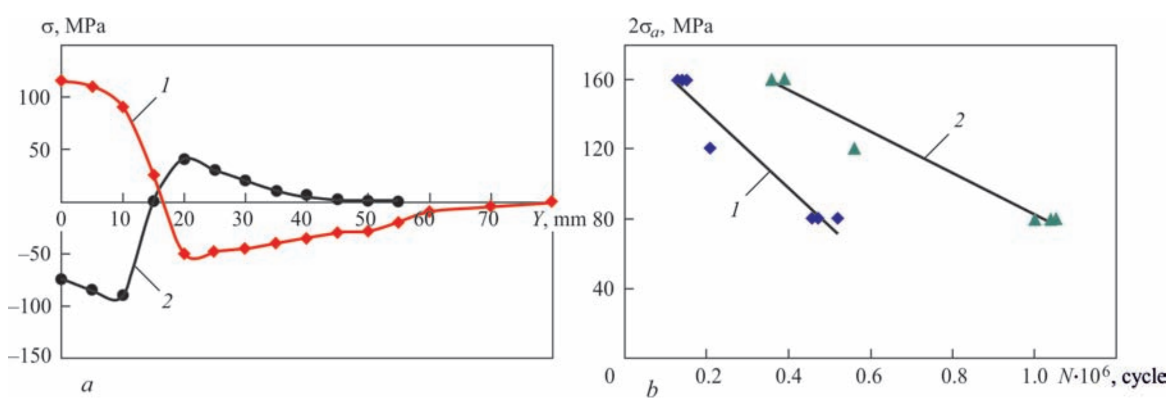

Figure 16. Effect of EDT on residual stresses and life of welded joints of alloy AMg6, made by TIG welding: *a* — residual stresses before (*1*) and after (*2*) treatment; *b* — results of fatigue tests of welded specimens without (*1*) and with (*2*) treatment

Figure 17. Manual tool and mobile power source for EDT

dustrial atmosphere of moderate climate was modeled by holding of specimens of T-type and butt welded joints of 350×70×12 mm size of steel 15KhSND in moisture chamber during 1200 h at 40 °C temperature and 98 % air humidity. Fatigue tests of specimens were carried out at the from-zero change in tension at frequency of 5 Hz. The obtained fatigue curves of test joints are given in Figure 18. The test results show that the life limits on the base of 2 million cycles of T- and butt joints are increased by 47 and 39 %, respectively; cyclic life of welded joints is increased up to 7 times depending on levels of applied loads.

Development of reliable and efficient technologies and equipment for improving the wear resistance of parts occupies traditionally the important place in the research subjects of the Institute. They are demanded for metallurgical industry, power engineering, agricultural machine building, etc. The carried out integrated studies of main regularities of effect of technological parameters of arc surfacing on the principles of structure formation and change in physical-mechanical properties of deposits by layers depending on content of carbon in wheel steels, which varies in the range from 0.55 up to 0.75 %, promoted the development of the new technology of arc surfacing for restoration of wheel pairs of cargo railway cars [19], which contains the method and modes of surfacing, requirements for wheels preparation, chemical composition of materials being surfaced, preheating, the temperature of which depends on the carbon content in the wheel steel. The important feature of this technology is a slow cooling after surfacing at a rate ≤35–40 °C during 4–5 h. The application of the new technology allowed increasing the impact toughness of HAZ metal and resistance of deposited metal to brittle fracture by up to 2–3 times. The safe service life of the railway wheels was increased by two times.

The works of the Institute in the field of brazing, which started at the beginning of the 60 s of last century, contributed greatly to this trend of works. The developed scientific fundamentals of vacuum brazing of thin-walled structures from stainless steels of different classes were used for manufacture of critical-purpose products, such as honeycomb panels, antennas, etc. Nowadays, the study of physical-metallurgical processes, occurring during high-temperature vacuum brazing of high-temperature dispersion-hardened nickel alloys, the regularities of structure formation of

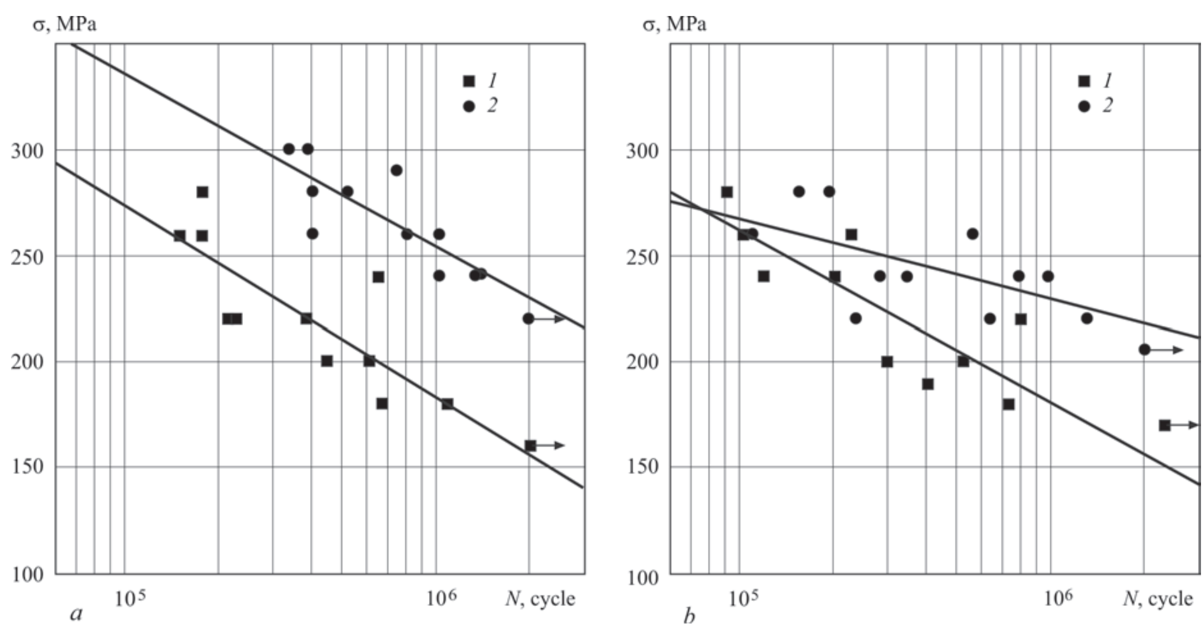

Figure 18. Fatigue curves of T- (*a*) and butt (*b*) welded joints of steel 15KhSND under effect at industrial atmosphere of moderate climate for 1200 h:: *1* — in initial state; *2* — after treatment by HMP method

Figure 19. Gas turbine engine compressor centrifugal wheel, manufactured by applying the new brazing alloy

brazed joints allowed developing the Ni–Pd–Cr–1Ge systems. As a depressant the germanium was used, which provides the structure of solid solution, based on palladium, in brazed welds. The brazed joints have a stable static strength of 1230–1290 MPa at room temperature and 1000–1030 MPa at 550 °C temperature, that is two times higher in comparison with an industrial brazing alloy. With the application of the developed brazing alloy the centered wheels of axial-flow compressor of gas turbine engine of dispersion-hardened nickel alloy (Figure 19), etc. are manufactured.

The successful progress of welding technologies and manufacture of long-life reliable structures of critical purpose is impossible without application of flaw detection and advanced methods of nondestructive testing of the welded joints quality.

The great achievement of the recent years is the design of a portable digital X-ray-TV equipment (Figure 20) on the base of high-sensitive solid-body converters. The portability, digital processing of images, low cost open up the new opportunities for carrying out the radiographic control in the field and shop conditions of different objects, which have no today possibilities of nondestructive testing. The application of the portable X-ray-TV complex helps to solve the problems of control of numerous gas-, oil- and hydro-distributing pipelines of small diameter, technological pipelines of petrochemical production.

Figure 20. Portable digital X-ray–TV equipment arranged on object

Figure 21. Robot with technical vision system for nondestructive testing of intricate geometry products [20]

Automation and robotization of the processes of nondestructive testing give an opportunity of increasing greatly the validity of taken decision about the imperfectness of products and excluding the human factor influence. A complex was designed for the nondestructive testing of products of intricate geometry, which included an industrial robot and technical vision system (Figure 21). Identification of geometry of the control object (CO) and scanning of its surface by eddy-current sensors are made by the complex Kaskad without human participation. It is capable: to define the position of CO by means of the technical vision system; to keep automatically the fixed interval between the sensors and CO; to stabilize the movement rate of the eddy-current converter on the CO surface; to form the certificate of object imperfection

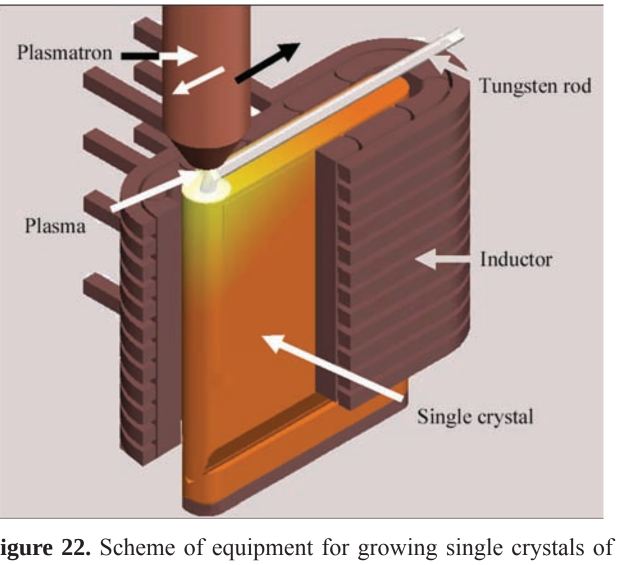

Figure 22. Scheme of equipment for growing single crystals of refractory metals

Figure 23. Single crystals of tungsten

(defects, defining the space coordinates of defects; to guarantee the high efficiency of control.

At the Institute, the metallurgical direction: special electrometallurgy continues the successful development, guaranteeing the high-quality steel production. However, its capabilities are no exhausted by this. It was occurred that by using the special electrometallurgy it is possible to grow single crystals of large sizes, which cannot be made by the traditional technology. The radically new methods of growing single crystals of refractory metals, developed at the Institute, are successfully realized in practice, where two different sources of electric heating, i.e. plasma-arc and induction [21], are used simultaneously (Figure 22). The plasma-arc source realizes the remelting of consumable material (rod) and forms a single-crystal body of a preset configuration, the induction source maintains a local metal pool from flowing out and creates a necessary temperature field in crystal, the crystal is growing at high temperature of preheating $(0.5–0.6)T_m$ [22]. As a result the stresses and density of dislocations are decreased (less than 10^6 cm^{-2}) in the growing crystal, that promotes the formation of more perfect single crystal structure. The single crystal preheating up to preset temperature is one of the key elements of this technology. The unique installation for production of large single crystals of tungsten and molybdenum in the form of plates of 20×170×160 mm size was designed (Figure 23). This technology is referred to the high-level additive technologies [23].

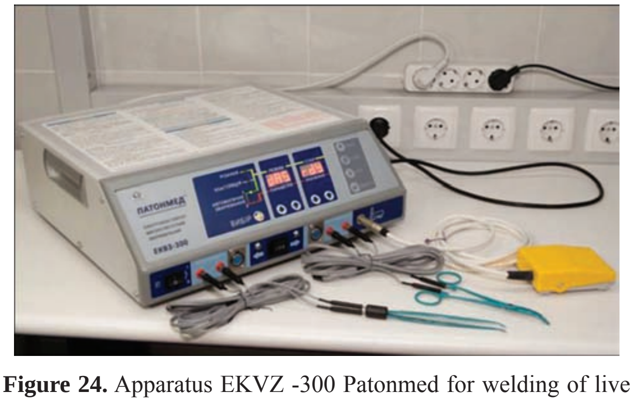

Figure 24. Apparatus EKVZ -300 Patonmed for welding of live tissues

Figure 25. Multifunctional thermosurgical apparatus EK-300 M1 Patonmed and surgical instruments

Welding, remaining as one of the main technological processes in different branches of industry, intruded into the new for it sphere: medicine. And now we can state that the dream of surgeons about quick and bloodless cutting and joining of live tissues without use of a sewing material was realized.

The Institute in the creative cooperation with leading medical establishments of Ukraine developed the technology and equipment (Figure 24) of high-frequency welding of soft live tissues [24–28]. At the given moment of time 200 different surgical procedures were developed and implemented, by which annually 35–40 thou operations are carried out in such fields as abdominal and thoracic surgery, traumatology, pulmonology, proctology, urology, mamaliology, ophthalmology, neurosurgery, etc. The developed apparatuses and instruments for the high-frequency welding of live tissues continue their improvement. It should be noted that many countries in the world showed interest to this technology.

And by this we did not stop. At the Institute a new process of nocontact convective-infrared treatment of live tissues has been developed. It passed the comprehensive checking and displayed its effectiveness. By its application both the emergency aid and also specialized surgical aid are given. It gives opportunity to stop bleeding from parenchimatous organs, spongy bones and small diameter vessels, sanation of infected and chronic purulent wounds in traumata, coagulation of tissue for making bloodless cutting, thermoablation of tumors and metastases. Each of mentioned technologies has its advantages and its applications. Their combination in one apparatus allows increasing the opportunities of the surgeons (Figure 25).

This far for the complete review of our works shows that on the base of the problem-oriented fundamental studies the new scientific technologies and equipment are successfully developed at the E.O. Paton Electric Welding Institute. We will continue also in future to work actively for such studies and developments which will be challenging and demanded at the world welding market.

1. Korzhik, V.N., Pashchin, N.A., Mikhoduj, O.L. et al. (2017) Comparative evaluation of methods of arc and hybrid plasmaarc welding of aluminum alloy 1561 using consumable electrode. *The Paton Welding J*., **4**, 30–34.
2. Korzhik, V.N., Sydorets, V.N., Shanguo Han, Babich, A.A. (2017) Development of a robotic complex for hybrid plasmaarc welding of thin-walled structures. *Ibid.*, **5**, 62–70.
3. Hamm, R.W. (2008) Reviews of accelerator science and technology. *Industrial Accelerators*, **1**, 163–184.
4. Paton, B.E., Nazarenko, O.K., Nesterenkov, V.M. et al. (2004) Computer control of electron beam welding with multicoordinate displacements of the gun and workpiece. *The Paton Welding J*., **5**, 2–5.
5. Maksimov, S. (2017) E.O. Paton Electric Welding Institute activity in the field of underwater welding and cutting. *Pidvodni Tekhnologii*, **6**, 37–45.
6. Paton, B.E., Lebedev, V.A., Maksimov, S.Yu. et al. (2011) Improvement of equipment for underwater mechanized and automated welding and cutting with flux-cored wire. *Svarka i Diagnostika*, **5**, 54–59 [in Russian].
7. Shapovalov, E.V., Dolinenko, V.V., Kolyada, V.A. et al. (2016) Application of robotic and mechanized welding under disturbing factor conditions. *The Paton Welding J*., **7**, 42–46.
8. Ustinov, A.I., Polishchuk, S.S., Demchenkov, S.A., Petrushinets, L.V. (2015) Effect of microstructure of vacuumdeposited Fe100-*x*Ni*x* ($30 < x < 39$) foils with FCC structure on their mechanical properties. *J. Alloys and Compounds*, **622**, 54–61.
9. Ustinov, A. I. (2008) Dissipative properties of nanostructured materials. *Strength of Materials*, **40**, 571–576.
10. Ustinov, A., Falchenko, Yu., Ishchenko, A. (2008) Diffusion welding of γ-TiAl alloys through nano-layered foil of Ti/Al system. *Intermetallics*, **16**, 1043–1045.
11. Ustinov, A., Falchenko, Yu., Melnichenko, T. (2013) Diffusion welding of aluminum alloy strengthened by Al2O3 particles through an Al/Cu multilayer foil. *J. of Materials Processing Technology*, 213(**4**), 543–552.
12. Zhdanov, S.L., Poznyakov, V.D., Maksimenko, A.A. et al. (2010) Structure and properties of arc-welded joints on steel 10G2FB. *The Paton Welding J*., **11**, 8–12.
13. Poznyakov, V.D., Zhdanov, S.L., Sineok, A.G. et al. (2011) Experience of application of S355J2 steel in metal structures of the roofing over NSC «Olimpijsky» (Kiev). *Ibid*., **6**, 45–46.
14. Lobanov, L.M., Paschin, N.A., Mihoduy, O.L. (2014) Repair the AMg6 aluminum alloy welded structure by the electric processing method. *Weld Research and Application*, **1**, 55–62.
15. Lobanov, L.M., Pashchin, N.A., Savitsky, V.V., Mikhoduj, O.L. (2014) Investigation of residual stresses in welded joints of heat-resistant alloy ML10 using electrodynamic treatment. *Problemy Prochnosti*, **6**, 33–41 [in Russian].
16. Knysh, V.V., Solovei, S.A., Kadyshev, A.A., Nyrkova, L.I., Osadchuk, S.A. (2017) Influence of high-frequency peening on the corrosion fatigue of welded joints. *Materials Sci*., **53,** 7–13.
17. Daavary, M., Sadough Vanini, S.A. (2015) Corrosion fatigue enhancement of welded steel pipes by ultrasonic impact treatment. *Materials Letter*, **139**, 462–466.
18. Fan, Y., Zhao, X., Liu, Y. (2016) Research on fatigue behavior of the flash welded joint enhanced by ultrasonic peening treatment. *Materials & Design*, **94**, 515–522.
19. Gajvoronsky, O.A., Poznyakov, V.D., Klapatyuk, A.V. (2014) *Method of restoration of high-carbon steel products*. Pat. 107301, Ukraine [in Ukrainian].
20. Dolinenko, V.V., Shapovalov, E.V., Skuba, T.G. et al. (2017) Robotic system of non-destructive eddy-current testing of complex geometry products. *The Paton Welding J*., **5–6,** 51–57.
21. Paton, B.E., Shapovalov, V.A., Grigorenko, G.M. et al. (2016) *Plasma-induction growing of profiled single crystals of refractory metals*. Kiev, Naukova Dumka [in Russian].
22. Shapovalov, V.A., Yakusha, V.V., Nikitenko, Yu.A. et al. (2014) Studying the temperature field of profiled tungsten single-crystals produced by plasma-induction process. *Sovrem. Elektrometall*., **3**, 31–35 [in Russian].
23. Shapovalov, V.A., Yakusha, V.V., Gnizdylo, A.N., Nikitenko, Yu.A. (2016) Application of additive technologies for growing large profiled single crystals of tungsten and molybdenum. *The Paton Welding J*., **5–6**, 134–136.
24. (2009) *Tissue-saving high-frequency electric welding surgery*. Ed. by B.E. Paton, O.N. Ivanova. Kiev, PWI, IAW [in Russian].
25. Paton, B.E., Krivtsun, I.V., Marinsky, G.S. et al. (2013) High-frequency welding and thermal treatment of live tissues in surgery. *Nauka i Praktyka*, **1**, 25–39 [in Russian].
26. Paton, B.E., Marinsky, G.S., Podpryatov, S.E. et al. (2012) *Welding high-frequency electrocoagulator EKVZ-300*. Pat. 72577U, Ukraine, Int. Cl. A61 B 18/12 [in Ukrainian].
27. Paton, B.E., Krivtsun, I.V., Marinsky, G.S. et al. (2013) Welding, cutting and heat treatment of live tissues. *The Paton Welding J*., **10–11**, 142–153.
28. Paton, B.E., Tkachenko, V.A., Marinsky, G.S., Matviichuk, G.M. (2014) *Method of joining human and animal biological tissues using high-frequency current*. Pat. 106513, Ukraine [in Ukrainian].

Received 30.10.2018