Boris E. Paton

Research and developments of the E.O. Paton Electric Welding Institute for nowadays power engineering

Abstract: Developments of the E.O. Paton Electric Welding Institute for power engineering have been presented, in particular, technologies for the 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 developments directed to increase the corrosion resistance of fuel elements and the safe service of NPP due to the application of high-temperature wear-resistant mechanized surfacing of pipeline stop valves with corrosion-resistant alloys. Practical recommendations for the repair of main pipelines without interruption of their operation are given. The investigations were carried out showing the possibility of the application of acoustic emission for monitoring welded structures operating at high temperatures. A method for the prevention of the catastrophic leakage of oil from damaged pipes of wells of oil-production platforms has been developed.

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 in many respects defines the scales and rates of growth of the world economy. By the most prudent estimates the total energy consumption on the planet will twice increase in the XXI century. The generation of electric energy will grow dramatically (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 of fossil fuel utilization are becoming more and more threatening: atmospheric outbursts lead not only to the pollution of the environment and the deterioration of the health of the world population, but also to global changes in climate.

Today the efforts of the world community are directed to the following:

Academician B.E. Paton - E.O. Paton Electric Welding Institute, Kiev, Ukraine

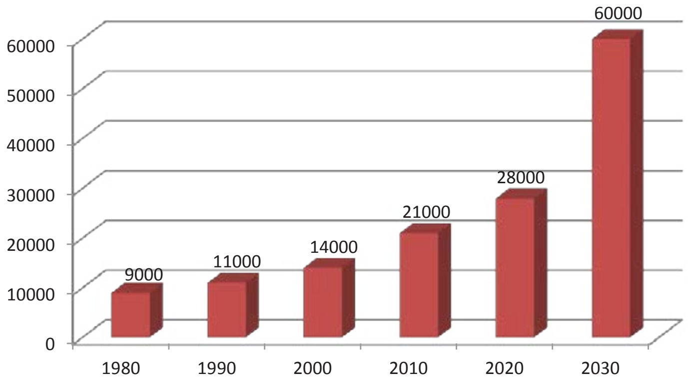

Figure 1. Growth of world energy generation

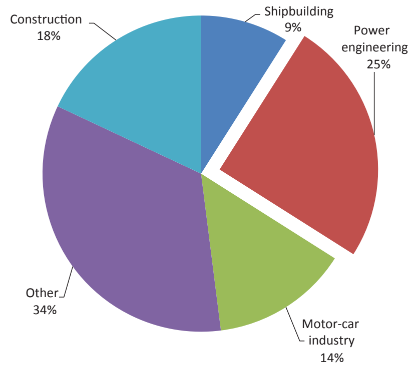

Figure 2. Welding market as per 2011-2012

- increase in efficiency of power consumption;
- development of economically-grounded energy sources;
- reducing harmful emissions through 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.

Scientists and specialists-welders make a great contribution to the development of energy effective, ecologically clean technologies and products. Todays 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 equipment market, despite short-term declines in times of global economic crisis, is still steadily increasing. In 2012 the volume of world welding market was 17 billion USD and as to estimation of experts it will increase to 22 billion USD in the next five years. Its largest share refers to the welding market in power engineering (Figure2). 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 performs a wide range of work 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 a length of more than 10m. 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).

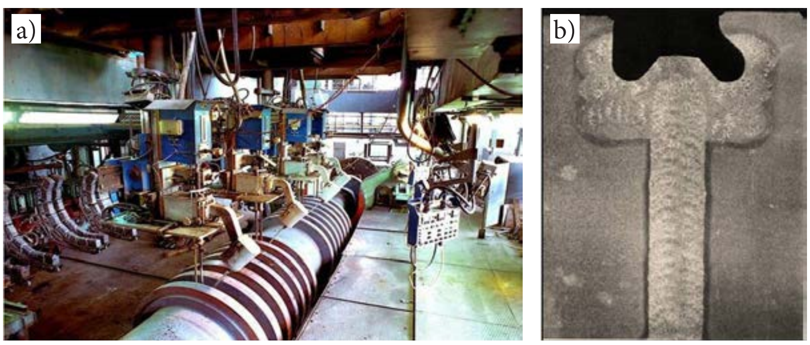

Figure 3. Automatic submerged-arc welding of rotor of steam turbine of 1000 MW capacity for NPP (a) and macrosection of weld metal of steam turbine rotor (b)

In the 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 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 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.

A 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. The high geometric accuracy of chamber walls provides new possibilities in the design of high-precision manipulators for gun and workpiece control. To control the manipulators and the whole welding process, software was developed with a friendly graphical operator interface. 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

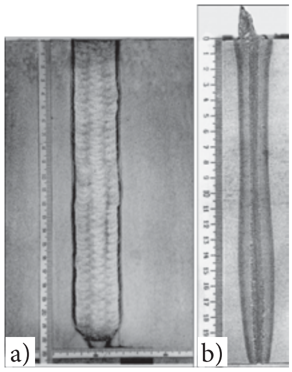

Figure 4. Macrosections of cross-section of low-alloy thick steel circumferential welds made by multilayer submerged-arc welding (a) and single-pass EBW (b)

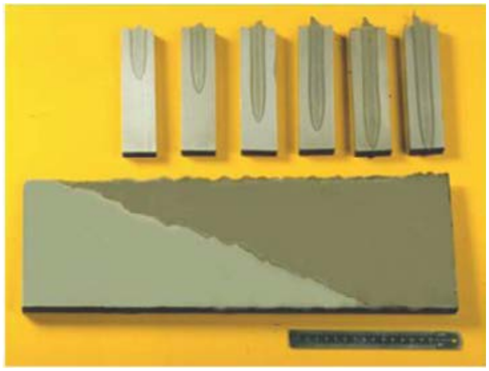

Figure 5. Macrosections of region of circumferential weld closing in EBW of 150 mm thick steel 15Kh2NMFA

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

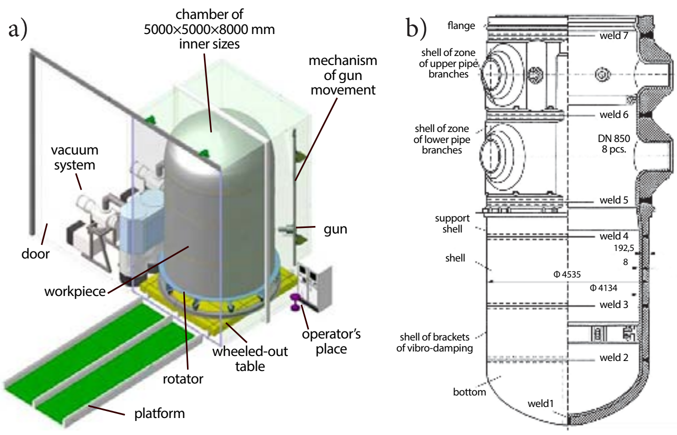

Figure 7. Schematic diagram of industrial installation for EBW of circumferential welds of bodyof reactor WWER-1000 (a) and scheme of reactor body (b)

circumferential welds of the body of reactor WWER-1000 is shown in Figure 7.

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

One of the ways of reducing the expenses for NPP service is the increase in the cycle of the reloading of the nuclear fuel that also requires an increase in the 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.

Investigations carried out to solve the problem, directed the development of a method of depositing thick silicon carbide based coatings on the 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 the 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 mm/min and the production of 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 a high strength of adhesion between the substrate and the 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

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

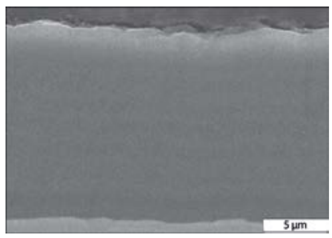

Figure 9. Microstructure of coatings on silicon carbide base

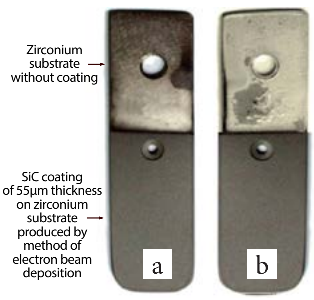

Figure 10. General view of zirconium specimens before (a) and after (b) testing the corrosion resistance of coatings at high temperature

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 the substrate whereas the specimens without coatings undergo the intensive corrosion in the uncoated area of the zirconium specimen at the same conditions.

The E.O. Paton Electric Welding Institute together with Kiev Polytechnic Institute has developed technology and equipment for transverse ribbing of plane-oval pipes using flash-butt welding and then used these tubes to manufacture a series of energy-efficient heat exchangers (Fig. 11).Transverse ribbing of the plane-oval pipes by using flash-butt welding has a number of indisputable advantages: high manufacturability without the application of consumables; almost perfect thermal contact between the pipe and the rib; high intensity of convective heat exchange and low aerodynamic resistance. When updating boilers of average and low capacity, the application of economizers with plane-oval ribbed pipes is a very efficient method of fuel saving. Moreover, a high economic effect is achieved in this case.

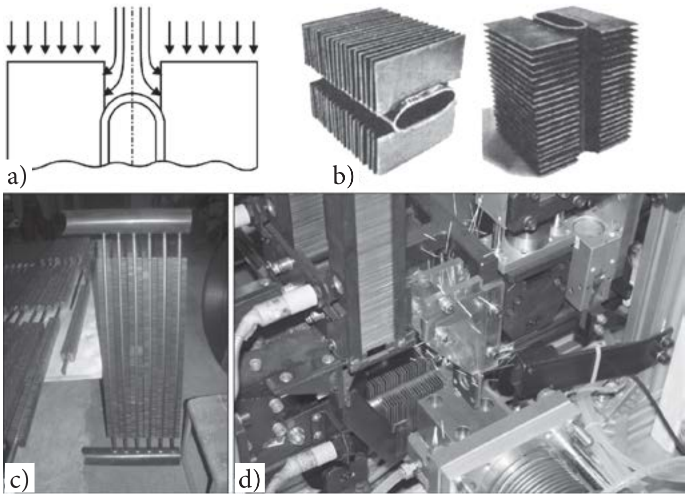

Figure 11. Plane-oval pipes with a transverse ribbing for energy-saving heat-exchanging devices: a - scheme of heat carrier flow; b - pipe elements; c - section of economizer--disposal unit of 0.2 MW capacity; d - automated installation for flash-butt welding of plane-oval pipes

In connection with the growing need of the 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 the development of alternative methods (transportation of the liquefied gas by tankers or compressed gas in special vessels), pipeline transport still remains the preferred method of natural gas supply to consumers.

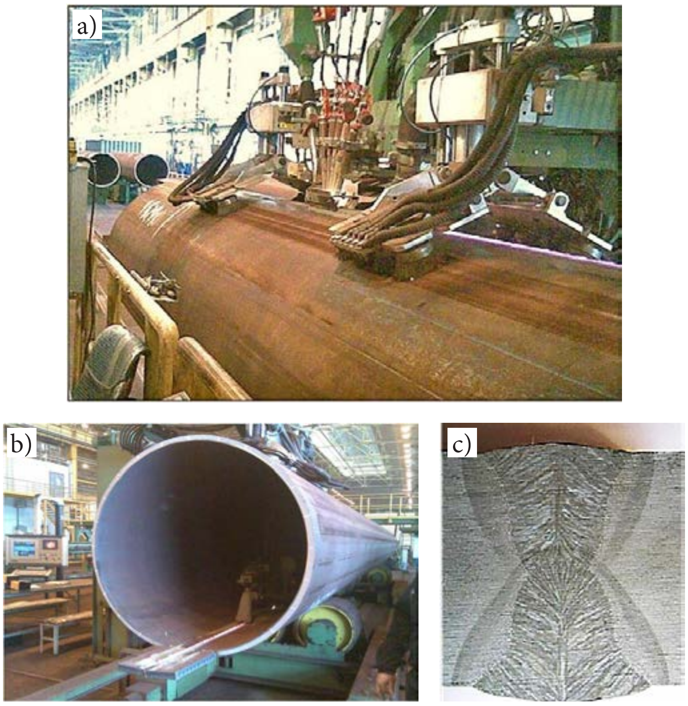

Figure 12. Multiarc submerged welding of 1420 mm diameter pipe of 40 mm wall thickness:
a – 5-arc welding of external weld, 110 m/h speed;
b – 4-arc welding of inner weld, 110 m/h speed;
c – macrosection of pipe welded joint

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 the purpose of manufacturing pipes in the workshop, 4- and 5-arc welding processes were developed with increasing frontal arc current up to 1900 A, which allowed a reduction in the dimensions of the groove, increased travel speed and reduced the consumption of welding consumables. (Figure 12). The additional advantage in this case is a favorable configuration of the fusion line, which improves test results on impact bending of metal of welded joints, especially of thick-walled pipes. The technology is recommended for welding of pipes with wall thicknesses from 25 to 50 mm.

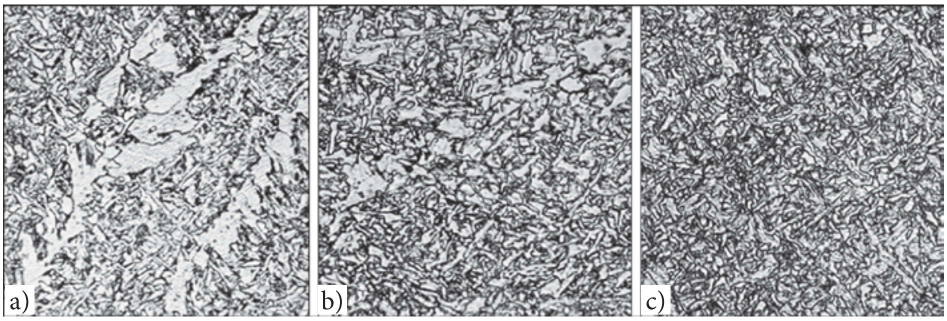

Figure 13. Microstructure (X500) of weld metal of pipes of K60 strength class steel, produced by applying different welding consumables:
a – Mn-Mo system of alloying, acid fused flux, polygonal ferrite is 20-25%; acicular ferrite is 35-45%; KV_{-30} = 27-30 J/cm²;
b – Mn-Ni-Mo system of alloying, aluminate agglomerated flux of low basicity, polygonal ferrite 3-5%, acicular ferrite 75-80%; KV_{-30} = 80-100 J/cm²;
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/cm²

During the manufacture of pipes of small and average wall thicknesses it is possible to apply multiarc welding with an 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. To provide high values of toughness, a system of controlling of chemical composition and structure of weld metal of pipes was developed at the Institute. It is based on the application of submerged multiarc welding, where welding wires of different chemical composition are set at separate arcs, which allows dosing control of content of alloying elements in weld metal at a high accuracy depending on the composition of applied pipe steel, welding conditions and other factors. During the manufacture of pipes, a combination of agglomerated aluminium flux of low basicity and welding wires containing manganese and molybdenum; manganese, nickel, and molybdenum; or manganese, molybdenum, titanium, and boron. The required chemical composition of the weld is attained by a change in the number of arcs with a welding wire of any alloying system and the use of different feeding speeds of the individual arcs. The control of the chemical composition of pipe weld metal provides a favorable structure. Figure 13, c shows the microstructure of the metal of a longitudinal weld of a gas and oil pipe of 1420 mm diameter with a 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 the weld metal, for example, impact toughness in the limits of 180-200 J/cm² 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 the manufacture of pipes with wall thickness from 16 to 40 mm of steel of K60-K65 strength class (category X70-X80) for main pipelines.

During the construction of main pipelines, the E.O. Paton Electric Welding Institute together with the organizations of OJSC «Gazprom» gained great experience in the 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 «Sever» equipment (Figure 14) and other flash-butt welding machines, more than

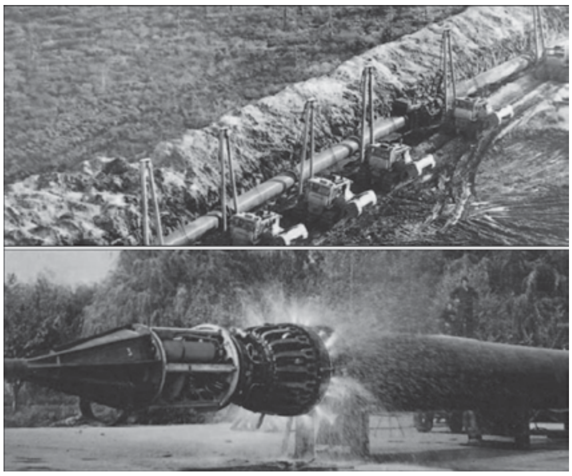

Figure 14. «Sever» equipment of types for pipe welding of main oil and gas pipelines

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

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

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/cm²) 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 the heat treatment of joints made by FBW, using a postweld local induction heating, was developed. Mechanical properties of welded joints in an as-heat treated state were as follows: (σt = 550.6-561.4 MPa, bending angle is 180°, KCV_{+20} = 147.9-219.5, KCV_{-20} = 86.8-171 J/cm². It was found that the highest values of impact toughness of welded joints, made by FBW on steel of strength class K56 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.

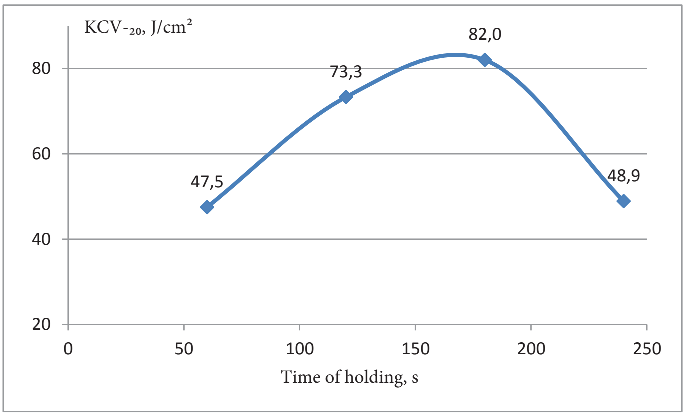

Figure 15. Dependence of average values of impact strength on holding time at 1000°C temperature of heat treatment

During tests of a reference batch of joints, made at optimum condition with next heat treatment, the quality of joints met 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 the 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 the program and the quality of joints.

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

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

The service reliability of heat and nuclear power station operation depends greatly on leak-tightness and high wear resistance of sealing surfaces of pipeline stop valves. Erosion and corrosion wear, thermal fatigue cracks, as well as the appearance of burrs on the friction surfaces are the main causes of 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 allow significant extension of service life of stop valves and increase of their 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, practical recommendations have been worked out for the repair welding of pipelines without interruption of their operation. These recommendations include a number of engineering methodologies and procedures for the assessment of long-range pipelines with known defects, as well as planning repairs using 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

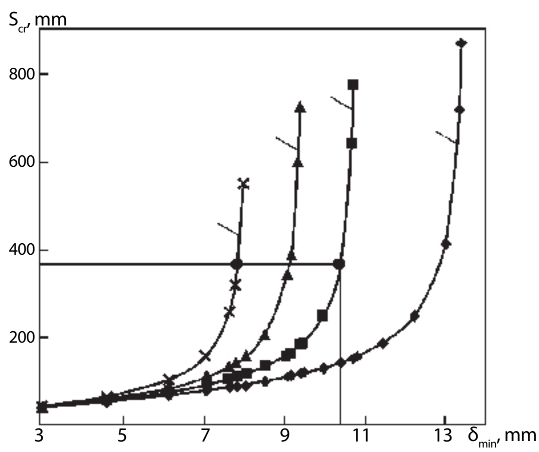

Figure 17. Dependence of critical length of defect of a local thinning type s_{cr} on minimum allowable thickness δ_{min} of wall of 1420×20 mm pipe of steel 17G1S at different internal pressure: 1 – 4.5; 2 – 5.25; 3 – 6.0; 4 – 7.5 MPa

of a degree of decreasing the load-carrying capacity of the pipeline both in service and also during repair (Figure 17). Special attention is paid to the problems of planning repair works using different supporting structures such as welded bands, sealing couplings, couplings with a compound filler.

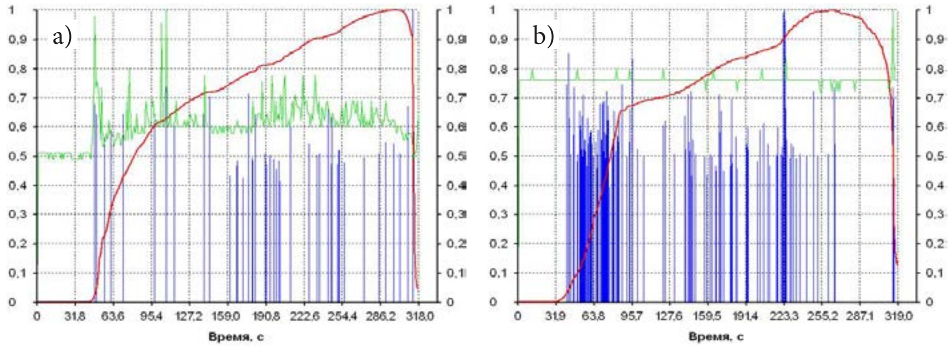

Figure 18. Comparison of signals of acoustic emission in tensile specimens of steel 15Kh1M1F at room temperature (a) and 500°C (b) (A – amplitude; A_v – amplitude of continuous emission; P – loading)

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

A 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 the Gulf of Mexico at an oil production platform where the 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 successfully passed the tests (Figure 20). A 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 the module in a vertical position and preventing the ability of the escaping stream of oil to push

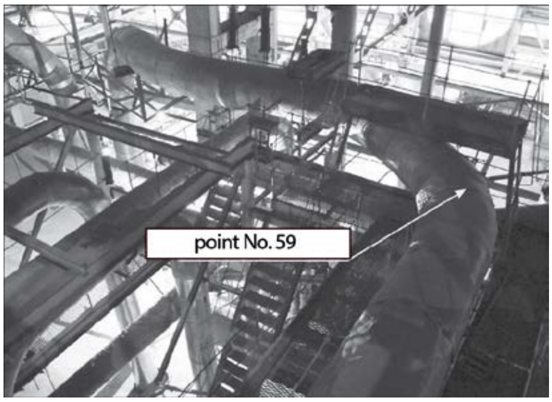

Figure 19. One of points of measurement by AE of operation activity of pipeline of steam intermediate overheating at Kiev HES-6

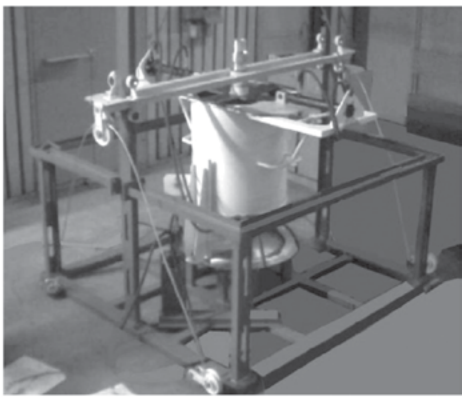

Figure 20. Module for joining the damaged pipes of wells

it aside. Moreover, the possibility of detachment of the module from its place of fixation resulting from dynamic shock is prevented by holes available in the module design providing the intensive free flow of oil flow into the surrounding environment. Then these module holes are closed. For this purpose, hydraulic cylinders and special shutters are used, envisaged by the module design. After completion of the operation of the hydraulic cylinders and the closing of the module holes, the oil is directed into the required direction along the pipeline.

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

The article is based on the lecture given at the International Conference "Welding and Allied Technologies - the present and the future" organised on 25-26.11.2013 in Kiev, Ukraine.