RESEARCH AND DEVELOPMENTS OF THE E.O. PATON ELECTRIC WELDING INSTITUTE FOR NOWADAYS POWER ENGINEERING

B.E. PATON
E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

Some developments of the E.O. Paton Electric Welding Institute for power engineering have been presented, in particular, technologies for welding of large-size turbine rotors, electron beam welding of thick billets of high-strength steels, technologies of submerged-arc welding and flash-butt welding with a pulsating flashing of pipes for main large-diameter gas pipelines, technology and equipment for manufacture of energy-saving heat-exchanging devices. Outlined are the developments, directed to increase in the corrosion resistance of fuel elements and safe service of NPP due to application of high-temperature wear-resistant mechanized surfacing of pipeline stop valves with corrosion-resistant alloys. Practical recommendations for repair of main pipelines without interruption of their operation are given. The investigations were carried out showing the possibility of application of acoustic emission for monitoring welded structures, operating at high temperatures. Method for prevention of catastrophic leakage of oil from damaged pipes of wells of oil-production platforms has been developed. 20 Figures.

Keywords: *submerged-arc welding, flash-butt welding with pulsating flashing, electron beam welding, protective coatings of fuel elements, ribbed plane-oval pipes, ultrasonic testing of welds, acoustic emission, wear-resistant surfacing, technical diagnostics*

The progress of power engineering defines in many respects the scales and rates of growth of the world economy. By the most prudent estimates the total energy consumption in the planet will twice increase in the XXI century. The generation of electric energy will grow most intensively (Figure 1), which by 2030 will reach 40 % of the world demand for the energy resources. Coal, oil and gas will remain the main source of energy in the nearest decades. However, their deposits are exhausted, and exploration of new ones will require significant investments. Moreover, the ecological consequences from the fossil fuel utilization are becoming the more and more threatening: atmospheric outbursts lead not only to the pollution of environment and deterioration of health of population, but also to the global changes in climate.

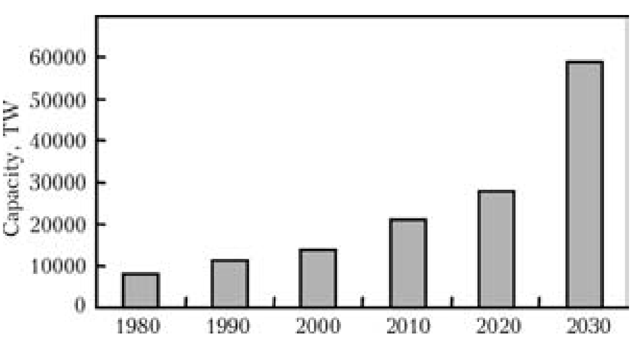


Figure 1. Growth of world energy generation

Today the efforts of the world community are directed to:

- increase in efficiency of power consumption;
- development of economically-grounded energy sources;
- reduction of harmful outbursts by applying new technologies and more ecologic types of fuel, such as natural gas, nuclear energy and renewable sources. Solution of these complicated problems, directed to the creation of the power engineering of future, depends more than ever on the research results, their quick and effective application.

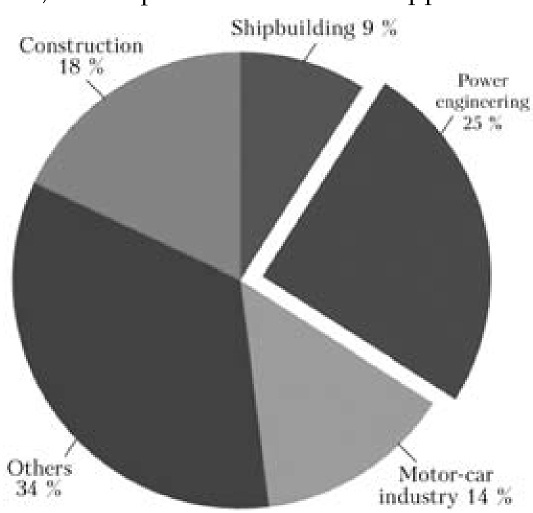


Figure 2. Welding market as per 2011–2012

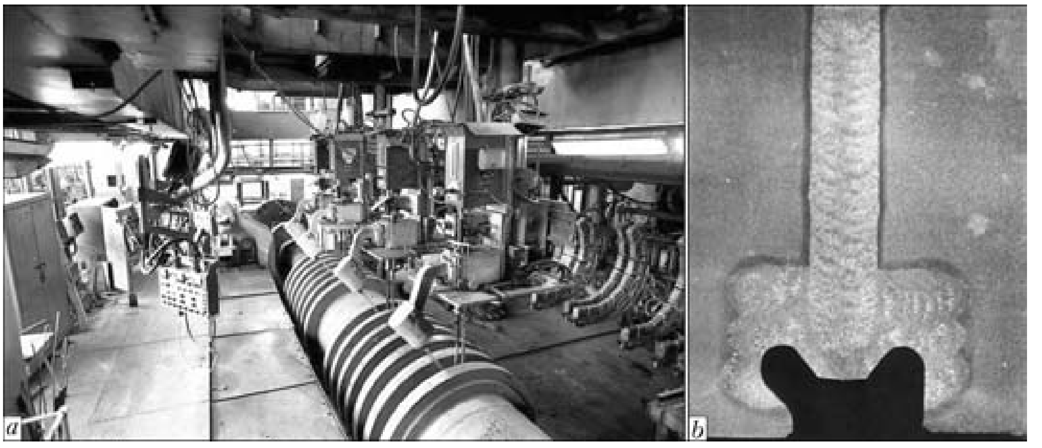


Figure 3. Automatic submerged-arc welding of rotor of steam turbine of 1000 MW capacity for NPP (*a*) and macrosection of weld metal of steam turbine rotor (*b*)

The scientists and specialists-welders make a great contribution to the development of energy-effective, ecologically clean technologies and products. The nowadays welding production is one of the science intensive inter-industry constituents of the world economy. In the industrialized countries more than a half of the national gross product is produced by application of welding technologies. The welding market, in spite of short-time declines in the period of world crisises, continues confidently growing. In 2012 the volume of world welding market was 17 billion USD and as to estimation of experts it will increase in the nearest five years up to 22 billion USD. Its largest share refers to the welding market in power engineering (Figure 2). It is predicted that it will increase by 30 % in the nearest three years.

Today there is a powerful arsenal of technologies, which allow producing permanent joints of different structural and functional materials.Welding technologies give opportunity to develop the unique designs of power equipment, such as turbines, power boilers, bodies of NNP reactors, etc.

The E.O. Paton Electric Welding Institute is fulfilling a large complex of works in the field of welding and related technologies for power engineering. As applied to turbine construction, the technology and specialized equipment have been developed and implemented in industry for assembly and automatic narrow-gap submerged-arc welding of large-size rotors of powerful steam turbines for heat and nuclear electric stations using one and the same assembly-welding stand. In this case the rotors of cylinders of low and medium pressure are manufactured of separate discs, thus excluding the rather difficult problem of producing large-size heavy all-forged billets for rotors of mass up to 200 t and length of more than 10 m. The installation for assembly and welding is completed by four machines for automatic submered-arc welding with a program control of the process of bead layout in a narrow groove and system of electrode tracking at the bottom and walls of the groove (Figure 3).

In manufacture of products of power machine building it is necessary to weld billets of thick high-strength steels. Electron beam welding (EBW) is rather effective in this case, providing high efficiency of the welding process, high quality of joints and minimum deformations. At the E.O. Electric Welding Institute the research and developments were made for creation of technologies and equipment for EBW of structural

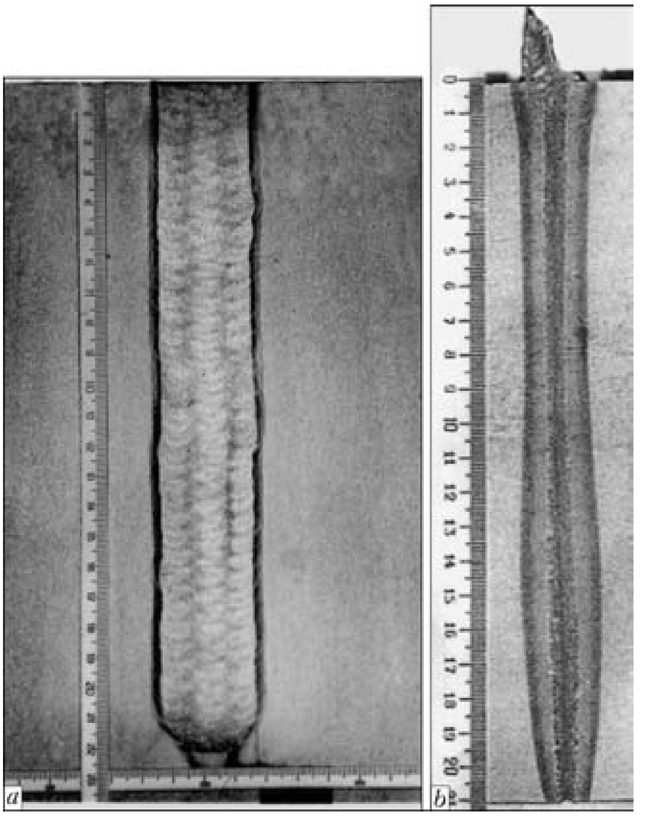


Figure 4. Macrosections of cross-section of low-alloy thick steel circumferential welds made by multilayer submerged-arc welding (*a*) and single-pass EBW (*b*)

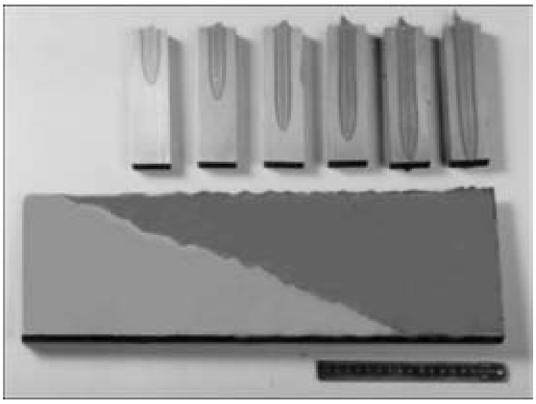


Figure 5. Macrosections of region of circumferential weld closing in EBW of 150 mm thick steel 15Kh2NMFA

steels of up to 210 mm thickness (Figure 4). Stable formation of welded joints and prevention of defects in metal of deep welds is attained by beam scanning with its parallel transfer along and across the welding direction.

The task of producing welded joints of high quality is significantly complicated at the area of the circumferential weld closing where the root defects are occurred. This task was solved by applying the beam scanning, beam focusing in the plane by 10 mm above the weld middle and inclination of butt plane and welding beam for angle 10° with respect to horizon. In Figure 5 the quality formation of rounding in weld root and complete absence of defects is well seen.

New generation of large-size vacuum chambers, technologies of their assembly and EBW has been developed (Figure 6). A principal distinguish feature of these chambers is the use of two vacuum-tight and strong shells joined between themselves by stiffeners. High geometric accuracy of chamber walls provides new possibilities in design of high-precision manipulators of gun and workpiece. To control the manipulators and all the process of welding, the software

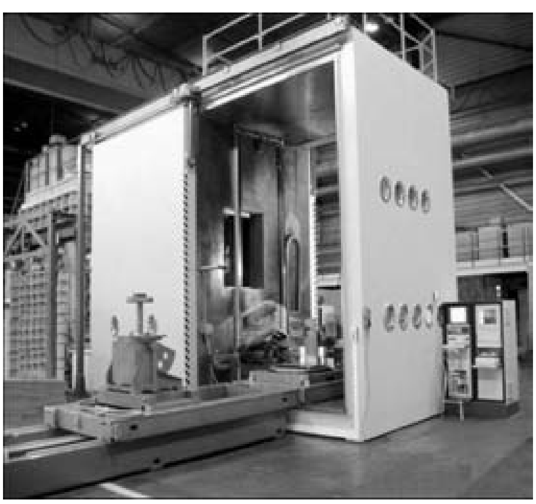


Figure 6. EBW equipment manufactured at the E.O. Paton Electric Welding Institute

with a convenient graphic interface of the operator was developed.

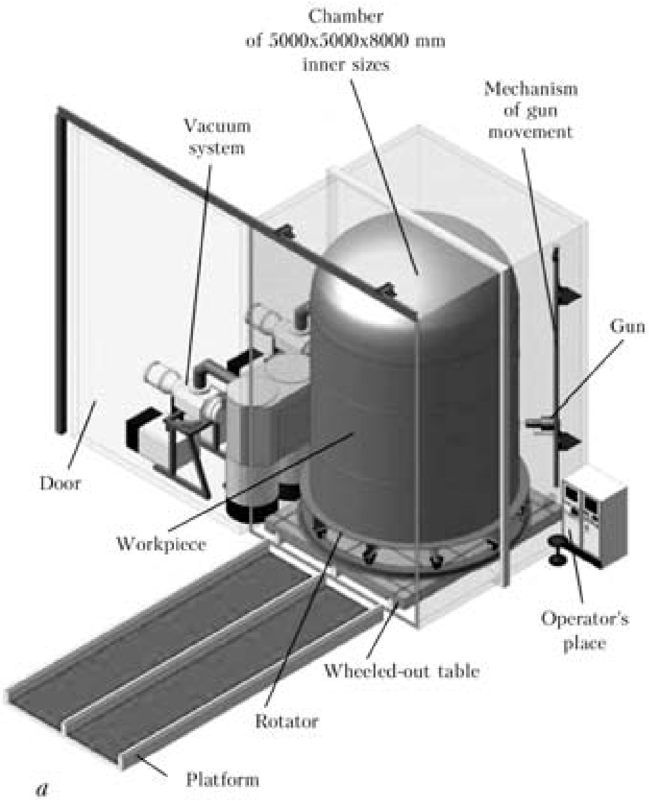
The developed technology of EBW of high-strength thick steels is challenging for its application for manufacture of NPP reactor bodies. As the practice shows, the duration of arc welding of circumferential welds in reactor body is hundreds of hours, while the EBW of such weld will take several hours, The schematic diagram of the offered industrial installation for welding circumferential welds of body of reactor WWER-1000 is shown in Figure 7.

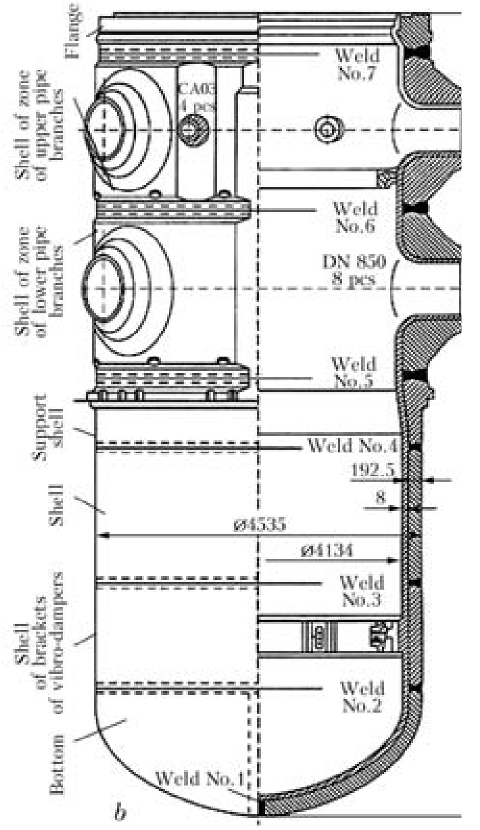
The progress of the nuclear power engineering is indispensably connected with increase in safety of nuclear reactors and reduction of expenses for their service. The cause of emergency situation at the nuclear station Fukushima-1 was the chemical interaction of zirconium shells of fuel elements with a steam. Steam-zirconium reaction led to hydrogen generation, causing explosion.

One of the ways of reducing the expenses for NPP service is the increase in cycle of reloading of the nuclear fuel that also requires the increase in corrosion resistance of zirconium alloys in water under regular conditions of the reactor operation. Therefore, the development of methods and technology of manufacture of fuel elements, providing increase in corrosion resistance of zirconium shells in water and steam under regular and emergency conditions, is urgent.

One of the ways of solution of this problem is the application of protective coatings on the surface of zirconium shell of fuel elements, which should provide its longer service life under the regular condition and in case of emergency situation to reduce significantly the probability of occurrence of steam-zirconium reaction.

To solve the put problem the investigations were carried out, directed to the development of method of deposition of thick coatings on silicon carbide base on zirconium shells of fuel elements. The offered method is based on application of a high-speed electron beam deposition of thick coatings of inorganic materials, developed at the Institute. The use of powerful electron beam guns in stationary mode allows evaporation of metallic and ceramic materials in vacuum at high speed and to form coatings on their base having a preset structure. This method can provide deposition of coatings on the base of silicon carbide at the rates of 5–10 μm/min and to produce coatings on long shells of fuel elements at the rate of about 1 m/min. The distinguished feature of the developed method is the possibility of combining the process of coatings deposition with other processes which are necessary to provide high





Fugure 7. Schematic diagram of industrial installation for EBW of circumferential welds of body of reactor WWER-1000 (*a*) and scheme of reactor body (*a*)

strength of adhesion of substrate and coating, modifying the coating structure, etc.

The appearance of fragments of zirconium shells of fuel elements without coating and with coating is presented in Figure 8. The developed procedure of deposition provides the homogeneous defect-free coating along the surface with negligible roughness and high adhesion strength, high hardness, without defects both in the coating itself as well as at the coating-substrate interface (Figure 9).

The E.O. Paton Electric Welding Institute together with A.A. Bochvar VNIINM carried out investigations of corrosion resistance of coatings at high temperatures (emergency mode of fuel element operation), which showed their resistance to oxidation. As is seen from Figure 10, the coating during tests preserves integrity and a good adhesion with a substrate whereas the specimens without coatings undergo the intensive corrosion in uncoated area of the zirconium specimen at the same conditions.

The E.O. Paton Electric Welding Institute together with Kiev Polytechnic Institute has developed the technology and equipment for transverse ribbing of plane-oval pipes by the method of flash-butt welding and manufacture on their base of a wide assortment of energy-saving heat-exchanging devices (Figure 11). Transverse ribbing of the plane-oval pipes by the method of flash-butt welding has a number of indisputable advantages: high manufacturability without ap-

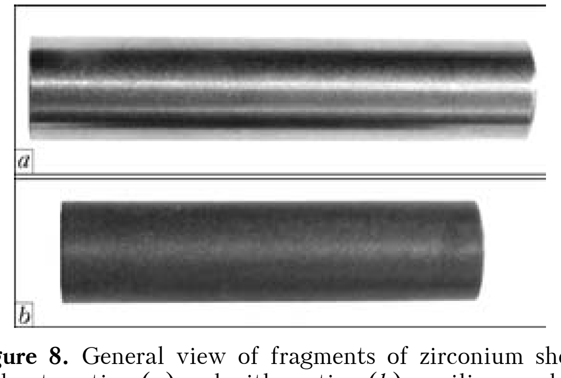


Figure 8. General view of fragments of zirconium shells without coating (*a*) and with coating (*b*) on silicon carbide base

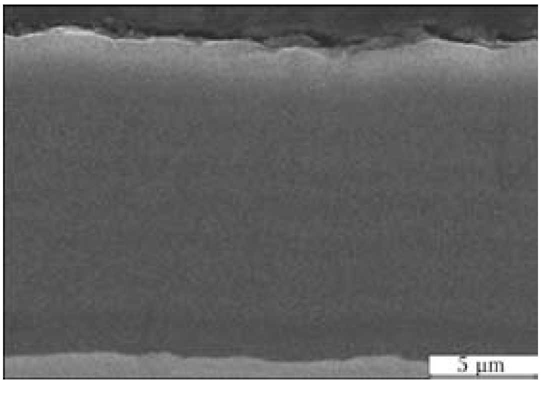


Figure 9. Microstructure of coatings on silicon carbide base

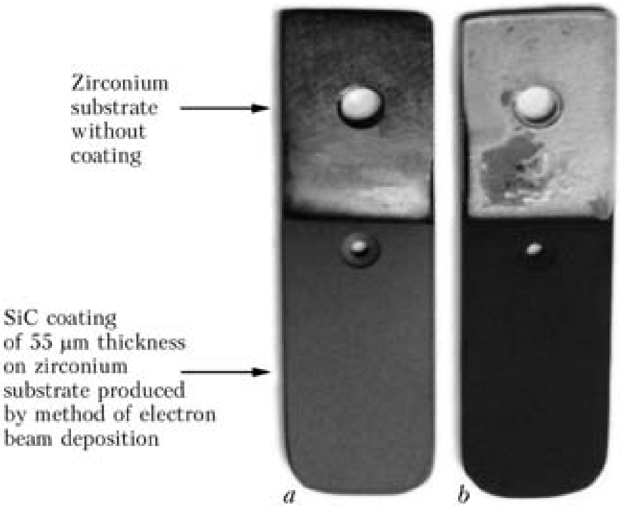


Figure 10. General view of zirconium specimens before (*a*) and after (*b*) testing the corrosion resistance of coatings at high temperature

plication of consumables; almost perfect thermal contact between ribs and a pipe; high intensity of convective heat exchange and low aerodynamic resistance. When updating the boilers of average and low capacity the application of economizers with plane-oval ribbed pipes is very efficient method of fuel saving. Moreover, a high economic effect is achieved in this case.

In connection with the growing need of world economy in power resources the problem of reliable transportation of hydrocarbon fuel from the regions of its extraction to the main consumers is very challenging. In spite of development of alternative methods (transportation of the liquefied gas by tankers or compressed gas in special vessels), the pipeline transport still remains the preferred method of natural gas supply to the consumers.

The new technology of submerged multiarc welding with a combined supply of arcs to improve the quality characteristics of welded joints due to optimization of arcs phasing, conditions of their burning and set-up parameters of electrodes was investigated. For series manufacture of pipes, the 4- and 5-arc welding processes with the current of front arc increased up to 1900 A have been designed, which allowed reducing the groove sizes, increasing the welding speed and decreasing the consumption of welding consumables (Figure 12). The additional advantage in this case is favorable configuration of fusion line, which improves test results on impact bending of metal of welded joints, especially of thick-wall pipes. The technology is recommended for welding of pipes with wall thickness from 25 to 50 mm.

During manufacture of pipes of small and average thickness of a wall it is possible to apply the multiarc welding with electrode of smaller diameter (3.2 mm) at the first arc, characterized by deep penetration, sufficiently favorable weld formation and some decrease in energy input.

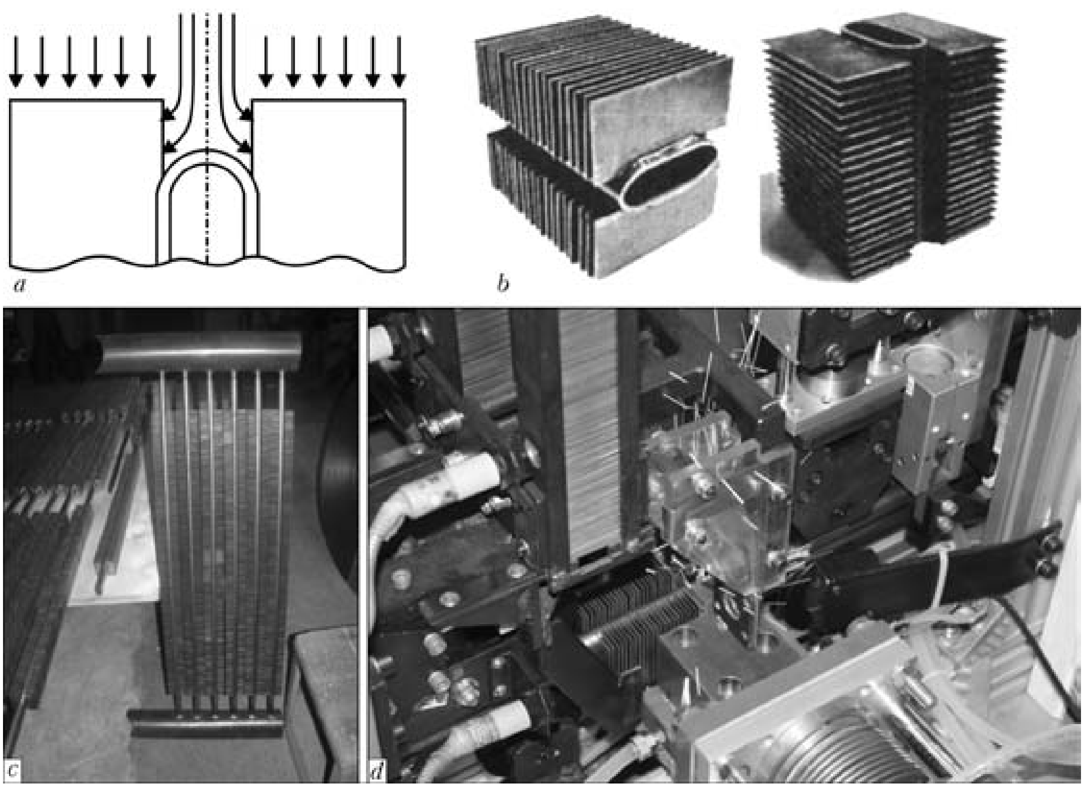


Figure 11. Plane-oval pipes with a transverse ribbing for energy-saving heat-exchanging devices: *a* — scheme of heat carrier flow; *b* — pipe elements; *c* — section of economizer-disposal unit of 0.2 MW capacity; *d* — automated installation for flash-butt welding of plane-oval pipes

To provide high values of toughness the system of control of chemical composition and structure of weld metal of pipes was developed at the Institute. It is based on application of submerged multiarc welding, where welding wires of different chemical composition are set at separate arcs, that allows dosing control of content of alloying elements in weld metal at a high accuracy depending on composition of applied pipe steel, welding conditions and other factors. During manufacture of pipes the combination of agglomerated aluminium flux of low basicity and welding wires containing manganese, molybdenum or manganese, nickel, molybdenum, or manganese, molybdenum, titanium, boron. The required chemical composition of weld is attained by change in number of arcs with welding wire of any alloying system and different speed of its feeding at separate arcs. The control of chemical composition of pipe weld metal provides the most favorable its structure. Figure 13, *c* shows microstructure of metal of longitudinal weld of gas and oil pipe of 1420 mm diameter with 25 mm wall thickness, made of steel of K60 strength class (category X70), composed of 85–90 % acicular ferrite and less than 1 % of intergranular polygonal ferrite. Such structure guarantees high tough characteristics of weld metal, for example, impact toughness in the limits of 180–200 J/cm^2 on the specimens with a sharp notch at temperature of –30 °C.

The developed combination of welding consumables and new processes of multiarc submerged welding, also that with increased current of front arc, including recommendations on optimization of conditions and set-up parameters, were realized at different pipe welding plants of Ukraine and Russia in manufacture of pipes with wall thickness from 16 to 40 mm of steel of K60-K65 strength class (category X70-X80) for main pipelines.

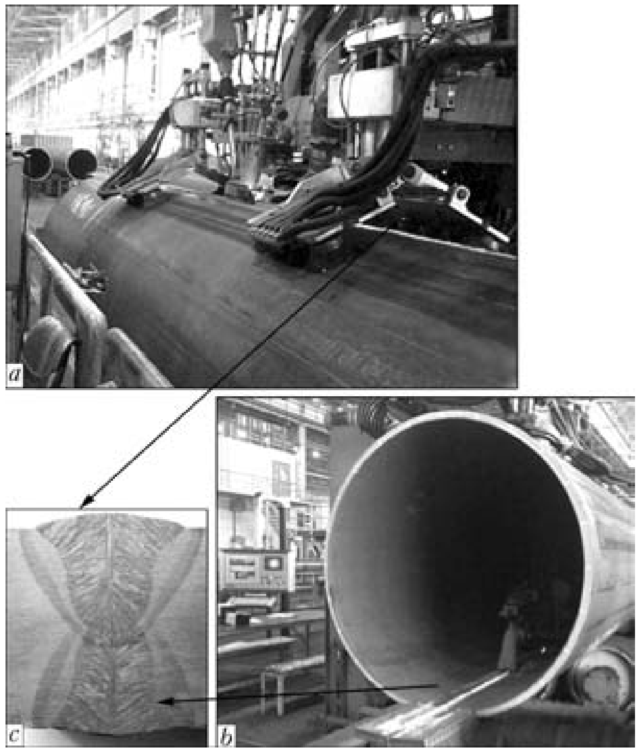


Figure 12. Multiarc submerged welding of 1420 mm diameter pipe of 40 mm wall thickness: *a* — 5-arc welding of external weld, 110 m/h speed; *b* — 4-arc welding of inner weld, 110 m/h speed; *c* — macrosection of pipe welded joint

During construction of main pipelines the E.O. Paton Electric Welding Institute together with the organizations of OJSC «Gazprom» gained great experience in application of position flash-butt welding of pipelines under field conditions in different climatic regions, in particular in the regions of the Extreme North. Using complexes «Sever» (Figure 14) and other flash-butt

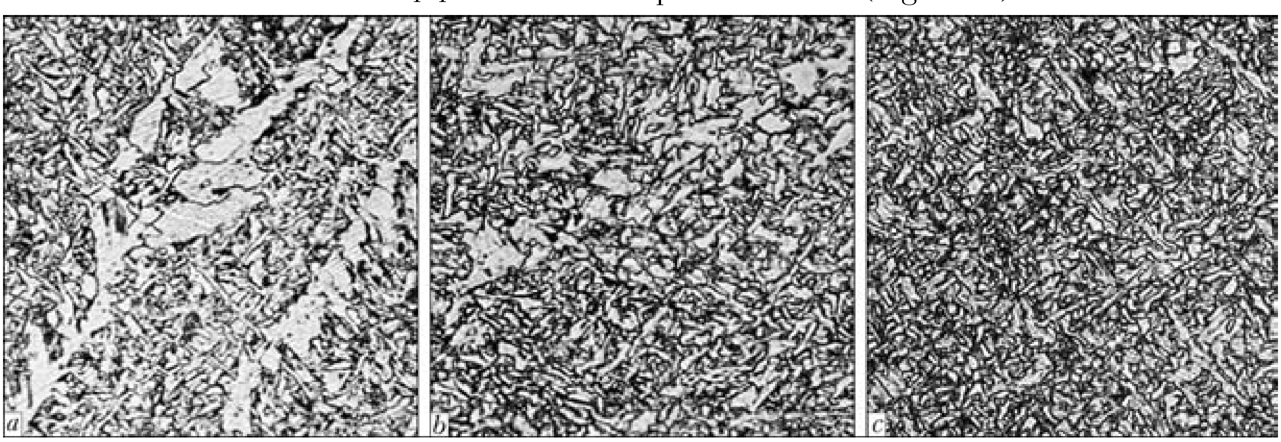


Figure 13. Microstructure (×500) of weld metal of pipes of K60 strength class steel, produced by applying different welding consumables: *a* — Mn–Mo system of alloying, acid fused flux, polygonal ferrite is 20–25 % ; acicular ferrite is 35–45 %; KV_{-30} = 27–30 J/cm^2; *b* — Mn–Ni–Mo system of alloying, aluminate agglomerated flux of low basicity, polygonal ferrite 3–5 %, acicular ferrite 75–80 %; KV_{-30} = 80–100 J/cm^2; *c* — Mn–Mo–Ti–B system of alloying, aluminate agglomerated flux of low basicity, polygonal ferrite of less than 1 %, acicular ferrite 85–90 %; KV_{-30} = = 180–200 J/cm^2

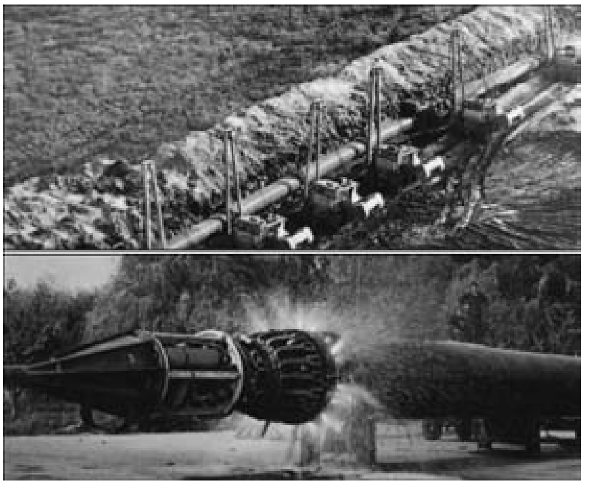


Figure 14. Complex «Sever» for pipe welding of main oil- and gas pipelines

welding machines, more than 70 000 km of different pipelines including those of large diameter were welded which are now successfully operating.

At the present time the Institute is developing the new process of flash-butt welding of pipes with a pulsating flashing (FBW). Its novelty consists in the fact that due to application of quick-response systems for control of welding machine and new algorithms of control a great intensification of heating is possible at the same installed capacity of electric power source.

The process of pulsating flashing has a number of advantages as compared to the continuous flashing. Thus, the mode of welding using pulsating flashing reduces the time of welding of circumferential butt as compared to the continuous one from 3.5–4 min to 2 min, and tolerance for flashing is decreased almost twice. The latter is very important since losses of metals are significantly decreased. Due to the use of systems of automatic control of flashing speed it was managed to obtain the quality welding at lower values of specific power, than that in welding of pipes using complexes «Sever». Therefore in welding of pipes of 1420 mm diameter with 27 mm wall thickness the source with installed peak power of up to 1300 kV/A is applied.

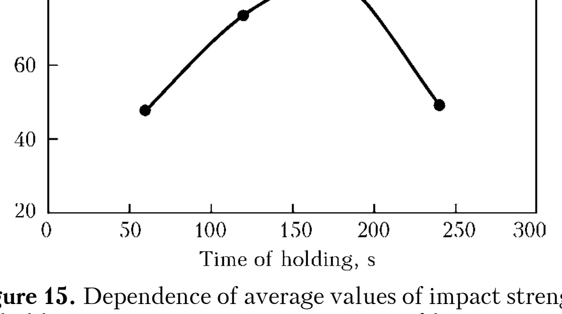


Figure 15. Dependence of average values of impact strength on holding time at 1000 °C temperature of heat treatment

In accordance with the requirements of international standards API1104 and DNV-OS-F101 the mechanical properties of welded joints were determined in the state after welding and heat treatment. Thus, in the as-welded state the strength values (σ_t = 516.0–523.6 MPa) and bending angle (180° at the absence of cracks) meet the set requirements, whereas impact toughness is lower than the standard requirements (KCV_{+20} = 13.3–17.1; KCV_{-20} = 6.1–9.7 J/cm^2) because of the presence of a coarse-grain structure with increased ferrite content in the heat-affected zone.

To increase the impact toughness, the technology of heat treatment of joints, made by FBW, using a postweld local induction heating, was developed. Mechanical properties of welded joints in as-heat treated state were as follows: (σ_t = 550.6–561.4 MPa, bending angle is 180°, KCV_{+20} = 147.9–219.5, KCV_{-20} = 86.8–171 J/cm^2. It was found that the highest values of impact toughness of welded joints, made by FBW on steel of K56 class of strength, can be obtained at temperatures of normalization 950–1000 °C and duration of heating within 2.5–3.0 min (Figure 15), and cooling after heating should be performed at the rate of not less than 8 °C/s.

At tests of reference batch of joints, made at optimum condition with next heat treatment, the quality of joints meets completely the requirements of standards.

Simultaneously with the development of the welding technology, the algorithms of revealing defects in joints, made by FBW, were determined using means of updated ultrasonic flaw detection. Systems and algorithms of in-process computerized control of welding parameters were also developed, which allow evaluating joint quality just after welding completion. Moreover, the automatic system provides a printed document for each butt, indicating real values of all welding process parameters, their deviations from those preset by program and quality of joints.

Technology of nondestructive testing of thick-wall pipe circumferential welds, made by FBW, was developed. Technology is based on applying the echo-mirror method of ultrasonic testing which is realized using transducers connected in tandem.

It is characteristic that defects in FBW are located in one plane of the joint. At FBW of thick-wall pipes this plane is always normal to the pipe axis that facilitates the detection of defect location where it is not necessary to account for all the signals from structural heterogeneity of metal, coming from regions which are located beyond the joint plane. Two categories of defects are distinguished which can be revealed by the ultrasonic testing: defects due to chemical heterogeneity of metal and defects caused by violation of welding conditions. Algorithms of evaluation of defects of joints, made by FBW, are determined which are harmonized with references at UST of joints made by electric arc welding methods.

As a result of these investigations, the technology of nondestructive testing of pipe joints, made by FBW, which is required in accordance with standards as an obligatory operation, was certified.

As a result of carried out investigations, the E.O. Paton Electric Welding Institute in collaboration with «Pskovelectrosvar» plant designed a complex of equipment for FBW of offshore pipelines of 1219 mm diameter and 27 mm wall thickness for application in pipe laying barge (Figure 16). The complex has been manufactured and is at the stage of testing.

The service reliability of operation of heat and nuclear power stations depends greatly on leak-tightness and high wear resistance of sealing surfaces of the pipeline stop valves. Erosion and corrosion wear, thermal fatigue cracks, as well as appearance of burrs on the friction surfaces are the main causes of the pipeline stop valves coming out of order.

Materials, technology and equipment were developed for mechanized surfacing of parts of power pipeline steam-water high-parameter stop valves of all the types and sizes. Surfacing with high-temperature wear- and corrosion-resistant alloys is widely used, that allowed significant extension of service life of stop valves and increase of its reliability. The improvement of processes of surfacing the stop valve sealing surfaces will be realized by its automation and development of new wear-resistant alloys.

At the Institute, the practical recommendations have been worked out for the repair welding of pipelines without interruption of their operation. These recommendations include a complex of procedures and engineering instructions for evaluation of state of main pipelines with revealed defects, as well as for planning the repair by pressure welding. As applied to typical defects of main pipelines (local and general corrosion damages of metal, cracks, shape defects), the criteria are offered for evaluating their admissibility from the positions of a degree of decreasing the load-carrying capacity of the pipeline both in service and also during repair (Figure 17). A special attention is paid to the problems of planning the repair works using different supporting structures, such as: welded bands, sealing couplings, couplings with a compound filler.

Figure 16. Complex for flash-butt welding of offshore pipelines of 1219 mm diameter and 27 mm wall thickness

As the equipment for heat and nuclear power stations is operating at high temperatures and pressures, then the application of traditional means of nondestructive testing in service is impossible. Therefore, it is necessary to develop methods and means for monitoring of technical state of power engineering objects. Investigations were carried out, which showed for the first time the possibility of application of methods of acoustic emission for this purpose. Figure 18 gives diagrams of tensile tests of specimens of steel 15Kh1M1F at room temperature and 500 °C. As is seen, the acoustic activity is preserved at all the stages of material deforming at high tempera-

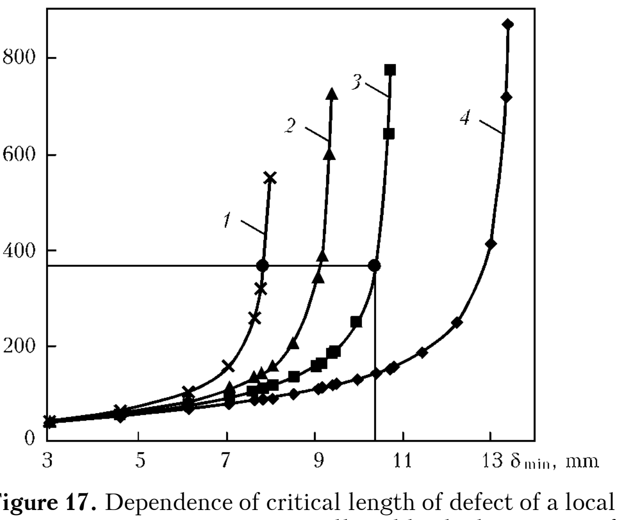


Figure 17. Dependence of critical length of defect of a local thinning type s_{cr} on minimum allowable thickness δ_{min} of wall of 1420 × 20 mm pipe of steel 17G1S at different internal pressure: *1* — 4.5; *2* — 5.25; *3* — 6.0; *4* — 7.5 MPa

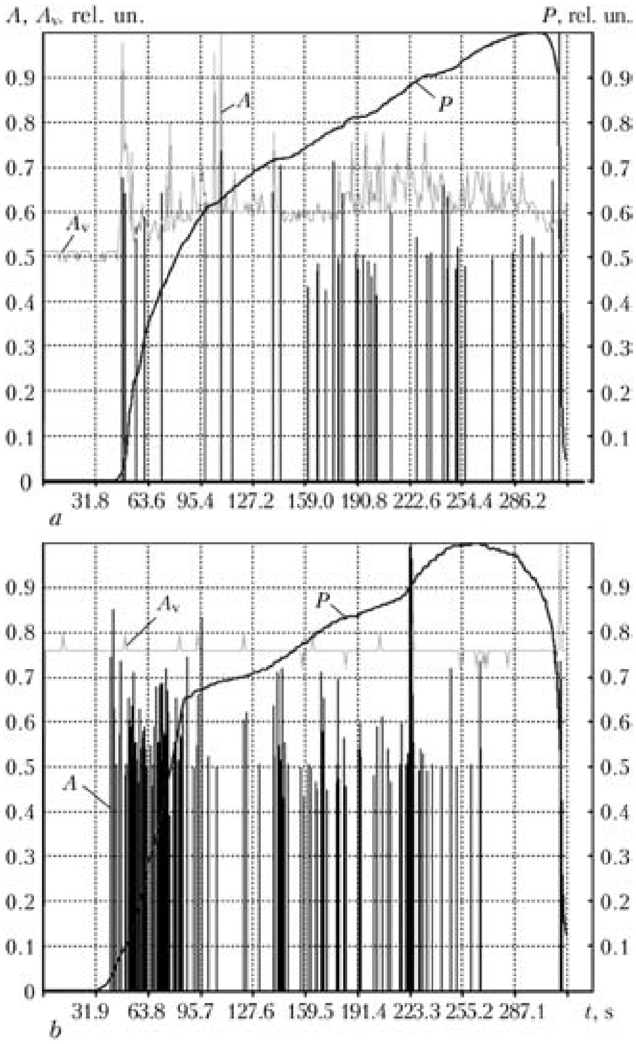


Figure 18. Comparison of signals of acoustic emission in tensile specimens of steel 15Kh1M1F at room temperature (*a*) and 500 °C (*b*) (A — amplitude; A_v — amplitude of continuous emission; P — loading)

ture, thus allowing prediction of fracture loads with a sufficient validity.

«Program of works of continuous acoustic-emission monitoring in equipment of HES «Kievenergo» has been developed and realized. At the first stage the diagnostic reference parameters of pipelines of hot intermediate overheating, preheaters of high pressure and deairators were investigated, system of continuous monitoring of pipelines of intermediate overheating was designed and assembled. System was put into experimental service (Figure 19). Decision was taken for implementation of means and technology of continuous acoustic-emission monitoring of equipment of other HES.

As is known, accidents at oil-gas productions lead to drastic ecological consequences. One of such accidents occurred in 2010 in Gulf of Mexico at oil production platform, where uncontrollable leakage of oil took place from damaged well at the 1500 m depth. Specialists of the Institute developed a method of joining the damaged pipes of wells during oil leakage. A connecting module was designed and manufactured, which passed successfully the tests (Figure 20). Functional scheme of its operation is as follows. Using hoisting mechanisms the module is lowered to a damaged part of the well. It is clamped by technological devices which maintain module in vertical position and do not give opportunity of coming out flow to remove it aside. Moreover, there is now dynamic shock and detachment of module from the place of fixation due to necessary holes available in the module design, which provide a free flowing of intensive oil flow into surrounding environment. Then these module holes are closed. For this purpose, the hydraulic cylinders and special shutters are used, envisaged by the module design. After completion of operation of hydraulic cylinders and closing of module holes the oil is directed into a required direction along the pipeline.

Figure 19. One of points of measurement by AE of operation activity of pipeline of steam intermediate overheating at Kiev HES-6

Figure 20. Module for joining the damaged pipes of wells

Such are the developments of the Institute, designed for the nowadays power engineering. Investigations and development of new technologies are continued.

Received 01.07.2013