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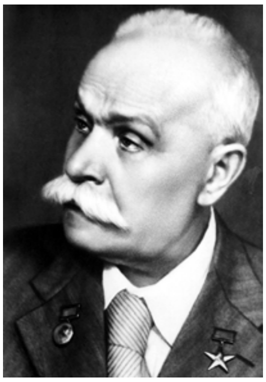
75 YEARS OF THE E.O. PATON ELECTRIC WELDING INSTITUTE OF THE NAS OF UKRAINE


Prof. Evgeny O. Paton

Rapid development of economy of the Russian Empire at the end of the 19th century required highly qualified engineering staff. The Kiev Polytechnic Institute (KPI) was founded in Kiev in 1898 to educate such specialists. The first rector of KPI Prof. V.L. Kirpichov invited young scientists to work as teachers at the Institute. Among them was Evgeny Oskarovich Paton, who at that time already was a known scientist in the field of bridge construction. During the years of his work in Kiev, Evgeny Paton designed and constructed many unique bridges and other structures, and completed a number of fundamental studies on bridge construction. In 1904 he became the Head of the Bridge Chair at KPI.

In 1929, Evgeny Paton was elected a full member (academician) of the All-Ukrainian Academy of Sciences, which led to accelerated development of structural mechanics, metallurgy, materials science and electric welding in Ukraine. New academic institutes were founded, thus launching active R&D activities in the field of technical sciences.

E.O. Paton initiated setting up of the welding laboratory at the Chair of Engineering Structures for comprehensive investigations of welded structures and metallurgical processes, welding metals science and physics of the arc discharge with subsequent development of welding equipment, consumables and technologies. To address all these challenges, the Electric Welding Institute was founded in 1934, and E.O. Paton was appointed the director of the Institute. Mechanisation and automation of welding were considered to be among the most important tasks of the Institute from the very first years of its existence.


Prof. Boris E. Paton

In 1939–1940, the Institute headed by E.O. Paton developed the method for automatic submerged-arc welding and unique technology for automatic welding of armoured bodies of tanks, air bombs and artillery systems. During the Great Patriotic War the staff of the Institute continued the research activity under factory conditions. In 1942, V.I. Dyatlov discovered the phenomenon of self-regulation of electrode melting in submerged-arc welding. Investigations into this phenomenon by B.E. Paton, together with A.M. Makara, P.I. Sevbo and M.N. Sidorenko, were used to develop portable, simple and reliable automatic welding devices.

Automation of the welding process made it possible to increase within the short time period the output of tanks and substantially improve the quality of the welded joints. Tank T-34 manufactured by Uralvagonzavod in Nizhny Tagil and other factories of the country was recognised by experts to be the best medium-weight tank of the Second World War. Lives of many thousands of tank crews were saved thanks to its reliable welded armour. In 1943, E.O. Paton was awarded the title of the Hero of Socialist Labour of the USSR for his contribution to increase in defence


The first building of the E.O. Paton Electric Welding Institute

potential of the country. In 1945, the Electric Welding Institute was named after Evgeny Oskarovich Paton.

In the post-war years the Institute performed investigations into the processes of electrode heating and melting, formation of electrode drops, problems of arc stability and self-regulation of the arc in metal-electrode welding. Static properties of automatic submerged-arc welding devices were studied, and method for analysis of operation of the automatic devices by static volt-ampere characteristics was suggested (B.E. Paton). Peculiarities of electric, thermal and metallurgical processes in submerged-arc welding, methods for adjustment of chemical composition and mechanical properties of the weld metal and welded joints were studied, and technologies for submerged-arc welding of different grades of steels were developed (B.E. Paton, V.K. Lebedev, A.M. Makara, and D.M. Rabkin).

By that time, automatic submerged-arc welding became one of the most efficient welding processes. However, the industry required novel developments in this field. E.O. Paton initiated profound study of the metallurgical processes occurring during submerged-arc welding. Within a short period of time, theoretical principles of metallurgy of submerged-arc welding and surfacing were laid down (I.I. Frumin, D.M. Rabkin, V.V. Podgaetsky, I.K. Pokhodnya), and high-capacity production of fused fluxes was organised (V.V. Podgaetsky, E.I. Lejnachuk, V.I. Galinich).

The high-speed welding technology, welding consumables and highly productive welding equipment were worked out at the Institute. Due to these developments, for the first time in the country, production of high-quality large-diameter pipes was launched at the Khartsyzsk Pipe Plant (B.E. Paton, R.I. Lashkevich, B.I. Medovar, S.L. Mandelberg, A.A. Rybakov). This laid the theoretical foundation for modern mass production of large-diameter pipes at the Khartsyzsk, Chelyabinsk, Vyksa, Volzhsky and other plants for high-capacity gas transportation systems in the USSR and now the CIS countries.

Submerged-arc welding with forced weld formation was used for construction of the all-welded bridge across the Dnieper River in Kiev. The bridge was named after E.O. Paton, principal ideologist of welded bridge construction and technical manager of design and erection of this unique facility. Further on the flux-cored wire arc welding method with forced weld formation was worked out at the Institute. It was widely used for construction of the Moskovsky and Yuzhny bridges across the Dnieper River in Kiev, a bridge across the Volga River in Saratov, for building of main pipelines, metallurgical and chemical plants and ship hulls.

In 1950, B.E. Paton was appointed a Deputy Director on Science at the Institute, and in 1953, after the death of E.O. Paton — Director of the E.O. Paton Electric Welding Institute of the Academy of Sciences of the Ukrainian SSR. He initiated working out of research programs, which were then approved by the decision-making authorities, for investigation of welding processes and development of equipment, materials and technologies, for setting up of new research institutes and factory laboratories, and for building of specialised plants for welding equipment, consumables and welded structures. Fulfilment of these programs was under a constant control, and work plans were corrected according to the latest predictive-analytic and economic research of the welding fabrication situation all over the world (V.N. Bernadsky, P.F. Kharchenko, V.S. Kutsak, A.A. Mazur, F.Kh. Bijtsev, S.M. Akkuratnova, P.V. Ignatchenko, B.M. Efetov, V.I. Snezhko, L.V. Katyukha). Accomplishment of these programs determined advancement of the welding science and technology in the second half of the 20th century not only in the USSR, but in many foreign countries as well. The USSR became the leading country in the world in the welding field, and our American colleagues used to call Kiev the world capital of welders.

As early as in the second half of the 1940s, E.O. Paton set up a task for scientists of the Institute — to invent a method for mechanised welding suitable for operation under field conditions. While searching for this method, G.Z. Voloshkevich succeeded in finding a new welding process — electroslag welding. B.E. Paton foresaw a great future for this process. He concentrated efforts of the Institute team on addressing the most important problems of electroslag welding. The scientists promptly worked out a method for welding thick (up to 4 mm) metal. Application of electroslag welding made radical changes in the technology of manufacture of such products as high-pressure boiler drums, heavy press and rolling mill beds, hydroturbine impellers and shafts, etc. (B.E. Paton, G.Z. Voloshkevich, A.M. Makara, Yu.A. Sterenbogen, I.I. Sushchuk-Slyusarenko, I.I. Lychko).

According to predictive estimates of experts, arc welding with its all possible modifications will remain to be the basis of welding production. Scientists and engineers of the Institute focus on further improvement of this process.

The method of arc welding in carbon dioxide atmosphere was worked out. Its implementation fostered raising the level of welding mechanisation (D.A. Dudko, I.I. Zaruba, A.G. Potapievsky).

Investigation of the processes of electrode metal melting and transfer, and interaction of metal with gases and slags were carried out. Principles of gas absorption and desorption were established. New generation of low-toxic welding electrodes was developed (I.K. Pokhodnya, I.R. Yavdoshchin, A.E. Marchenko), and the world-largest production of electrodes for manual arc welding was set up. The welders' working conditions were dramatically improved, and level of their occupational diseases decreased many times. Wide-scale utilisation of low-toxicity electrodes was fostered by the efficient work of the Pilot Plant for Welding Consumables operating under the Institute and headed by P.A. Kosenko.

Results of the investigation into metal science problems of arc welding, cold, hot and hydrogen-induced cracking mechanisms, and peculiarities of delayed fracture of welded joints laid the foundation for creating novel materials and technologies for welding of high-strength, high-temperature, heat-resistant and high-alloy steels and alloys, cryogenic engineering materials (A.M. Makara, B.I. Medovar, B.S. Kasatkin, A.E. Asnis, Yu.M. Gotalsky, M.I. Kakhovsky, V.F. Musiyachenko, K.A. Yushchenko, L.I. Mikhoduj, V.I. Gordonny, V.F. Grabin, M.M. Savitsky, A.K. Tsaryuk, V.D. Poznyakov), and aluminium and titanium base alloys (D.M. Rabkin, A.Ya. Ishchenko, S.M. Gurevich, V.N. Zamkov, L.S. Kireev).

The studies of surface engineering are advancing at the Institute. The equipment, technologies and consumables for mechanised cladding and spraying of wear-resistant alloys on surfaces of movable operating elements of machines and mechanisms used in mining and smelting, building, power engineering and machine building were developed (I.I. Frumin, I.K. Pokhodnya, Yu.A. Yuzvenko, I.A. Ryabtsev, Yu.S. Borisov, K.A. Yushchenko, A.P. Zhurda, M.L. Zhadkevich).

Peculiarities of flux-cored wire welding were studied. A number of self-shielding and gas-shielded flux-cored wires for various purposes were developed, and their production was organised (I.K. Pokhodnya, A.M. Suptel, V.N. Shlepakov). Now this area is one of the leading in the world welding science and technology.

Novel opportunities for exploration of the continental shelf, construction and repair of port structures, building of pipeline crossings across the rivers and other facilities were revealed (B.E. Paton, I.M. Savich, S.Yu. Maksimov).

Considerable attention is paid to the problem of using the phenomenon of arc constriction in welding and other allied processes. New technological processes of microplasma welding and cutting with the constricted arc (D.A. Dudko, V.S. Gvozdetsky, B.E. Paton, K.K. Khrenov), and microwelding of electronic equipment (A.A. Rososhinsky) were elaborated.

Fundamental studies were carried out in the field of flash butt welding (V.K. Lebedev, S.I. Kuchuk-Yatsenko). The influence of short circuit resistance of flash butt welding machines on the welding process was investigated. It was found out that the resistance has a high effect on stability and energy indicators of resistance heating of metal. Using current and voltage feedback, the possibilities for the dramatic enhancement of these indicators by means of programmed control of major melting parameters were established. The algorithms of regulation of these parameters were determined. Through the experiments performed, the ingenious systems for multifactor control of the flash butt welding process were constructed. The continuous flash butt welding process, differing from the existing technologies in lower power consumption and higher productivity, was developed. This made it possible to reliably join parts with a large cross section area, such as rails, pipes and rolled metal. Several generations of the original machines were built. Now they are used in many countries all over the world, for example, for rail welding. Application of such machines solved the problem of continuous «velvety» railways. Unique inside-pipe flash butt welding equipment complexes «Sever» for main pipelines up to 1420 mm in diameter, to be used under the Extreme North conditions, were produced. In addition, noteworthy are the machines for welding high-strength aluminium and titanium base alloys, which are still functioning at Russian and Ukrainian rocket production plants.

Modern engineering is characterised by an increasingly wider use of a new generation of structural materials, i.e. steels and alloys with a controlled degree of dispersion and structure, composite metal- and intermetallic-matrix materials, complex polymers reinforced with a metallic component, single crystals and super pure metals. Innovative technological processes of solid-state joining are developed, which are modifications of classical cold welding, friction welding, resistance welding, arc welding, diffusion bonding with activation of the surface effects of the joining zone, and magnetic pulse welding.

The ingenious technologies of explosion welding were developed. They found application for production of various parts, repair of pressurized pipelines, wiring of power transmission lines, installation of communication cables, etc. (V.M. Kudinov, V.G. Petushkov, L.D. Dobrushin, L.A. Volgin).

As early as in the 1950s, scientists of the Institute forecast the promising future for application of the electron beam for producing various thick-walled parts of steel and high-strength aluminium and titanium alloys and other materials. The complex problems for providing stability of the electron beam in metal vapour atmosphere were successfully addressed. Peculiarities of formation of narrow and deep welds were studied, and ways of control to ensure reproducibility of optimal welding conditions were found. Results of this research enabled to build the advanced internationally recognized equipment (B.E. Paton, O.K. Nazarenko, G.I. Leskov). Today the Institute exports the high-power electron beam units to many countries all over the world.

Much consideration is given to the application of welding and cladding lasers. The first practical results were obtained in 1969. Then, on the basis of the developments of the I.V. Kurchatov Institute for Atomic Energy and E.O. Paton Electric Welding Institute, CO_2 lasers with up to 10 kW power were developed, and the process of laser and constricted arc metal heating was investigated. Today the top priority is attached to solid-state and fibre-optic semiconductor lasers, whose efficiency is higher than of gas-discharge lasers, thus allowing transfer of radiation to the welding spot via fibre light guides.

In the mid 1960s, the E.O. Paton Electric Welding Institute developed tungsten-electrode arc welding over the layer of the activating flux-paste, later called A-TIG welding (B.E. Paton, A.M. Makara, B.N.

Kushnirenko, V.N. Zamkov). Evaporation of the activating flux provides contraction of the arc column, which increases the weld penetration depth several times, raises the welding efficiency and improves the weld shape. This original technology was worked out in the USSR and now is successfully developed in the CIS countries. The upgraded PATIG technology has gained wide recognition in foreign countries (K.A. Yushchenko).

Theoretical foundations for the arc welding processes that use activating fluxes were worked out. Main mechanisms of the impact by flux additives on thermal and dynamic characteristics of the electric arc and shape of the weld pool were established. The explanation to the mechanism of deep penetration of metal was suggested. Physical processes taking place in the near-anode layer of the arc plasma, on the surface and inside the weld pool were studied (I.V. Krivtsun, V.F. Demchenko, K.A. Yushchenko).

Agglomerated fluxes that make it possible to actively influence the course of the welding metallurgical processes, control structure and properties of the welds and welded joints were developed (K.K. Khrenov, D.M. Kushneryov, V.V. Golovko).

At the end of the 1980s, the Institute started investigating the hybrid (laser-arc and laser-plasma) welding and materials treatment processes. The investigations made it possible to determine that the laser beam and arc plasma interaction may cause a special type of the gas discharge — the combined laser-arc one, whose properties differ from those of the electric arc and focused laser radiation supported discharges. The use of the combined discharge opens up the new opportunities for thermal and electromagnetic energy concentration control. Designs of direct and indirect action laser-arc plasma torches were suggested, and a range of integrated various-purpose plasma torches was built. The innovative processes of hybrid laser-plasma welding and cladding, including hybrid laser-microplasma welding of thin metals, were developed (B.E. Paton, V.D. Shelyagin).

In the 1960s, the Institute initiated studies of the technology for production of various coatings and composite materials by way of electron beam evaporation of components and condensation of vapour on the surfaces of parts or special substrates. The electron beam coating technology widely used in some industrial sectors allows a several times increase in service life of numerous parts, such as gas turbine blades (B.E. Paton, B.A. Movchan, A.I. Ustinov).

The introduction of active gases or corresponding admixtures of active metals to the vapour flow permitted widening the range of structures of the condensed materials and coatings (multiphase, laminated, porous and graded). These are various protective and structural coatings, special foils, magnetic fluids, structural elements of solid oxide fuel cells and catalytic devices, filters, membranes, etc.

As early as in the first half of the 1960s, B.E. Paton was thrilled with an idea of applying welding for assembly of metal structures in space. This idea was supported by Prof. S.P. Korolyov, General Designer. Preliminary research was conducted, including testing of welding equipment and methods on board the flying laboratory under the short-term dynamic weightlessness conditions. The first technological experiment on welding in the near-Earth space was carried out in 1969. Cosmonaut V.N. Kubasov performed experimental welding by the electron beam, plasma arc and consumable electrode methods on board the «Soyuz-6» spaceship. Investigation of the weld formation under the zero gravity conditions demonstrated that sound and well-shaped welds could be made in space.

In 1979, the idea of deposition of various metal coatings on surfaces of elements of the space stations and devices was successfully tested. Special device «Isparitel» was developed, and the versatile hand tool (VHT) for welding, brazing and coating was created. In 1984, cosmonauts S.E. Savitskaya and V.A. Dzhanibekov tested VHT in the outer space. This test launched the cycle of systematic multi-purpose research and experiments to optimise structural elements and technologies for construction of large-size orbital structures and facilities. In 1986, a structure was assembled in space as a dismountable truss («Mayak» experiment). Brazing of units of the truss structures was performed for the first time ever. Results of these experiments were applied in the device developed by the E.O. Paton Electric Welding Institute for deployment and folding of multiple-use solar cell panels in the orbital station «Mir».

Many years' research and achievements in the field of space technologies were highly appreciated by Yu.P. Semyonov, RAN Academician and General Designer of rocket and space complexes at RPC «Energiya». Results of these efforts were summarised in monograph «Welding in Space and Related Technologies» by B.E. Paton and V.F. Lapchinsky (1997). Investigations in the field of space technologies are continued until now (E.A. Asnis).

For many years B.E. Paton has been heading research on electrotechnical welding processes and electrothermics. Novel power supplies were elaborated (V.K. Lebedev, N.G. Ostapenko, I.I. Zaruba, A.S. Pismenny, V.V. Andreev, A.E. Korotynsky, M.N. Sidorenko, A.V. Lebedev), and systems for control and automatic regulation of the welding equipment and instruments were studied (N.V. Podola, Yu.M. Lankin, F.N. Kisilevsky).

Today, the research on optimal design of control systems and search for automatic regulation parameters, which could fit as closely as possible the process of formation of a welded joint, are continued at the Institute.

The new pulsed arc welding method that enables to control the electrode metal transfer was created. Hence, the problem of mechanised consumable electrode welding of aluminium and titanium alloys and stainless steel was successfully solved (B.E. Paton, P.P. Shejko, N.V. Podola).

Methods for automatic control of electrode metal melting and transfer with short circuits of the arc gap in carbon dioxide welding were developed, and the corresponding equipment allowing achievement of the high stability values in implementation of this process was constructed.

The negative effect of different perturbations occurring during welding can be levelled by using the control systems that are capable of processing a large volume of information and generating the required regulating actions. The first samples of such systems were made at the beginning of the 1970s (B.E. Paton, F.N. Kisilevsky). The intensive research efforts in this area led to the development of the automatic microprocessor-based control systems for welding processes, units and production lines.

Results of the investigations performed by the Institute are used by its Design Bureau for development of prototypes of welding equipment (P.I. Sevbo, A.I. Chvertko, B.E. Paton, V.F. Moshkin, M.G. Belfor, V.A. Sakharnov). The prototype models of such equipment are manufactured by the Experimental Production, while the mass production is organised at the Pilot Plant for Welding Equipment of the E.O. Paton Electric Welding Institute, as well as at other Ukrainian, CIS and foreign enterprises. G.B. Asoyants and M.I. Bobrovnik, who headed the Pilot Plant for Welding Equipment and Experimental Production of the Institute for many years, contributed greatly to their advancement.

Traditionally, the Institute pays much attention to constructing efficient, reliable and durable welded structures. The package of fundamental and applied research in the field of static and cyclic fatigue life of welded joints, their brittle and fatigue fracture resistance and low-temperature performance was completed. Standards for designing and manufacturing welded assemblies of critical-application metal structures were worked out. Novel types of highly efficient welded building structures, highway and railway bridge span structures, heavy-duty mining and metallurgical complex machines, and unique transformable structures were created (V.V. Shevernitsky, G.V. Raevsky, A.A. Kazimirov, V.I. Trufyakov, O.I. Shumitsky, L.M. Lobanov, V.I. Kirian).

Construction of a number of prominent structures was an outcome of the R&D activities of scientists of the Institute in the field of welded building structures. Among them is the unique E.O. Paton all-welded bridge across the Dnieper River. The principles, approaches and structural technological decisions elaborated during its erection paved the way for a wide application of welding in bridge engineering. The bridge was nominated the outstanding welded structure of the 20th century by the American Welding Society. The experience gained in erection of the E.O. Paton bridge was used for constructing other bridges across the Dnieper River in Kiev (Yuzhny, Moskovsky, Gavansky, Podolsko-Voskresensky, highway and railway bridges), and bridges in Dnepropetrovsk, Zaporozhie, as well as the bridge across the Smotrich river in Kamenets-Podolsk.

Development of the technology for deployment of coiled tanks for storing oil and oil products demonstrates the innovative approach to erecting factory assembled welded structures (G.V. Raevsky). It helped to rapidly solve the problem of reconstruction of the tank fleet of the country destroyed during the war.

The Institute for a number of years was involved in the research that focused on strength of tubular welded structures (V.I. Novikov, O.I. Shumitsky, V.A. Kovtunenko, E.F. Garf, V.S. Girenko).

Together with the «Ukrproektstalkonstruktsiya» Research Institute, designs and manufacturing technologies were developed. They were successfully implemented for erecting the unique TV towers in Kiev, Saint Petersburg, Yerevan, Tbilisi, Vitebsk and Kharkov. A high interest in the problems of pipe welding is explained by the intensive exploration of the continental shelf and need for a wide-scale construction of off-shore stationary platforms for oil and gas production. Scientists of the Institute investigate strength of the tubular welded joints under the conditions of cyclic loading. They elaborate special procedures for fatigue design of the welded joints. A set of normative documents regulating designing of the off-shore structures was worked out.

The welding technologies developed by the E.O. Paton Electric Welding Institute were successfully applied in construction of the Great Patriotic War museum and the «Motherland» monument in Kiev (K.A. Yushchenko).

Of high importance is the package of the research performed by the Institute, which is aimed at developing and implementing high- and increased-strength steels. The long-term use of the critical welded structures made from high-strength steels (high-capacity mining and oil production equipment, continental shelf oil and gas production platforms, heavy-duty trucks, road-construction and load-lifting machinery, building structures, etc.) proves the reliability and efficiency of the developed materials and technological welding processes (B.S. Kasatkin, V.F. Musiyachenko).

Much consideration in the research performed by the Institute is given to evaluating strength of the structures with service defects, as well as to determining and extending their service life. B.E. Paton is the initiator and scientific supervisor of targeted science and technology program «The Problems of Service Life and Safe Operation of Structures, Buildings and Machines». Many academic institutes, universities, branch institutes and industrial enterprises are involved in fulfilment of this program.

Enormous attention is paid to development of the methods for non-destructive testing and diagnostics. Automated units for ultrasonic inspection of large-diameter pipes, drill bit bodies, power plant assemblies, welded joints of light alloys and non-metallic materials were built. Computerised flaw detectors and high-frequency acoustic microscopes receive an increasingly wider acceptance. Efficient application fields for low-frequency ultrasonic waves and contactless introduction of acoustic waves into objects have been found. Systems for digital radiation monitoring and methods for laser interferometry are developed.

The work on acoustic emission diagnostics has been widely recognized. Systems for continuous monitoring of welded structures, which ought to meet the increased requirements for their safe operation, were created (L.M. Lobanov, A.Ya. Nedoseka, V.A. Troitsky).

The Institute is active in mathematical modelling of welding processes, technologies, structures, kinetics of development of stresses and strains. Methods were developed for prediction of mechanical properties, safe remaining life of welded joints and assemblies (V.I. Makhnenko, L.M. Lobanov).

Along with investigations of welding processes and technologies, the Institute for many years has been involved in materials science research. New structural material and their production technologies are developed, and study of the «composition–structure–properties» relationship regarding the materials for manifold purposes is carried out. The E.O. Paton Electric Welding Institute has become a major materials science centre.

The Institute has a high-capacity base to conduct physical and chemical investigations of materials properties (G.M. Grigorenko), employing highly qualified specialists in metal physics, metals science, electron microscopy, mass-spectroscopy, Auger spectrometry, analysis of gases in metals and welds, and X-ray element analysis. Fitted with the up-to-date research equipment, the Institute provides the highest-level implementation of the sophisticated materials science research.

In 1954, B.E. Paton initiated the research on using the electroslag process for improvement of the quality of metals and alloys. As a result, a cardinally new area in metallurgy was formed — electroslag remelting, which shortly found a wide application and was internationally recognized. Companies from many countries all over the world purchased licences for this process. It is applied to improve properties of heat-resistant, stainless, tool, ball-bearing and other steels, as well as special alloys. By combining the processes of electroslag remelting and casting, manufacture of hollow ingots, pressure vessels, stop valves for heat and nuclear power stations, cast dies, shafts of marine engines and other critical products was arranged (B.I. Medovar, Yu.V. Latash).

The process of electroslag cladding of rolling mill rolls was developed, where the liquid filler metal is used. Physical and metallurgical problems of the electroslag technologies are studied (B.I. Medovar, L.B. Medovar), and magnetic hydrodynamics of the electroslag processes is investigated (Ya.Yu. Kompan).

The work on refining of metals and alloys by the electron beam was started as early as in 1959. Electron beam melting proved to be the effective method for improving the quality of special steels, nickel and iron base alloys, as well as the reliable technology for producing super pure niobium, titanium and alloys based on them (B.A. Movchan).

In recent years the electron beam technology for producing titanium ingots has been successfully advanced. New high-strength titanium alloys doped with aluminium, zirconium, niobium and iron, as well as designs of commercial electron beam cold-hearth melting furnaces were developed. Many of them have no analogues in the world practice (M.P. Trigub, V.N. Zamkov, S.V. Akhonin).

The method, equipment and technology for plasma arc remelting of metals and alloys are further advanced. After the development of the AC plasmatron, potential of the plasma arc technologies dramatically increased. It enabled to boost reliability of the melting units and power supplies.

Plasma arc remelting is used to produce high-quality multi-component and precision alloys (V.I. Lakomsky, G.M. Grigorenko). This process allows alloying metals with gas-phase nitrogen for production of high nitrogen steel. The innovative technology developed by the Institute for plasma arc refining of surfaces of the ingots made from precious alloys turned out to be quite efficient. The plasma-slag technology is being developed (M.L. Zhadkevich, V.A. Shapovalov). Many of the above technologies were implemented at the Pilot Plant for Special Electrometallurgy of the E.O. Paton Electric Welding Institute (M.L. Zhadkevich, A.P. Povarchuk).

In recent years, out-of-furnace processing of metallurgical melts is widely applied in the world metallurgical practice. Flux-cored wires are used at the Institute for this purpose. The new types of wires containing high-activity elements for microalloying, modification and desulphurisation of steels and cast iron were created. The technology and equipment for production of large-diameter flux-cored wires were developed (I.K. Pokhodnya, V.F. Alter). This research area was further developed at the I.N. Frantsevich Institute for Problems of Materials Science, Donetsk Polytechnic Institute, Donetsk Research Institute for Ferrous Metallurgy and at the «Versatile Equipment» Plant.

Today, the injection metallurgy method is widely utilised at the Ukrainian and Russian metallurgical plants, where tens of millions of tons of steel melts were treated with its help.

The E.O. Paton Electric Welding Institute successfully develops investigations in the field of brazing and soldering of metals and alloys. The scientific bases were worked out for vacuum brazing of structures from various grades of stainless steel. Ingenious filler metals for brazing of parts from heat-resistant nickel alloys, technological processes and filler metals for brazing of advanced materials, including intermetallic, precipitation-hardened, carbon materials, titanium- and aluminium-base alloys, and ingenious reactive fluxes for brazing of aluminium were developed.

The innovative brazing technologies are widely used for producing aircraft engines, space and drilling equipment (V.F. Khorunov).

In the post-war years, the huge deposits of oil and gas were discovered in the territory of the USSR. In this connection, the E.O. Paton Electric Welding Institute developed unique technologies and equipment for flash position butt welding of pipes — complexes «Sever», which were widely applied for construction of main pipelines from steels of different strength grades (B.E. Paton, V.K. Lebedev, S.I. Kuchuk-Yatsenko, V.A. Sakharnov). Using flash butt welding, over 70,000 km of pipelines were built, including 6,000 km of large-diameter gas pipelines under the Far North conditions. The innovative technology for automatic position butt welding of pipes by using self-shielding flux-cored wires and forced weld formation — complex «Styk», was elaborated (B.E. Paton, I.K. Pokhodnya, V.N. Shlepakov, V.E. Paton, V.Ya. Dubovetsky). By using this technology, over 10,000 km of main gas and oil large-diameter pipelines were built. Among them are the «Druzhba», «Central Asia–Centre», «Urengoj–Pomary–Uzhgorod», «Khiva–Beineu», «Shebelinka–Izmail», «Yamal–Western Border», «Yamal–Povolzhie» and other gas pipelines.

Much consideration is given to implementing the latest achievements of modern science and technology in practical medicine. In the 1990s, B.E. Paton suggested using welding for joining live tissues and organised a creative team of scientists of the E.O. Paton Electric Welding Institute, A.A. Shalimov Institute for Surgery and Transplantology and Central Hospital of the Security Service of Ukraine (SBU). This cooperation allowed devising a new method for joining (welding) soft live tissues (B.E. Paton, V.K. Lebedev, A.V. Lebedev).

The process for welding live tissues has been constantly upgraded and enhanced in the last years. Properties of tissues of various organs of the post-surgical patients were investigated, new welding equipment and control methods for the welding process were created, mathematical modelling of heating of the tissues with the high-frequency current flowing through them was carried out, and electrophysical properties of biological tissues and strength of the welded joints were determined. The electric current power supply with the automatic control system was developed, and instruments for welding various types of biological tissues were worked out. New samples of the equipment were successfully tested at medical institutions. The wide experience was accumulated within a short period of time — over 20 thousand operations were performed on different human organs. The method for welding live tissues is used at the hospitals of Kiev and 11 regions of Ukraine. It is mastered by medical institutions Moscow and Saint Petersburg and tested in foreign countries. The time of surgical operations has dramatically decreased, as well as the probability of post-surgical complications, and blood losses were minimised.

Specialised councils work at the Institute, dealing with awarding the doctor's and candidate's degrees. Associates of the Institute defended over 130 theses for the degrees of the Doctors of Sciences and over 700 theses for the degrees of the Candidates of Sciences. The Institute publishes a number of scientific-and-technical journals — «Avtomaticheskaya Svarka» (Automatic welding), «Sovremennaya Elektrometallurgiya» (Advances in electrometallurgy) and «Tekhnicheskaya Diagnostika i Nerazrushayushchy Kontrol» (Technical diagnostic and non-destructive testing), as well as «The Paton Welding Journal», which is disseminated abroad.

Tens and hundreds of talented scientists and engineers have grown at the Institute. And it is not without a reason that there are many academicians and corresponding members of the NAS of Ukraine among the Institute staff. Nine works, in which scientists of the Institute participated, were awarded the USSR Lenin Prizes in Science and Technology, 24 works — the USSR State Prizes, and 34 works — the State Prizes of the Ukrainian SSR and Ukraine. Names of these scientists are known not only in our country, but also far beyond its borders.

Many of the above works are outcome of the efforts of a big and united team. The unity of the Institute's team is provided by personal qualities of its leader. Boris Paton is always full of ideas, which he generously shares with his colleagues.

One of the main principles laid down by Evgeny O. Paton in foundation of the Institute and further developed by Boris E. Paton consists in performing targeted fundamental research and ensuring the close relation of science and industry. This principle has been constantly made into reality for over 75 years of the Institute's history.

Scientific and design departments of the Institute, experimental workshops, Design Bureau, engineering centres, experimental productions and pilot plants have been established during the entire history of the Institute. They are integral parts of the system that makes for successful implementation of the research results into production.

Realisation of this system made it possible to produce unique structures, equipment, materials and technologies, whose application accelerated development of many industries, such as machine and ship building, space and rocket complex, aircraft engineering, power generation, mining, metallurgy and chemical production, construction and operation of pipeline transportation systems, building sector, etc.

Devoted work of the team of the Institute was highly appreciated by the state and received wide international recognition. The Institute was awarded the Orders of Lenin, October Revolution and Red Banner of Labour. Many associates of the Institute were also awarded the orders and medals of the USSR and Ukraine.

Prof. I.K. Pokhodnya, PWI

STRENGTH AND STRUCTURE OF ALUMINIUM ALLOY WELDED JOINTS MADE BY FRICTION STIR AND NON-CONSUMABLE ELECTRODE WELDING

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Comparative analysis of the degree of softening and level of strength of welded joints of ductile low-alloyed aluminium alloys and high-strength complex-alloyed aluminium alloys produced by friction stir and non-consumable electrode welding has been performed. It is shown that the strength of welded joints of ductile low alloys is the same with both welding processes. Deformation strengthening of welds of high-strength complex aluminium alloys achieved in friction welding provides a higher level of their strength in fusion welding.

Keywords: *friction stir welding, argon-arc welding, consumable electrode, aluminium alloys, degree of softening, ultimate strength, structure*

Aluminium alloys are widely used in fabrication of welded structures in different fields of mechanical engineering. Requirements made of them, and, hence, the alloy grades used in their fabrication, change, depending on the purpose and service conditions. So, for instance, for lightly loaded components or individual complex-shape elements the ductile low-alloyed aluminium alloys can be used, which lend themselves easily to bulk deformation even in the cold state. High-strength complex aluminium alloys are used in critical structures exposed to considerable force impact. In order to produce permanent joints, non-consumable electrode argon-arc welding (TIG) is used in most of the cases, providing the required weld quality and high level of their strength [1–5].

At present friction stir welding (FSW) is more and more widely used for fabrication of diverse welded structures from aluminium alloys. The principle of weld formation is based on metal heating up to the ductile state as a result of friction, its stirring across the entire thickness of the edges being welded and deformation in a closed volume [6, 7]. Such a method of producing permanent joints is the most acceptable for ductile materials with a low melting temperature. It may be realized for various aluminium alloy grades and has several advantages compared to other processes of producing a permanent joint [8, 9]:

- weld formation in the solid phase allows avoiding hot cracks, oxide film macroinclusions, pores and other defects, which are due to metal melting and solidification in fusion welding;
- metal heating in the welding zone as a result of friction eliminates ultraviolet radiation of the arc, fume and metal vapour evolution and lowers the noise level;
- joint formation without metal melting can be performed without shielding gas application in any position;
- absence of arc discharge and molten metal eliminates burning out of alloying elements in the weld and the need to increase their content through application of filler materials;
- producing the weld without the arc discharge allows freely using this process in the presence of strong electromagnetic fields;
- stirring of plasticized metal at excess pressure in a limited volume leads to fractionation of oxide inclusion macroparticles, thus lowering the requirements to preheating of the surfaces of edges being welded;
- tool tip penetration to the entire depth of the butt allows welding metal of various thickness without any special edge preparation;
- running of the welding process at a lower temperature leads to lowering of the degree of material softening and level of residual stresses in structures;
- improvement of the efficiency of power utilization at FSW and lowering of metal heating temperature in the welding zone reduce the energy consumption of the process compared to fusion welding;
- welding process lends itself easily to automation and thus provides a stable quality of welds without the need for a highly skilled operator.

Owing to such advantages, the FSW process opens up broader technological capabilities for fabrication of welded structures from such alloys, which cannot be joined by fusion welding, because of hot cracking in welds; provision of a higher level of weld strength in heat- and work-hardened aluminium alloys; joining metastable alloys produced by rapid solidification of metal from the melt, composites and nanomaterials; producing welded components, which it is not cost-effective or practically impossible to extrude or cast as one piece from batch-produced individual sections.

The purpose of this work is comparison of the strength, degree of softening and structure of welded joints of ductile low-alloyed and high-strength complex-alloyed aluminium alloys produced by FSW and TIG welding.

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Table 1. Mechanical properties of sheets from aluminium alloys 1.8 mm thick

Alloy grade	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	α, deg
AMtsN	218	178	6	180
AMg2M	176	88	23	180
AMg5M	332	160	22	142
AMg6M	359	210	22	96
1420	459	322	11	50
1201	423	303	12	60
1460	565	523	9	36

Experimental studies were conducted using ductile high aluminium alloys AMtsN, AMg2M and AMg5M, as well as high-strength complex-alloyed aluminium alloys AMg6M, 1420, 1201 and 1460. Mechanical properties of welded sheets 1.8 mm thick are given in Table 1. TIG welding was conducted at the speed of 20 m/h in MW-450 system (Fronius, Austria), using respective filler materials (Table 2); FSW was performed in a laboratory unit designed at PWI. The produced welded joints were used to prepare standard samples to determine the ultimate strength at uniaxial tension. Testing was conducted using an all-purpose servohydraulic system MTS 810. TIG-welded samples were tested after removal of the beads flush with the base metal, as well as with additionally scraped reinforcement, as both types of the joints are used in welded structures. In samples made by FSW reinforcements or beads are absent, so that no additional mechanical hogging of the welds was required. Degree of metal softening in the welding zone was assessed by the results of measurement of its hardness in ROCKWELL instrument at 600 N load and sphere diameter of 1/16". For welded joints of ductile AMtsN and AMg2M alloys metal microhardness was measured using PMT-2 microhardness meter at 0.1 N load. Microstructural studies of the produced welded joints were conducted using MIM-8M optical microscope. Before examination the cross-sections of joints made by TIG welding and FSW were prepared by electrolytical polishing and additional etching in a solution of chloric, nitric and hydrofluoric acid.

Conducted experimental studies allowed assessment of the degree of softening, level of strength and structural features of joints produced by fusion and solid-phase welding. It is established that at TIG welding of ductile low-alloyed aluminium alloys AMtsN and AMg2M minimum hardness is found in the HAZ metal, which is where samples fail at tension, whereas in welded joints of AMg5M alloy minimum metal hardness is found in the weld central part. Therefore,

Table 2. Modes of welding aluminium alloys by different processes

Alloy grade	TIG-welding				FSW	
	Filler material (size, mm)	$v_{w.f}$, m/h	I_w, A	Q_{Ar}, l/min	N, rpm	v_w, m/h
AMtsN	AMtsN (4.5×2.0)		140	15	2880	38
AMg2M	AMg2M (4.5×2.0)	--	135	15	2880	38
AMg5M	SvAMg5 (1.6)	82	140	15	1420	14
AMg6M	SvAMg6 (1.6)	82	130	15	1420	8
1420	SvAMg63 (1.6)	82	130	20	1420	14
1201	Sv1201 (1.6)	82	145	15	1420	14
1460	Sv1201 (1.6)	82	140	20	1420	8

Table 3. Ultimate strength of aluminium alloy welded joints produced by different welding processes

Alloy grade	TIG-welding				FSW	
	Sample with reinforcement		Sample without reinforcement		Sample without reinforcement	
	σ_t, MPa	Fracture site	σ_t, MPa	Fracture site	σ_t, MPa	Fracture site
AMtsN	113	HAZ	113	HAZ	113	ZTMI
AMg2M	170	Same	170	Same	170	HAZ
AMg5M	320	»	300	Weld	320	Same
AMg6M	345	FZ	324	Same	336	ZTMI
1420	373	Same	320	»	342	FZ
1201	296	»	239	»	310	Same
1460	311	»	257	»	309	ZTMI

Note. Average values arc given from the results of testing 3--5 samples.

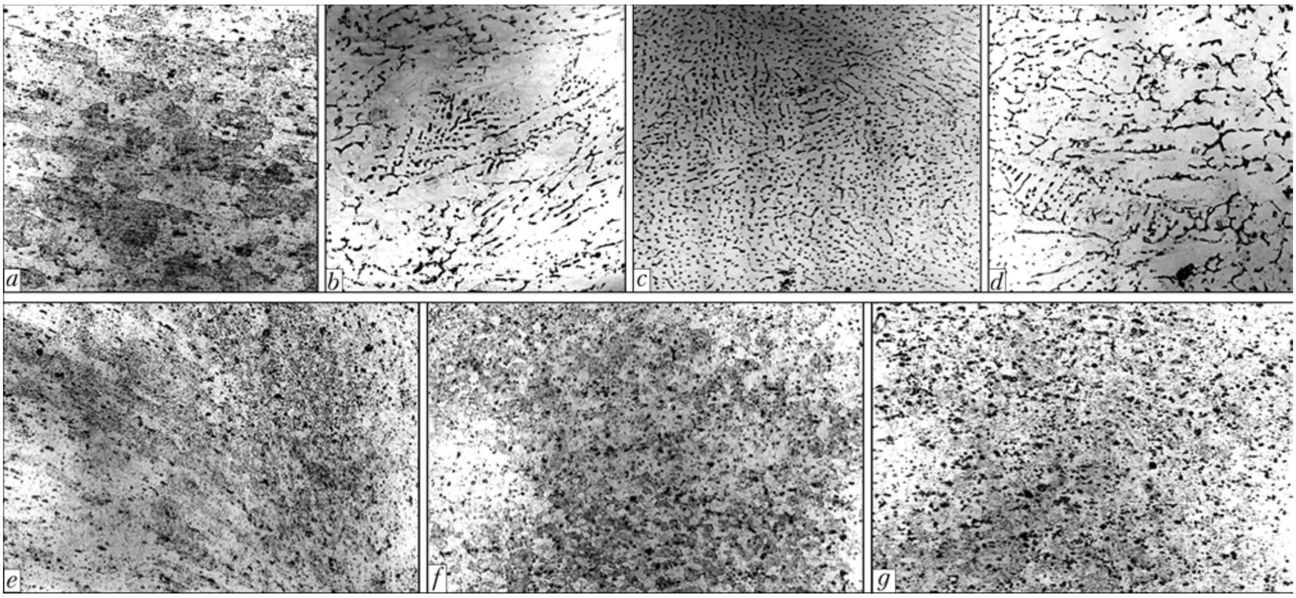

Figure 1. Microstructure (×400) of base metal (*a*) and welded joints of AMg2M alloy made by TIG welding (*b, d* ---- FZ of weld with base metal, *c* ---- weld) and FSW (*e, g* ---- ZTMI from the side of tool advancing and retreating; *f* ---- weld nugget)

samples without reinforcement fail in the weld, and those with a reinforcement fail in the HAZ.

At FSW of AMtsN alloy minimum metal hardness is found in the zone of thermomechanical influence (ZTMI) from the tool retreating side, which is where sample failure occurs. Welded joints of AMg2M and AMg5M alloys produced by FSW fail in the HAZ, where metal hardness is minimum. It should be noted that minimum values of metal hardness in the fracture zone of samples of AMtsN and AMg2M alloy welded joints, produced by both the welding processes, are approximately the same, and their ultimate strength is on the level of 113 and 170 MPa, respectively (Table 3). Only samples without reinforcement from AMg5M alloy, made by TIG welding, have a somewhat lower (300 MPa) strength and fail in the weld central part, where the metal is characterized by minimum hardness. Therefore, structural changes in the weld metal and its fusion zones (FZ) with the base metal, occurring in fusion or solid-phase welding of these alloys practically do not affect welded joint strength.

Nature of metal softening in the HAZ at FSW is different for high-strength complex-alloyed wrought and heat-hardenable alloys.

In solid-phase welding of AMg6M alloy formation of finely-dispersed grains in the weld leads to its deformation strengthening (Figure 2, *a*). Therefore, failure of such samples occurs in the HAZ, where metal hardness is minimum, and strength is on the level of 336 MPa. Samples without reinforcement made by TIG welding fail in the weld and have the ultimate strength of 324 MPa. Maximum strength (345 MPa) is characteristic for samples with a reinforcement failing at tension in FZ of the weld with the base metal.

In heat-hardenable alloys (1420, 1201 and 1460) the solid solution is in an oversaturated state. Therefore, thermomechanical impact on welds, in addition to grain refinement, also results in metal softening, which is due to precipitation of excess intermetallic phases from the solid solution and their coagulation. Fine strengthening phases in the weld nugget partially dissolve, while coarse low-melting intermetallic inclusions partially melt, forming a new solid solution. As a result, softening, which is due to precipitation of excess phases, prevails over strengthening, achieved as a result of grain refinement in FSW welds (Figure 2, *b*). Hardness of weld metal, its FZ with the base metal and ZTMI is practically the same, samples of heat-hardenable alloys fail in these zones.

In welded joints of such alloys made by TIG welding, minimum metal hardness is observed in the weld

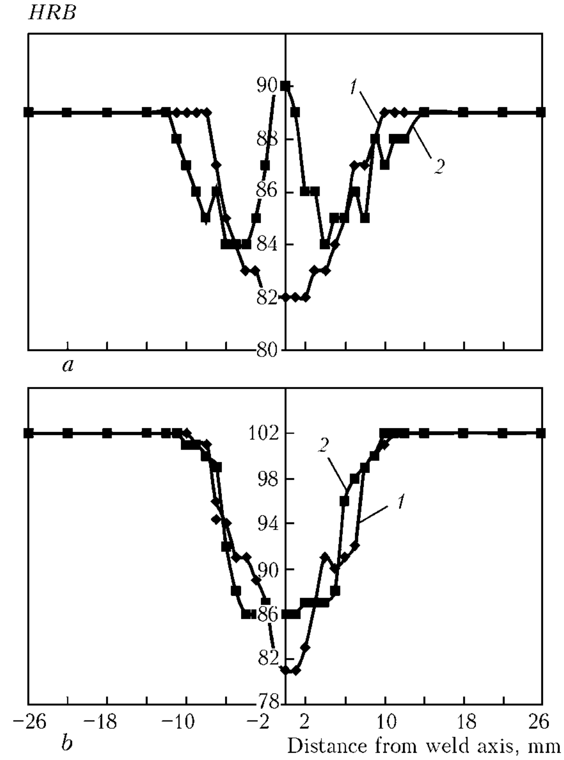

Figure 2. Hardness distribution of metal of welded joints of alloys AMg6M (*a*) and 1420 (*b*) made by TIG welding (*1*) and FSW (*2*)

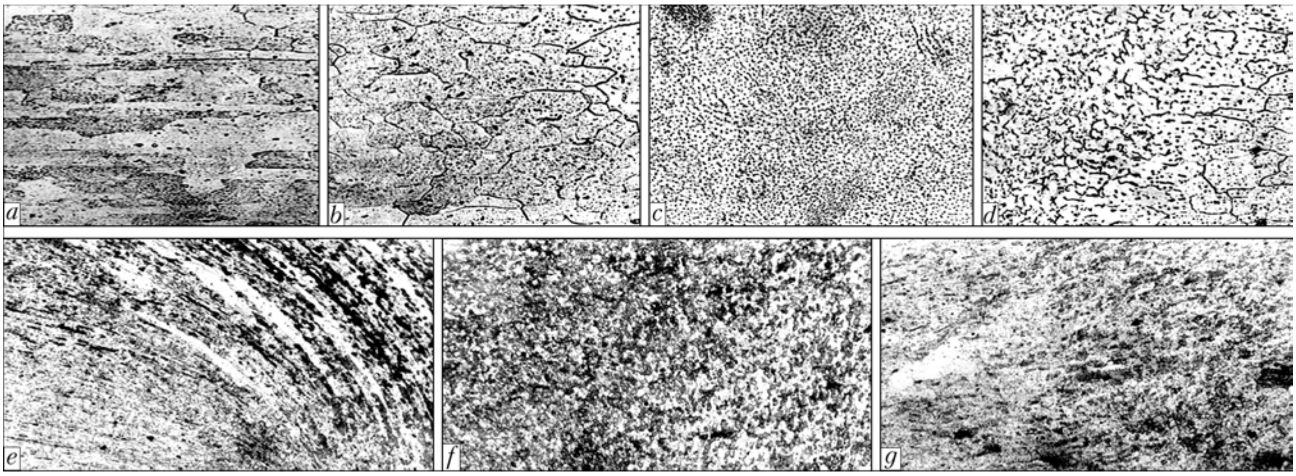

Figure 3. Microstructure (×400) of base metal (*a*) and welded joints of 1460 alloy made by TIG welding (*b*, *d* ---- FZ of weld with base metal; *c* ---- weld) and FSW (*e*, *g* ---- ZTMI from the side of the tool advancing and retreating, respectively; *f* ---- weld nugget)

central part, which is where samples without reinforcement fail. However, the ultimate strength of welded joints made by FSW, is always higher than that of samples without reinforcement, made by TIG welding. Difference in strength essentially depends on the composition of the welded alloy. While for 1420 alloy it is just 22 MPa, for 1460 and 1202 alloys is 52 and 71 MPa, respectively. This is due to the features of weld formation at TIG welding and FSW. Formation of a solid-phase joint as a result of displacement of plasticized metal in a limited volume at excess pressure promotes grain refinement, increase of volume fraction of boundaries and intermetallic phase fractionation. In fusion welding coarse grains of cast weld metal solidify from the weld pool melt at a low rate of its cooling (Figure 3).

Samples with a reinforcement produced by TIG welding, always fail in the FZ of the weld with the base metal, and have a higher strength than samples without reinforcement failing in the weld metal. However, compared to samples made by FSW, their ultimate strength can be higher (1420), lower (1201) or be on the same level (1460), depending on the properties of the welded aluminium alloy.

In conclusion it should be noted that strength of welded joints of ductile low-alloyed aluminium alloys made by FSW and TIG welding is practically on the same level, as samples fail in the HAZ, where the degree of metal softening is the same.

Deformation strengthening of welds occurring at FSW of high-strength complex-alloyed aluminium alloys AMg6M, 1420, 1201 and 1460 provides a higher level of their strength than that of samples without reinforcement made by TIG welding.

Displacement of plasticized metal at excess pressure in a limited space at FSW promotes formation in the weld central part of a nugget with an ultrafine structure, and in the ZTMI formation of curved elongated and equiaxed grains oriented in the direction of tool displacement. Grain refinement, increase of volume fraction of their boundaries and fragmentation of intermetallic phases in welds at FSW of aluminium alloys promotes a lowering of their softening level compared to TIG welding.

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CONTROL SYSTEM FOR BEAM SCANNING IN ELECTRON BEAM WELDING

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The microprocessor-based control system for scanning of the electron beam in electron beam welding and software for graphical design of scans are described. The system makes it possible to implement the scans with an arbitrary resultant distribution of the electron beam power density in the welding zone. Design of a scan comprises setting a path and instantaneous power of the electron beam at each point, and imaging the resultant distribution of the beam power density. The program of changes in deflection coil currents is automatically calculated.

Keywords: *electron beam welding, electron beam scanning, microprocessor-based controller, graphical computer design of scan*

Properties of the electron beam (low lag and wide range of power adjustment) allow producing the welding heat sources with arbitrary surface distribution of the power density within the welding zone. The electron beam can provide an almost unlimited diversity of welding, heat and dimensional treatment parameters, as well as probing of a welded joint. Moreover, probing, welding and heat treatment can be performed simultaneously with the same beam. However, these advantages of the electron beam can be implemented in full only by using the electronic automation equipment. Comparatively many analogue-digital electronic devices providing periodic electromagnetic deflection of the electron beams for welding [1, 2] and heat treatment [3, 4] are available. Their drawbacks are low accuracy, complicated adjustment and limited functional capabilities. The electron beam units are often equipped with simple instrument sine-cosine generators.

Digital systems for periodic deflection of the electron beam are more perfect technically. Special shapes of periodic voltages in such systems can be formed by soft- or hardware. Every control computer used to equip the majority of advanced electron beam welding (EBW) units allows programming of almost any pattern of time variations of the electron beam deflection signal. However, frequency of such a signal is limited to tens of hertz, and the whole computer is loaded only with these functions.

These problems can be solved much simpler by hardware. The required program of one period of deflection of the electron beam is saved in read-only memory (ROM). The frequency-controlled code generator successively addresses the ROM cells, and code of the electron beam electromagnetic deflection, which is saved in them, is converted by a digital-analogue converter (DAC) into a proportional analogue voltage [5, 6]. The key drawback of these generators is inconveniency in programming of ROM. To re-program ROM, it is necessary to remove the ROM chip from the panel, place it to a programmer, and save to it a new program preliminarily prepared on the computer. It is time-consuming and very inconvenient in practice.

Modern microcontroller systems intended for programmed control of deflection of the electron beam and fitted with special software for computer design of scans are free from all these drawbacks.

Block diagram of the microcontroller generator of scans is shown in Figure 1. Control part of the system is based on CYGNAL microcontroller C8051F022. Standard serial interface RS-232 provides communi-

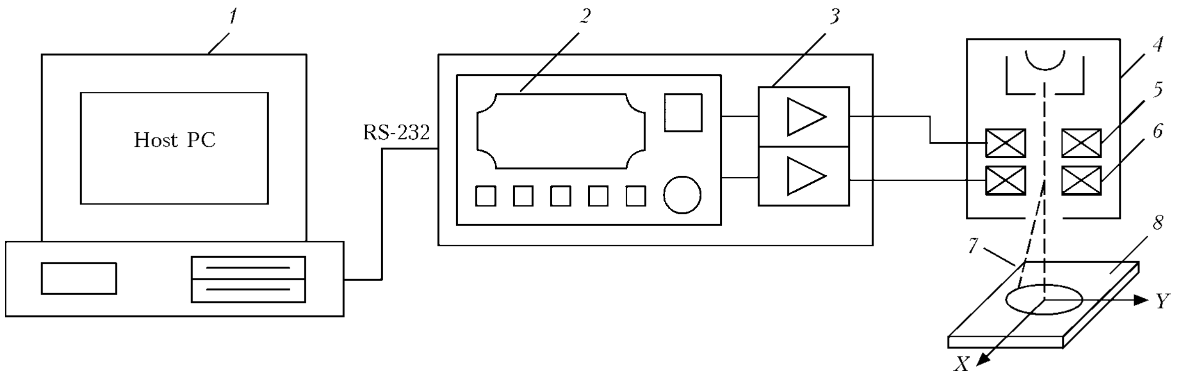

Figure 1. Block diagram of electron beam scanning controller for welding: *1* ---- computer; *2* ---- controller; *3* ---- power amplifier; *4* ---- electron beam gun; *5* ---- coil for deflection of electron beam by axis *X*; *6* ---- coil for deflection of electron beam by axis *Y*; *7* ---- electron beam; *8* ---- workpiece

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Figure 2. General view of electron beam scanning controller for welding

cation with the computer. Up to 32 programs can be loaded from the computer to microcontroller via this interface, after which it can operate off-line. If communication with the computer is continuous, the quantity of programs is practically unlimited. It takes a few milliseconds to save a program in the controller, and saving can be performed even during welding.

Being part of the microcontroller, DAC devices provide conversion of the digital scan code into analogue voltages, which are fed to high-power voltage–current converter *3* (Figure 1). The controller is fitted with its own controls to correct the scan amplitude separately by coordinates X and Y and simultaneously by both coordinates XY, adjust scan frequency F, and choose any of scans P saved in the controller memory. All current ancillary information, such as the scan number, relative scan amplitude by each coordinate and scan frequency, is indicated on the multiline liquid-crystal display. General view of the controller is shown in Figure 2.

The «Scan Design» software is meant for rapid graphical design of the path of movement of the beam over the heating surface caused by periodical electromagnetic deflection in EB welding and heat treatment. Periodical deflection of the electron beam is usually provided by setting the pattern of time variations of the electric current in deflection coils of the system for electromagnetic deflection of the electron beam gun. Relation of the electron beam path to the deflection coil current involves no problem only in the simplest cases of circular and linear scanning. This system makes it possible to design not only the path of the electron beam, but also the intensity of heating at any point of the path. In addition, in design it is possible to view a resultant distribution of the electron beam power density within the heating region by allowing for the finite values of radius of the electron beam. The screen of computer design of a scan is shown in Figure 3.

The path of the electron beam is displayed in square window «Electron Beam Path» (see Figure 3) with relative sizes of ±128 by coordinates X and Y. The electron beam takes successively 16 positions within

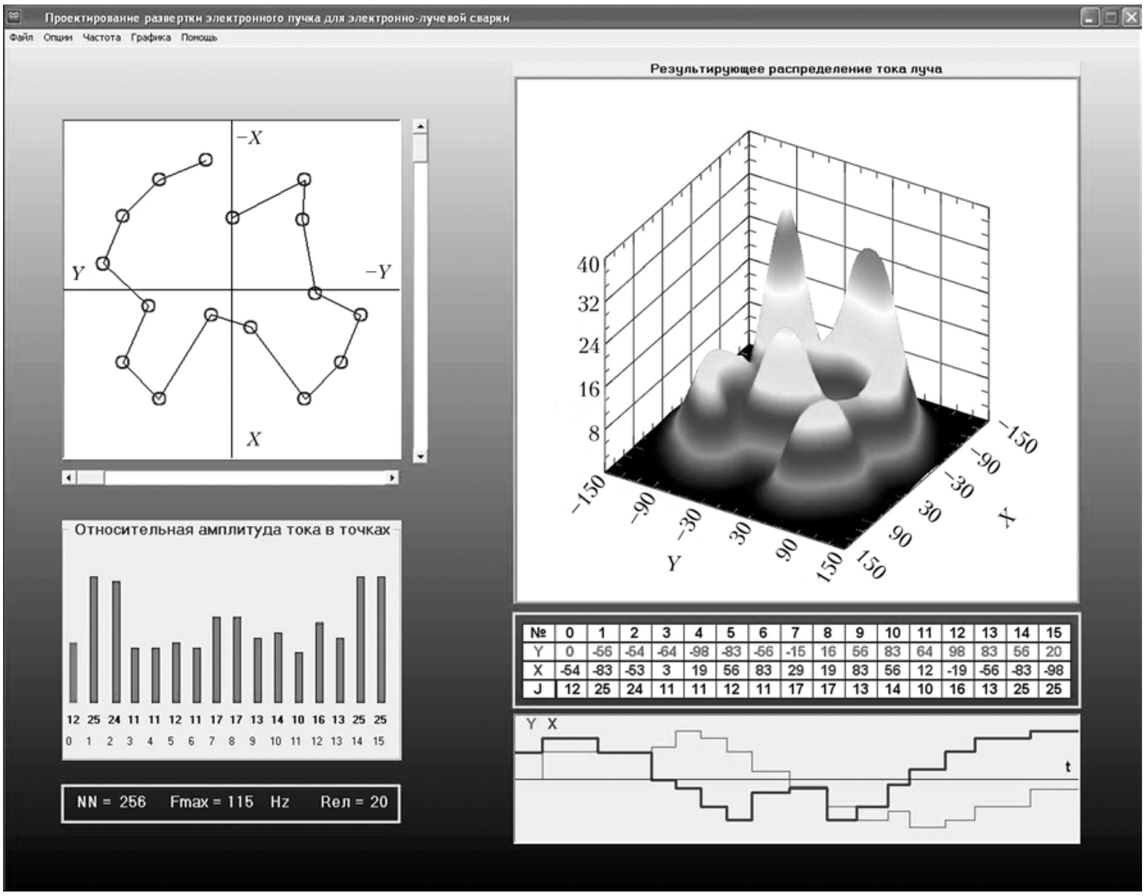

Figure 3. Screen for computer design of scanning

the region of its impact per cycle of periodical scanning. Stop position of the beam at each of the 16 points of the path is displayed in the form of a small-diameter circle. Movement of the beam from one point to the other is shown by connecting straight lines. Position of each point of the beam in a scanning cycle is set by dragging its image with the mouse to any location of the «Electron Beam Path» window. Digital value of coordinates of each point is indicated in a corresponding cell of the Table shown in Figure 3. Therefore, in a general case the electron beam may have any path.

Intensity of the thermal effect of the electron beam at each point is determined from a relative time of dwelling in it, i.e. by part of the scanning period during which the beam stops at a given point. A change in the relative time of dwelling of the electron beam at a point is equivalent to a relative change of the beam current at the given point with an identical time of its dwelling at each point. Naturally, for this the electron beam scan frequency should be sufficiently high. The time of dwelling of the beam at each point is set with certain discrete value Δt. Total number N of time intervals in one scanning period T is set by the program from 16 to 256. The scanning period may be varied from $16\Delta t$ to $256\Delta t$. The minimal value of Δt is determined only by the circuit design and elemental base of the scanning controller being used. For example, for the described controller based on CYGNAL microcontroller C8051F022, the minimal value of Δt is 40 μs, and it can be increased with an increment of 40 μs to 4 ms.

In addition to the minimal value of Δt determined by the controller, the real maximal scanning frequency depends upon the inductance of the deflection coils, supply voltage of the deflection coil current amplifier and set scanning amplitude. The lower the inductance of the deflection coils, the higher the supply voltage, and the smaller the scanning amplitude, the higher is the maximum possible scanning frequency.

Relative density of the beam current is adjusted by varying the amplitude of a corresponding column of the columnar diagram by means of dragging the column top with the mouse. The relative density of the current (quantity of time intervals) in the rest of positions of the electron beam is automatically re-calculated, so that the scanning period remains unchanged. The quantity of the time intervals in each position of the electron beam (relative current density) is indicated in a column of the columnar diagram and in corresponding cell J of the table in Figure 3.

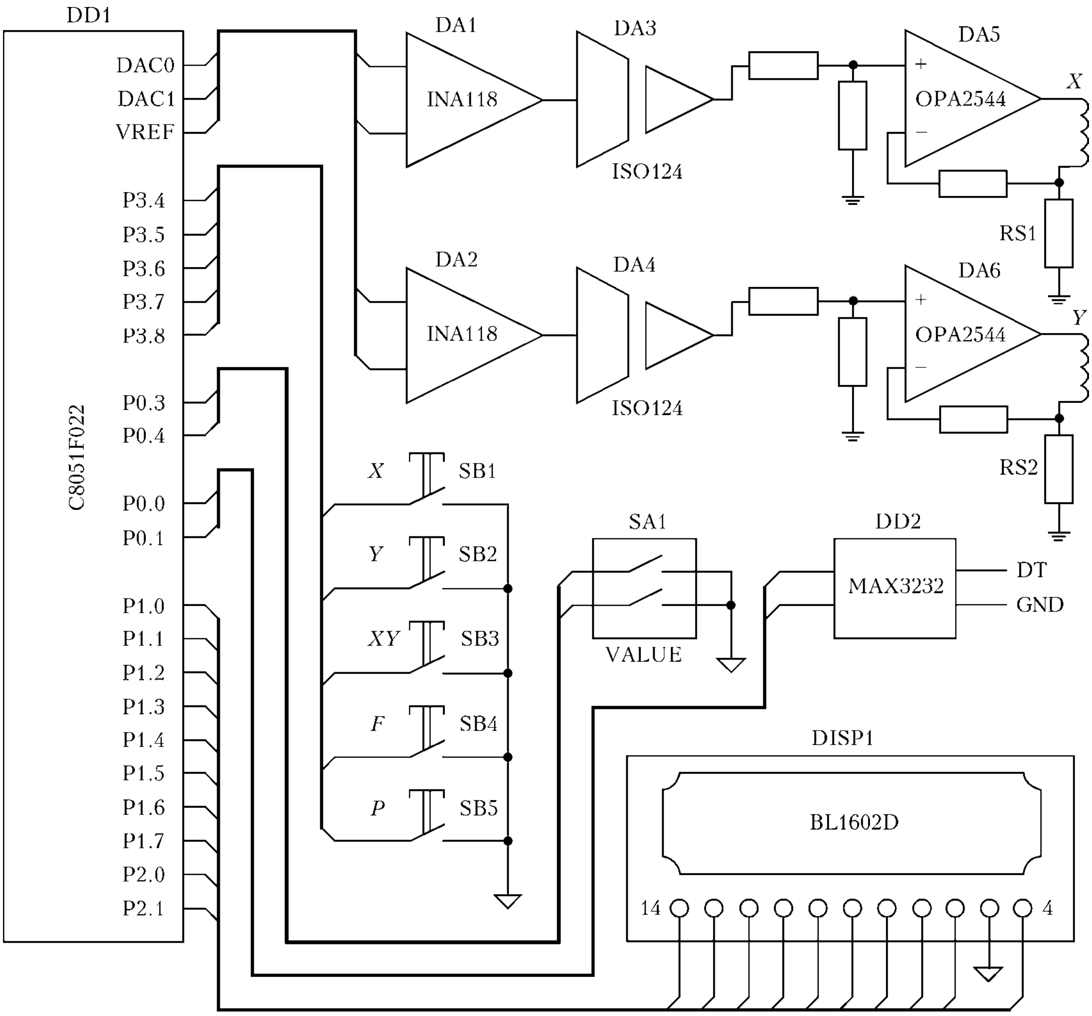

Figure 4. Functional scheme of electron beam scanning controller for welding

Owing to the thermal lag of the heating surface, the thermal effect of the periodically deflected electron beam is equivalent to the effect of a sum of 16 fixed beams distributed over the heating surface. The sum of currents of the equivalent fixed beams is equal to the current of the periodically deflected electron beam, whereas the current of each beam is proportional to the relative time of dwelling of the beam in a corresponding stop point. Therefore, according to the thermal effect, the periodically deflected electron beam can be represented as a fixed electron beam with a complex transverse distribution of the current density.

Analysis of the diagrams showing distribution of the current density of such a beam gives much more information for prediction of the electron beam thermal effect than analysis of the curves of the deflection coil currents, which is the case in normal practice. Resultant equivalent distribution of the current density shown in 3D diagram in the «Resultant Distribution of Beam Current» window is calculated as follows.

Electron beam power density $j(x, y)$ in the first approximation can be considered normal-circular:

$$j(x, y) = J_m \exp\left(-\frac{x^2 + y^2}{r_b^2}\right), \quad (1)$$

where J_m is the current density amplitude; r_b is the current density variance; and y, x is the distance from the beam centre to a given point.

The resultant current density due to an impact by the 16 simultaneously acting electron beams with amplitudes J_{mj} at points x, y will be

$$\bar{j}(x, y) = \sum_{i=1}^{16} J_{mi} \exp\left(-\frac{(x - x_i)^2 + (y - y_i)^2}{r_b^2}\right), \quad (2)$$

where J_{mi} is the current density amplitude at the i-th stop point of the beam; $J_{mi} = J_i/N$; J_i is the quantity of time intervals Δt of dwelling of the beam in its i-th stop point; N is the total quantity of time intervals in a scanning period; and x_i, y_i are the coordinates of the i-th stop point of the beam.

The real resultant current density of a scanned beam depends upon the radius of the beam in the welding plane. To obtain a more realistic image of the resultant distribution of the beam current in the beam-affected zone calculated from equation (2), the relative value of electron beam radius r_b is set in the «Beam Radius» window from the «Options» menu.

To make analysis of the resultant distribution more convenient, its image can be turned by changing the tilt angle and azimuth.

The designed scan is saved to a file by the «Save» command from the «File» menu, and to the controller — by the «Send to Controller» command from the «File» menu.

Deflection of the designed scan beam is saved to a file and controller PROM by the «Save» command.

Functional scheme of the microprocessor controller is shown in Figure 4. Analogue voltages of the scan from DAC outputs DAC0 and DAC1 of microcontroller DD1 come to inputs of coupling instrument amplifiers DA1 and DA2. Isolating amplifiers DA3 and DA4 provide galvanic isolation of control and power parts of the controller. High-power operational amplifiers DA5 and DA6 connected into the circuit with a deep negative output current feedback convert the scan voltages into the deflection coil currents. Buttons SB1–SB5 serve to select the parameter to be changed. Pulse rotation transducer SA1 with indication of direction is used to change the value of the selected parameter. The amplitude and frequency of scanning are adjustable from 100 % to 0 with a step of 1 %.

Microcircuit DD2 provides conversion of the levels of voltages of serial controller to computer communication interface RS-232.

CONCLUSIONS

1. The microprocessor generator of scans of the electron beam in the off-line operation mode allows reproduction of up to 32 saved scans of any level of complexity.

2. In communication with the computer via a serial interface, the quantity of the reproduced scans is practically unlimited. Replacement of a reproduced scan by any other from the computer can be done during welding with no interruption of the process.

3. Desirable distribution of density of the beam current within the heating zone and path of movement of the beam are set in scan design. Programs of variations of currents in the deflection coils are automatically calculated from them.

4. Selection of the electron beam path allows affecting not only the resultant distribution of density of the beam power, but also the hydrodynamic processes occurring in the weld pool, especially at low scan frequency.

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FEATURES OF CURRENT INVERTER DESIGN

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Features of current inverter operation are studied. Functional dependence of the duration of half-period (in radians) of the current inverter oscillation process on circuit Q-factor was derived. Performed analytical calculations of inverter current are presented in the graphic form in different systems of coordinates. A new design procedure was developed and new frequency-time characteristics of current inverters were calculated.

Keywords: *current inverter, heat treatment, complex frequency, resonance frequency, angular frequency, Q-factor, oscillatory circuit, characteristic resistance, half-period duration, working frequency, power balance*

At present inverter power sources are more and more widely used in different industries, including welding and related technologies. Their advantage consists not only in reduction of weight and overall dimensions and cost of active materials of the power source, but also in an essential improvement of controllability and quality of the technological processes.

Inverter power sources with conversion frequency of 1–3 kHz and high output power measured in tens and hundreds of kilovolt-amperes are widely used at present for heat treatment of welded joints and various metal structures by induction heating. Despite intensive progress of inverter engineering, the issue of development of high-quality and reliable power sources for heat treatment remains to be urgent, which is due to the requirements made of the power sources (relatively high power, duty cycle, operating conditions).

Powerful inverters for heat treatment were developed predominantly on the basis of parallel type inverter (current inverter), the principal diagram of which is given in Figure 1.

In order to improve the technical and operational characteristics of such converters (particularly, in terms of improvement of their controllability and reliability), a circuit of a new powerful inverter for heat treatment was developed, which is designed for operation both under the stationary and field conditions. Preliminary analysis of this circuit demonstrated its superiority over the known engineering solutions in many respects. It was, however, necessary to perform thorough analysis of the occurring transient processes. Design procedures for such inverters available in scientific-technical publications give only a general characteristic of the electromagnetic processes in the inverters and are not suitable for development of mathematically substantiated algorithms of their control. In order to successfully solve the defined problem, a new procedure was developed for design of such inverters with mathematically accurate equations of current and voltage in all the inverter elements. In this case several problems had to be solved.

The first was related to a rational selection of elementary functions, describing the transient processes in the inverter power source circuit. It came from the fact that in some publications, descriptions of transient processes in inverters widely use hyperbolic trigonometric functions — predominantly sines and cosines [1, 2]. On the other hand, hyperbolic functions are completely absent already in the first versions of expressions derived by the author for current and voltage in the inverter circuits. The known manual on electrical engineering [3] gives a certain mathematical proof of the irrationality and even incorrectness of these functions application for description of oscillation processes in RLC-circuits. Hyperbolic sines or cosines appear in equations, describing aperiodic processes. Mathematical description of periodic oscillation processes requires application of periodic functions, which is what regular trigonometric sines and cosines are. The more so, since they almost automatically appear when solving differential equations, provided Euler's formulas are used here. Further on the author strictly observed the classical solution of the composed differential equations without application of hyperbolic functions [4].

The second problem is connected with selection of an optimum method of solution of the initial differential equations. For capacitor voltage u_c the final differential equation has the form of

$$\frac{d^2}{dt^2}u_c + \frac{R}{L}\frac{d}{dt}u_c + \frac{1}{LC}u_c = \frac{RI}{LC}. \qquad (1)$$

As is seen from (1), the characteristic equation in our case is not in any way different from that for the

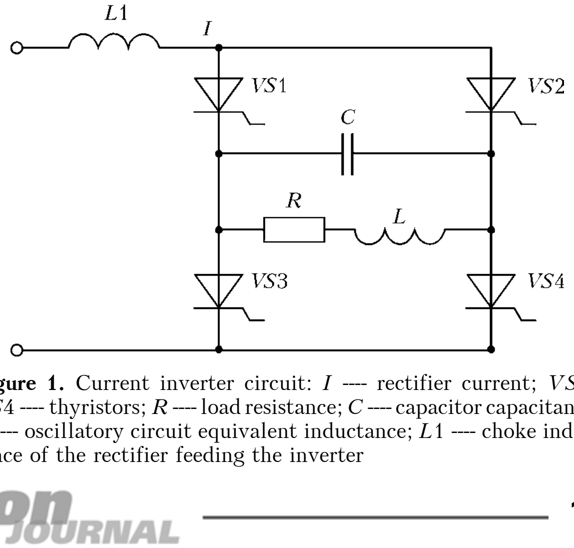

Figure 1. Current inverter circuit: I — rectifier current; $VS1$–$VS4$ — thyristors; R — load resistance; C — capacitor capacitance; L — oscillatory circuit equivalent inductance; $L1$ — choke inductance of the rectifier feeding the inverter

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series inverter. Other initial conditions in a current inverter, however, make solution of this equation much more complicated. The author came to the conclusion of the need to go back to the source of derivation of the finished mathematical expressions described in publications. All the solutions of the initial differential equations were derived using complex frequencies of natural oscillations, while their further transformations were performed in a complex shape.

Transition from the obtained expressions in a complex form to the conventional exponential and trigonometric functions was performed only at the final stage. With this purpose four most typical and most often encountered complex functions were used, which are a mathematical combination of roots of a characteristic equation and their exponential functions. In the absence of errors the final transition from complex functions to elementary functions is performed at complete disappearance of imaginary numbers, which was used as the most important criterion of the correctness of solution of the initial differential equations.

The third problem is related to transformation of the derived expressions to an illustrative and demonstrative level, suitable for further practical application. In order to simplify the derived expressions a new variable is traditionally introduced, namely phase angle $\theta = \omega t$, where ω is the angular (circular) frequency of the oscillatory circuit allowing for attenuation, and t is the real time. It was also possible to somewhat simplify the derived expressions by introducing into them the Q-factor of inverter oscillatory circuit as the second variable. All the currents and voltages of the oscillatory circuit were expressed in relative units.

The following values were taken as the basic unit values: $I = 1$ — current of the source powering the inverter; $\rho = 1$ — characteristic resistance of the oscillatory circuit. The following values were taken as unit values of voltage and power: $U = I\rho = 1$ and $P = I^2\rho = 1$. Thus, current and voltage in inverter circuits are given in relative units as functions of two variables, namely phase angle θ and Q-factor of oscillatory circuit.

In view of the absence of an accurate design procedure of even such simplified circuits of current inverters (see Figure 1), it was decided to ignore the actual thyristor properties at this stage, and consider switching time to be zero. Assuming instant switching of thyristors in the calculations is justified and even necessary, in order to clarify the natural properties of the current inverter.

At the change of time t from 0 to $T/2$ (where T is the period of steady-state oscillations of current inverter under load) phase angle θ changes from zero to θ_m. In other words, θ_m parameter is a half-period of inverter oscillation process, expressed in radians. In electrical engineering alternating current circuits and in various oscillatory circuits the oscillation process half-period in radians is usually equal to π. However, despite the thorough checking of the differential equation correctness, analysis of the first derived results of their solution showed that is we assume $\theta_m = \pi$, then matching of the initial and final conditions and completion of the design become impossible. This most often occurs at a mismatch between the assumed mathematical conditions and the real physical processes. In this connection, it was decided to consider parameter θ_m to be an unknown value, which depends on other inverter parameters and should be determined. After that matching the initial and final condition and obtaining the sought solution did not present any particular difficulties, which is also a kind of a criterion of the correctness of the intermediate calculations. During further transformations a transcendental equation was derived, establishing a functional dependence between values θ_m and Q:

$$\frac{\mathrm{tg}\theta_m}{\sqrt{4Q^2-1}} + \frac{1 + \left(\cos\theta_m + \dfrac{\sin\theta_m}{\sqrt{4Q^2-1}}\right) e^{-\theta_m/(\sqrt{4Q^2-1})}}{1 + \left(-\cos\theta_m + \sqrt{4Q^2-1}\,\sin\theta_m\right) e^{-\theta_m/(\sqrt{4Q^2-1})}} = 0. \quad (2)$$

A simple and effective procedure of computer solution of the derived transcendental equation was optimized for a unique determination of θ_m parameter as a function of the Q-factor. To check the correctness of computer calculation of θ_m parameter, some reference points were determined by the method of successive approximations in a programmable calculator. The derived dependence $\theta_m(Q)$ was used to perform further transformations to derive acceptable expressions of currents and voltages in inverter circuits. It should be emphasized that at all these stages purely mathematical transformations and simplifications, and not neglecting any values in view of their smallness, were performed. More over, additional verification of the derived expressions by adding infinite Q-factor to them and their transformation into simple and visual equations for an ideal oscillatory circuit were conducted at all the stages. As a result, mathematically accurate equations were derived, describing changes of currents and voltages in inverter circuits. Verification of final expressions for currents and voltages by the procedure of calculation of power balance was performed in the computer in MathCAD program, obtaining a complete equality of input power consumed from the current source and released in the load. This confirms the validity of the derived analytical dependencies, as well as the correctness of all the performed calculations. By the way, the author did not find any work on inverters, where the expressions for current and voltage, containing hyperbolic sines and cosines, were checked by the method of calculation of power balance. It is probable that application of hyperbolic sines and cosines for description of the oscillation process in current inverters can be attributed to the fact that the duration of oscillation half-period in radians was erroneously regarded as a constant value, always equal to π, whereas there exists a certain mathematical dependence of this duration on circuit Q-factor. Thus, the earlier conclusion on incorrectness of application of hyperbolic sines and cosines for description of the oscillation process found one more specific mathematical confirmation.

Let us consider some results of the performed investigations. Analysis of $\theta_m(Q)$ dependence, given in Figure 2, showed that at increase of the oscillatory circuit Q-factor above minimum critical value ($Q >$ > 0.5) duration of oscillation half-period in radians drastically decreases, and at $Q_2 = 1.124$ it reaches the minimum value $\theta_{min} = \theta_m(Q_2) = 2.319$. At further increase of Q-factor, values of studied parameter $\theta_m(Q)$ rise monotonically, and at $Q \to \infty$ $\theta_m(Q) \to$ $\to \pi$, as expected. Several numerical values of parameter $\theta_m(Q)$ are also given below:

Q	1	2	4	10	50	200	1000	10000	100000
$\theta_m(Q)$	2.323	2.375	2.505	2.683	2.911	3.021	3.086	3.124	3.136

Thus, the most important characteristic of parallel oscillatory circuit incorporated into the current inverter is established, namely duration of the half-period of the oscillation process in radians, which depends on the circuit Q-factor and varies in the range of $\theta_{min} \le \theta_m(Q) \le \pi$.

Hence the question: why in parallel oscillatory circuits of the current inverter is the duration of oscillation process half-period $\theta_m(Q)$ always smaller than π and why is it expressed by a rather complex mathematical dependence on the Q-factor, whereas in series oscillatory circuits of voltage inverter this half-period does not depend on the Q-factor and is always equal to π? And at the same time the angular frequency $\omega(Q)$ in both the cases is determined by one and the same dependence

$$\omega(Q) = \omega_0 \sqrt{1 - \frac{1}{4Q^2}}. \qquad (3)$$

This has a certain physical explanation. In a series oscillatory circuit the current varies by a known law of exponentially attenuating sinusoidal function and angular duration of the oscillation half-period in radians, irrespective of the attenuation degree, is always equal to π. Connection of constant voltage source to series oscillatory circuit does not lead to any qualitative changes in the nature of the transient process. It remains the same, as in the capacitor discharge to an active-inductive load.

The situation is totally different in the considered circuit of current inverter. Connection of the current source to parallel oscillatory circuit causes qualitative changes in the nature of the transient process and shortening of the duration of oscillation half-period to certain $\theta_m(Q)$ value occurs. Thus, the derived expression $\theta_m(Q)$ expresses not only the properties of the parallel oscillatory circuit proper, but also of its external connection circuit, determining the nature of energy flowing into this circuit from the current source.

Let us use the method of complex amplitudes to consider the shortening of the duration of current inverter oscillation half-period. Electric current in the

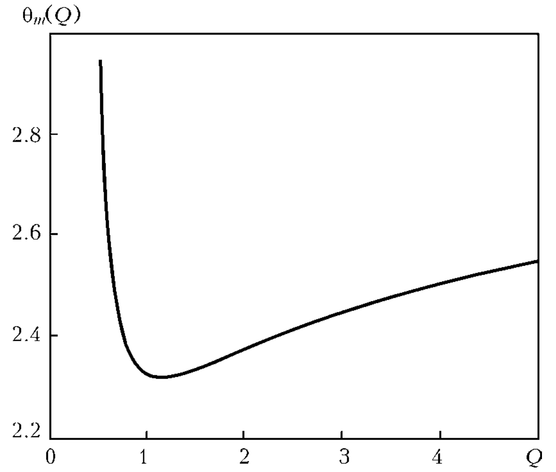

Figure 2. Dependence of duration of oscillation half-period in current inverter, θ_m, on Q-factor

load can be presented in the form of a vector rotating counter-clockwise at a certain angular velocity. Real instantaneous value of current is equal to the projection of this vector onto the real axis at a certain moment in time. In an ideal oscillatory circuit without losses the velocity of current vector rotation is determined by angular resonance frequency ω_0. At finite Q-factor of the oscillatory circuit, i.e. availability of losses, the velocity of current vector rotation decreases and is determined by angular frequency $\omega(Q)$ from equation (3). At unchanged Q-factor of the oscillatory circuit, angular velocity $\omega(Q)$ of current vector rotation remains constant. However, the amplitude of this vector changes in time. The nature of this change is determined by two factors. Energy losses in the load result in decrease (attenutation) of current vector amplitude. However, as a result of energy flowing into the oscillatory circuit from the current source the rotating vector amplitude increases. At the start of the half-period at $\theta = 0$, the current vector is located on the real axis and its projection onto this axis is equal to its amplitude. By the moment of the end of the half-period, angle of rotation of the current vector is equal to $\theta_m(Q)$ in radians. However, its amplitude increases as a result, so that its projection on the real axis is equal to the initial amplitude of current vector, taken with an opposite sign. Projection of the current vector on real axis at the end of the half-period is taken to be the new current vector at the start of the next half-period after the next switching of the thyristors. The new current vector begins the stage of its revolution through angle $\theta_m(Q)$. Thus, the studied process cannot be described using the current vector, continuously rotating with angular frequency $\omega(Q)$. There are individual periodically recurring angular sectors of $\theta_m(Q)$, within which the current vector rotates at constant angular velocity of $\omega(Q)$. Transition from one sector to another (at thyrisotr switching) is accompanied by a jump-like change of the current vector amplitude and phase.

In its dimension, parameter $\theta_m(Q)$ is directly related to angular frequency $\omega(Q)$, which appears when solving differential equations with application of com-

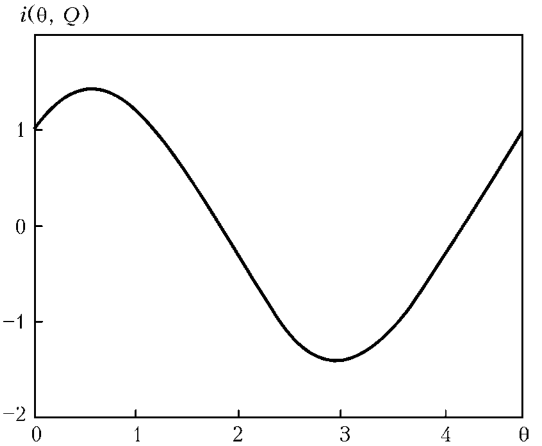

Figure 3. Dependence of load current $i(\theta, Q)$ on phase angle θ at circuit Q-factor of 2

plex frequencies of natural oscillations. Applied mathematical method of oscillation process investigation offers a polar system of coordinates, in which the studied current vector rotates at a constant angular frequency $\omega(Q)$ determined only by oscillatory circuit parameters. All the changes in the oscillation process caused during one half-period by active energy losses (attenuation), as well as energy feeding into the oscillatory circuit, may affect only the amplitude of this rotating current vector. Value $\theta_m(Q)$, considered by us to be the oscillation process half-period, turns out to be less than π, as it is determined by the properties of the entire inverter as a whole, and is actually measured in the initial polar co-ordinates assigned by the parameters of just the oscillatory circuit. It is generally believed that the period of rotation of any vector is equal to 2π, where 2π is the radian measure of the circumference. In our case period $2\theta_m(Q)$ is not equal to 2π. We have already explained the reason for appearance of this inequality by the fact that during thyristor switching in the current inverter there is no continuous rotation of the vector, but there occur periodical rotations of the vector through certain angle

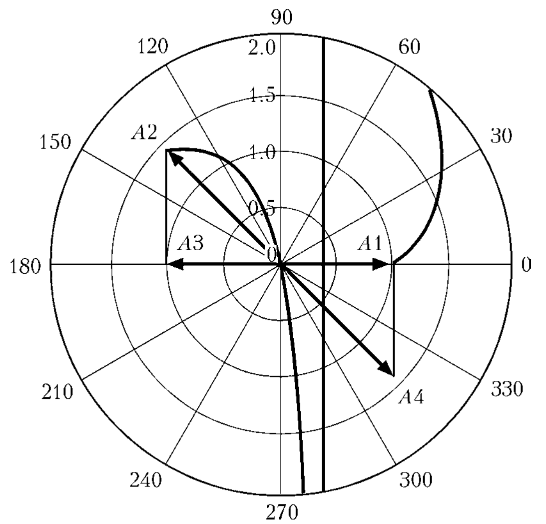

Figure 4. Dependence of amplitude of rotating current vector $A(\theta, Q)$ on phase angle θ at Q-factor of 2: $A1$ — initial position of current vector; $A2$ — final position of current vector after its rotation through angle $\theta_m(Q)$ and respective change of amplitude; $A3$ — projection of $A2$ vector on real axis ($A3 = -A1$)

$\theta_m(Q)$ with subsequent change of the initial conditions. This apparent contradiction can be eliminated, if we go into another polar system of coordinates, where the new current vector is rotating continuously with a certain increased equivalent angular frequency ω_e and period of its rotation is 2π. Then the real value of the period of steady-state oscillations of the current inverter in seconds can be given by the generally known dependence $T = 2\pi/\omega_e$. Direct numerical determination of ω_e presents considerable difficulties. Further on it will be shown how angular parameter $\theta_m(Q)$ can be used to readily calculate the new equivalent angular frequency ω_e of the current inverter.

Thus, a mathematical dependence of current inverter half-period $\theta_m(Q)$ was derived, which is unambiguously determined only by the Q-factor of its oscillatory circuit. Value $\theta_m(Q)$ does not depend on current powering the inverter, but, nonetheless, it simultaneously reflects those qualitative changes, which occurred in the oscillatory circuit under the impact of the current source. Therefore, a certain value of duration $\theta_m(Q)$ of the oscillation process half-period is a new most important characteristic parameter of inverter current, and a certain key element for its further analytical calculations. $\theta_m(Q)$ value allows deriving accurate mathematical equations of currents and voltages in all the current inverter circuits, calculating the required real frequency-time and energy parameters, natural external characteristics, as well as developing optimum algorithms of current inverter control.

Figure 3 gives the dependence of current in the load $i(\theta, Q)$ on phase angle θ during one half-period at circuit Q-factor equal to 2, while duration of current half-period $2\theta_m(2) = 4.75$, which is much smaller than 2π.

Dividing $i(\theta, Q)$ by $\cos\theta$, we will get expression $A(\theta, Q) = i(\theta, Q)/\cos\theta$ for determination of the amplitude of rotating current vector, used to describe the oscillation process in the studied inverter according to the method of complex amplitudes. The derived dependence $A(\theta, Q)$ is given in Figure 4 in polar co-ordinates and graphically illustrates the transient process in the current inverter. A complex law of variation of the current vector amplitude during the half-period can be noted. After the next thryistor switching, real current value $A3$ in the load is taken as its initial value, and the next half-period of the inverter oscillation process begins. Vector $A3$ will rotate through angle $\theta_m(Q)$ and will turn into vector $A4$, the projection of which onto the real axis is equal to $A1$. It is obvious that $A4 = -A2$. By that the full period of the current inverter oscillation process is completed.

Let us move over to calculation of new frequency-time parameters of the current inverter. As $\theta_m(Q) = \omega(Q)T(Q)/2$, we obtain a formula for determination of the real period of steady-state oscillations of the current inverter in seconds:

$$T(Q) = \frac{2\theta_m(Q)}{\omega(Q)}. \tag{4}$$

It is easy to prove that at $Q = \infty$ (i.e. for an ideal oscillatory circuit without losses) formula (4) gives the known expression $T(\infty) = 2\pi/\omega_0 = T_0$. From this formula we will derive an expression for determination of new equivalent angular frequency $\omega_e(Q) = 2\pi/T(Q)$ as a functional dependence on Q-factor:

$$\omega_e(Q) = \omega(Q)\,\frac{\pi}{\theta_m(Q)} = \omega_0\,\frac{\pi}{\theta_m(Q)}\sqrt{1 - \frac{1}{4Q^2}}. \qquad (5)$$

In the new system of co-ordinates the current vector rotates continuously with angular velocity ω_e and its phase angle varies in time by formula $\theta_e = \omega_e t = \theta/k$, where $k = \theta_m(Q)/\pi$, and $\theta = \omega t$ is the phase angle in the previous system of co-ordinates. New dependence of current in the load $i_e(\theta_e, Q)$ on phase angle θ_e can be derived from dependence $i(\theta, Q)$ presented in Figure 3, if we substitute $\theta_e k$ instead of angle θ. The current form will not change, and current period $i_e(\theta_e, Q)$ in radians will be equal to 2π. Amplitude dependence $B(\theta_e, Q) = i_e(\theta_e, Q)/\cos(\theta_e)$ of a continuously rotating current vector on angle θ_e in the new co-ordinate system is given in Figure 5 for comparison.

In the new system of co-ordinates the results of analytical calculations are reduced to the traditional concept of the oscillation process period in radians being equal to 2π. For this purpose it was necessary to move beyond the initial system of co-ordinates, which is determined directly by the oscillatory circuit parameters and is at the basis of all the calculations made. In this initial system of co-ordinates the period of the oscillation process in the studied current inverter is not equal to 2π. Thus, investigations performed by the author do not contradict, but just complement and precise the widely known fundamental classical knowledge on this subject.

The real frequency of steady-state oscillations of the current inverter is equal to

$$f(Q) = 1/T(Q) = \omega(Q)/2\theta_m(Q). \qquad (6)$$

Relative frequency of steady-state oscillations of current inverter $f_1(Q) = f(Q)/f_0 = \omega_e(Q)/\omega_0$ can be expressed as follows:

$$f_1(Q) = \frac{\pi}{\theta_m(Q)}\sqrt{1 - \frac{1}{4Q^2}}. \qquad (7)$$

Dependence $f_1(Q)$ is calculated and shown in Figure 6. For comparison the same Figure gives the dependence of relative oscillation frequency on Q-factor for the series oscillatory circuit

$$f_2(Q) = \sqrt{1 - \frac{1}{4Q^2}}.$$

As is seen from Figure 6, both the dependencies asymptotically approach a unity at $Q \to \infty$, however $f_2(Q)$ approaches it from below, and $f_1(Q)$ approaches it from above, with $f_1(Q) > f_2(Q)$ in all the cases. This is indicative of the fact that increase of the inverter current frequency as a result of shortening of the duration of the oscillation process half-period prevails over the decrease of this frequency as a result of attenuation. Thus, at current inverter analysis and calculation the determined $\theta_m(Q)$ dependence is not only of a great qualitative, but also quantitative importance, as it allows an essential improvement of the accuracy of calculations of all the required frequency-time and energy parameters.

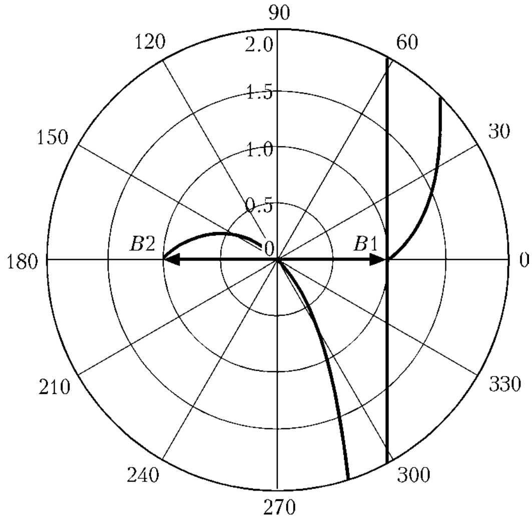

Figure 5. Dependence of amplitude $B(\theta_e, Q)$ of equivalent current vector on phase angle θ_e at $Q = 2$: $B1$, $B2$ — positions of current inverter at $\theta_e = 0$ and $\theta_e = \pi$, i.e. at moments of thyristor switching (here $B1 = -B2$)

It is known that if the Q-factor of the oscillatory circuit is smaller than critical value $Q_0 = 0.5$, the oscillation process changes to an aperiodic process. Dependence $f_1(Q)$ gives additional characteristic values of Q-factor of the parallel oscillatory circuit of the current inverter, which should be taken into account.

Thus, $Q_1 = 0.766$ is the Q-factor of the current inverter oscillatory circuit, at which the relative inversion frequency $f_1(Q_1) = 1$, i.e. current frequency in the oscillatory circuit despite the losses is equal to resonance oscillation frequency of an ideal circuit without losses. Value $Q_1 = 0.766$ can be taken as the minimum possible value of working Q-factor. However, a larger rated value of Q-factor needs to be selected ($Q_2 = 1.124$), particularly at unstable load. This is necessary so that even at maximum increase of load resistance, for instance, as a result of transient processes, the minimum value of Q-factor did not drop below Q_1. Otherwise, at $Q < Q_1$ an abrupt lowering of inverter operating frequency occurs, that may lead either to disturbance of the technological process proper,

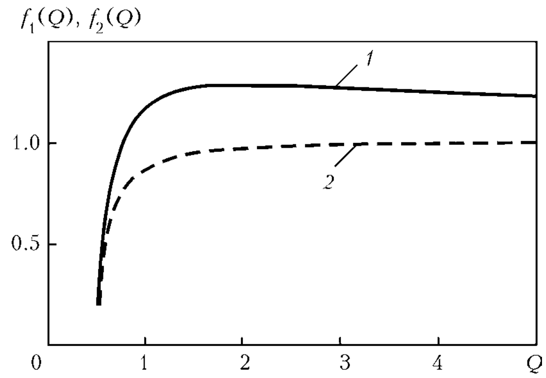

Figure 6. Dependence of relative oscillation frequency of current $f_1(Q)$ (*1*) and voltage $f_2(Q)$ (*2*) inverters on Q-factor

Comparative parameters of parallel and series inverters

Parameter	Current inverter	Voltage inverter
ω_0	$2\pi f_0$	$2\pi f_0$
$\dfrac{\omega(Q)}{\omega_0}$	$\sqrt{1 - 1/4Q^2}$	$\sqrt{1 - 1/4Q^2}$
T_0	$\dfrac{2\pi}{\omega_0}$	$\dfrac{2\pi}{\omega_0}$
θ_m	$\theta_m(Q)$	π
$T(Q)$	$\dfrac{2\theta_m(Q)}{\omega(Q)}$	$\dfrac{2\pi}{\omega(Q)}$
$\dfrac{f(Q)}{f_0}$	$\dfrac{\pi}{\theta_m(Q)}\sqrt{1 - 1/4Q^2}$	$\sqrt{1 - 1/4Q^2}$

or to further lowering of the Q-factor to critical value $Q = 0.5$ and complete violation of a stable inversion cycle. Range of Q-factors $Q_1 < Q < Q_2$ can be regarded as a division section between stable ($Q > Q_2$) and insufficiently stable ($Q < Q_1$) inversion modes.

Value $Q_M = 2$ is another determined characteristic value of Q-factor of the parallel oscillatory circuit as part of the current inverter, providing maximum relative frequency of the oscillation process $f_M = f_1(Q_M) = 1.28$. If characteristic resistance of oscillatory circuit $\rho = (L/C)^{0.5}$ remains unchanged, then at $Q_M = 2$ it is possible to determine the value of load resistance, at which the maximum relative frequency of inverter operation is achieved:

$$R_M = \rho / Q_M. \quad (8)$$

Matching of any value of real load resistance to its calculated value R_M is performed using a high-frequency power transformer.

Thus, the derived dependencies $\theta_m(Q)$ and $f_1(Q)$ allow performing optimum selection of current inverter Q-factor. Q-factor values above 50 are usually characteristic for radio engineering circuits. In this connection, we do not consider them, although the derived dependencies remain valid for all the Q-factors. For welding and other powerful industrial current inverters, it is desirable to have minimum values of Q-factor in order to lower the power of the circuit power elements. However, at load resistance fluctuations, the circuit should have a certain margin of oscillation process stability. Derived dependence $f_1(Q)$ provides a mathematical substantiation of selection of the range of current inverter working Q-factors, Q_w:

$$1.5 < Q_w < 3.0. \quad (9)$$

A characteristic feature of this range of Q-factors is a slight change of inverter working frequency. Characteristic value of Q-factor, $Q_M = 2$, of current inverter, at which the relative increase of inverter frequency is maximum, is in the same range. Deviations of load resistance from R_M value within certain ranges of Q-factor variation ($1.5 < Q < 3.0$) do not lead to any significant changes of inversion frequency. For constant stable load working Q-factor can be below 1.5 and can be close to Q_2.

Results of calculation and analysis performed for comparison of frequency-time properties of parallel and series inverter are summarized in the Table. As is seen from the Table data, the first three parameters of inverter current and inverter voltage are calculated in absolutely the same way. Their appearance is due to the generally accepted mathematical method of solving the initial differential equations using complex frequencies of natural oscillations. In the last three parameters duration of oscillation process half-period, expressed in radians and equal to number π for the series oscillatory circuit of voltage inverter, is replaced by a complex mathematical dependence $\theta_m(Q)$, calculated by the author for a parallel oscillatory circuit of the current inverter. It is used to perform the transition to real frequency-time parameters of the current inverter.

Thus, the obtained dependencies promote a more profound understanding of the very essence of the occurring physical phenomena in the current inverter circuit, performing correct selection and calculation of the inverter power section and its elements. Proceeding from these dependencies, it is easy to create substantiated control algorithms of inverter thyristors, both at its starting and during operation when forming the required external characteristics, which is not against the natural running of transient processes in inverter elements.

Based on the established and determined functional dependence of $\theta_m(Q)$, accurate analytical expressions of current, voltage and power were developed. This enabled a deeper insight into the current inverter energy parameters, and plotting its natural external characteristics. The author plans to present a more detailed analysis of these issues in his next work.

CONCLUSIONS

1. The derived functional dependence of the duration of half-period of working frequency $\theta_m(Q)$ on circuit Q-factor is the key element for calculation of all the parameters of the current inverter.

2. The proposed new procedure of current inverter design provides the required frequency-time parameters, as well as accurate analytical expressions for current and voltage, the accuracy and validity of which is confirmed by the method of calculation of power balance.

3. The revealed distinctive features of operation of a parallel oscillatory circuit as part of the current inverter, enable proposing and calculating its new characteristic parameters.

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PECULIARITIES OF APPLICATION OF SPLIT TEE-JOINTS IN REPAIR AND RECONSTRUCTION OF MAIN PIPELINES IN SERVICE CONDITIONS

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The effect of thickness of walls of the connecting elements, internal pressure during installation, and distance between the circumferential welds that connect a tee-joint to pipeline on geometric dimensions of the above welds was studied. Nomograms were plotted to determine allowable pressure in hydraulic tests of the resulting welded joints, depending upon the length of an installed tee-joint and rigidity of a pipeline. Examples of application of the design and technological solutions are given.

Keywords: *main pipeline, split tee-joint, circumferential welds, internal pressure, hydraulic tests, rigidity of shells, implementation of technological developments*

Appropriate procedures at a designing stage as well as in service conditions guaranty the safe operation of main pipelines and their reliable uninterrupted functioning. Proper organization of periodical technical diagnostics of the state of main pipeline elements and repair of detected inadmissible defects are of high importance in this direction among the service procedures. Around 42,000 km of main pipelines are functioning in the territory of Ukraine. According to statistics, approximately 5000--6000 defects are detected by periodical diagnostics of the state of pipelines per 100 km of their length. Significant part of the detected defects is inadmissible and requires repair. Classical repair of a pipeline associated with its stoppage, cleaning and replacement of defective regions is costly and accompanied by significant ecological disturbances. Therefore, methods for repair of pipelines without their removal from operation are intensively developed all over the world. Such methods are of a particularly high importance for Ukraine, in view of a very high concentration of population in areas of running of main pipelines and their long length. This problem is studied by a range of scientific and industrial organizations of the country, among which the E.O. Paton Electric Welding Institute of the NAS of Ukraine, Ivano-Frankovsk National Technical University of Oil and Gas, Sub-Company «Ukrtransgaz» should be noted.

One of the directions of advancement of the repair technologies is development of design-and-technological solutions and equipment, allowing joining of branch pipes to connect new consumers or small deposits to the main line, or replace long defective areas of a pipeline without its removal from operation by joining a temporary line (bypass) for a period of performing repair operations.

Design-and-technological schemes. As a rule, a bypass and four split tee-joints are used for replacement of defective regions in main pipelines (Figure 1).

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Straight-through tee-joints with a ratio of diameters equal to $d/D \leq 0.7$, which are installed directly on a pipeline by using technological rings, are employed in a case of connection of the bypass. Flush tee-joints (ratio $d/D = 1$), which are assembled on the pipeline by using technological transition ring spacers, are used for installation of closing devices. Their quantity is determined depending on the geometric parameters of the pipeline. Scheme of installation of such split tee-joints on the pipeline with the help of welding and their designs are shown in Figure 2.

In contrast to the technologies proposed by TDW and British Gas companies, in this case the split tee-joints are welded to the pressurised pipeline by using the overlap butt joints [1], instead of the fillet ones. This provides a number of advantages. A range of admissible heat inputs in welding of overlap butt joints is wider than in simple cladding or making of the fillet welds, which, in turn, allows regulating parameters and properties of the HAZ metal. In this connection, safety of performance of welding operations on a pressurised pipeline [2] and operational reliability of the resulting welded joints during in-

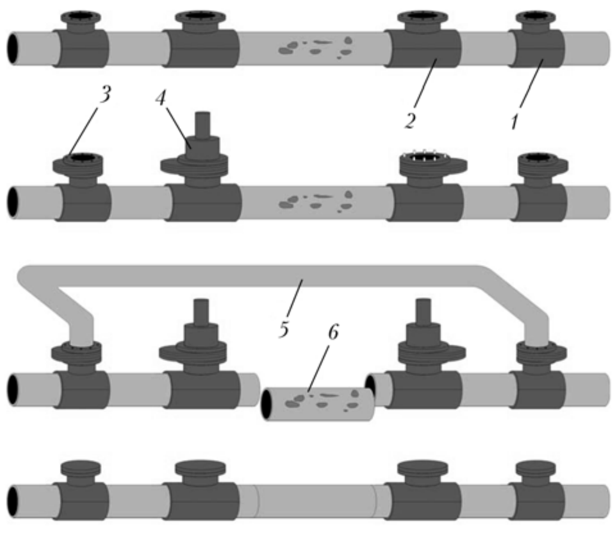

Figure 1. Scheme of replacement of defective regions of main pipelines: *1, 2* ---- transition and flush tee-joints, respectively; *3* ---- flat gate valve; *4* ---- closing device; *5* ---- bypass; *6* ---- defective region

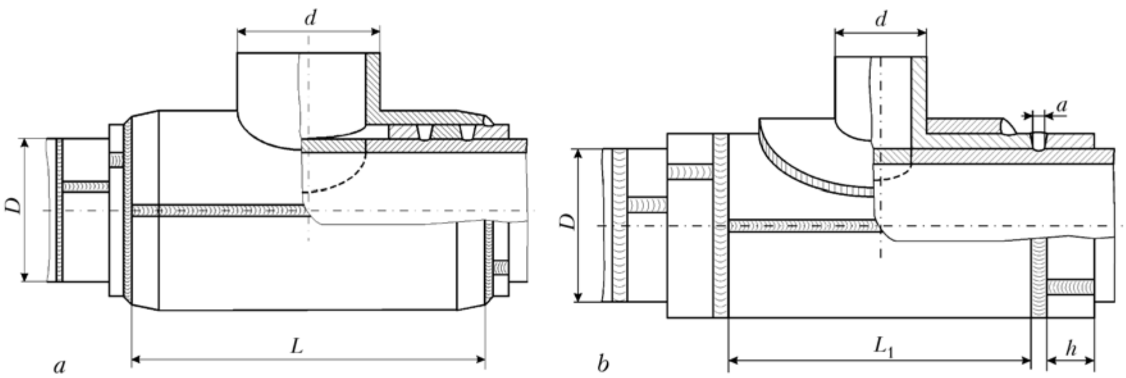

Figure 2. Schematics of split tee-joints: *a* ---- flush; *b* ---- transition (D and d ---- external diameters of the pipe and branch pipe, respectively); *a* ---- width of circumferential weld to pipe fusion zone; L ---- length of split tee-joint; L_1 ---- distance between circumferential welds; h ---- width of technological ring

crease. As experimentally proved, welded joints made by the proposed scheme have much higher shear stresses and bend resistance than the conventional fillet welds.

Besides, a change from fillet to overlap butt joints increases a fatigue limit of welded assemblies under repeated static loading by more than 50 %. This is attributable to reduction of the level of stresses in the weld to pipe wall fusion zone due to local restriction of bending strains in a loaded structural element.

The scheme of bypass line connection through the nipple--coupling welded assembly (Figure 3) is used in Ukraine for pipe branches with a diameters ratio of $d/D \le 0.5$. Such a scheme is patented in Ukraine and Russia. The structure comprises a split coupling, in one part of which a hole is made for the nipple welded to the pipeline through a previously deposited multilayer bead and connected with the coupling with a fillet weld.

The nipple--coupling welded assembly can be installed to connect new consumers or small deposits of hydrocarbon products to the main line, as well as to cut out crack-like defects from the wall of a pressurised pipeline. As a rule, cutting of holes in the pipelines is carried out by a mechanical method using a slotted mill though a globe valve or flat gate valve [3].

Calculation of circumferential welds. The split tee-joint to pipeline welded assemblies are subjected

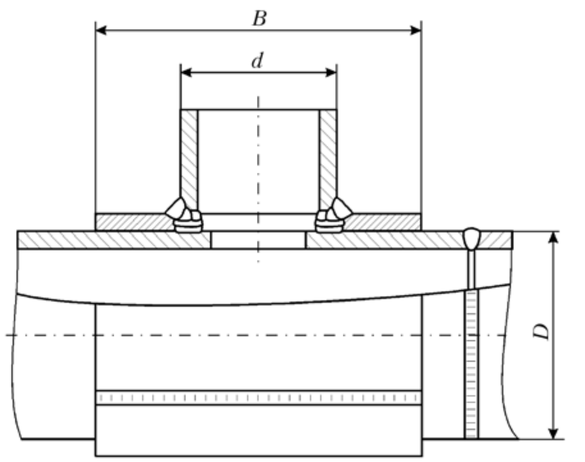

Figure 3. Schematic of nipple--coupling assembly: B ---- width of split coupling

during service to loads of a different character, which are caused by a change of internal pressure in the pipeline, variations of an ambient temperature, landslides etc. This makes it necessary to determine the required and sufficient size of a load-carrying part of the circumferential welds (width of the fusion zone of the weld which joins the tee-joint to the pipeline), so that they can withstand all the loads in operation of the pipeline.

Several ways of installation of the split tee-joints on the pipeline with or without pressure, and different conditions of holes cutting in the pressurised pipeline were considered in study [4]. In addition, the influence of design (fillet or overlap butt) of the split tee-joint to pipeline welded assemblies on ultimate values of geometric parameters of the welds was investigated. Calculations for determining the load-bearing capacity of such welds confirmed the advantage of the proposed overlap butt welds.

The task of the present study was to determine the ultimate geometric sizes of the circumferential welds in overlap butt split tee-joint to pipeline welded assemblies depending upon the internal pressure during installation and subsequent decreasing the pressure to zero.

Mathematical algorithm developed on the basis of the fracture mechanics criteria was used for determination of the required size of a load-bearing part of the welds depending upon the different input welding parameters and conditions. It provides the possibility to evaluate and forecast performance of different structural schemes used to connect shell elements to the pipeline by taking into account the presence of a natural stress concentrator in the form of interlayer gap 2ρ (sharp cavity), which is formed during installation of shells on the pipe surface and their welding with the circumferential welds.

According to studies [4, 5], the limiting state of the welded joints under static loading was determined by a two-parameter criterion of brittle-ductile fracture of material.

The following assumptions were made for solving the elastoplastic problem on determination of the above minimum permissible sizes of the welds, in accordance with the method described in [4]: the

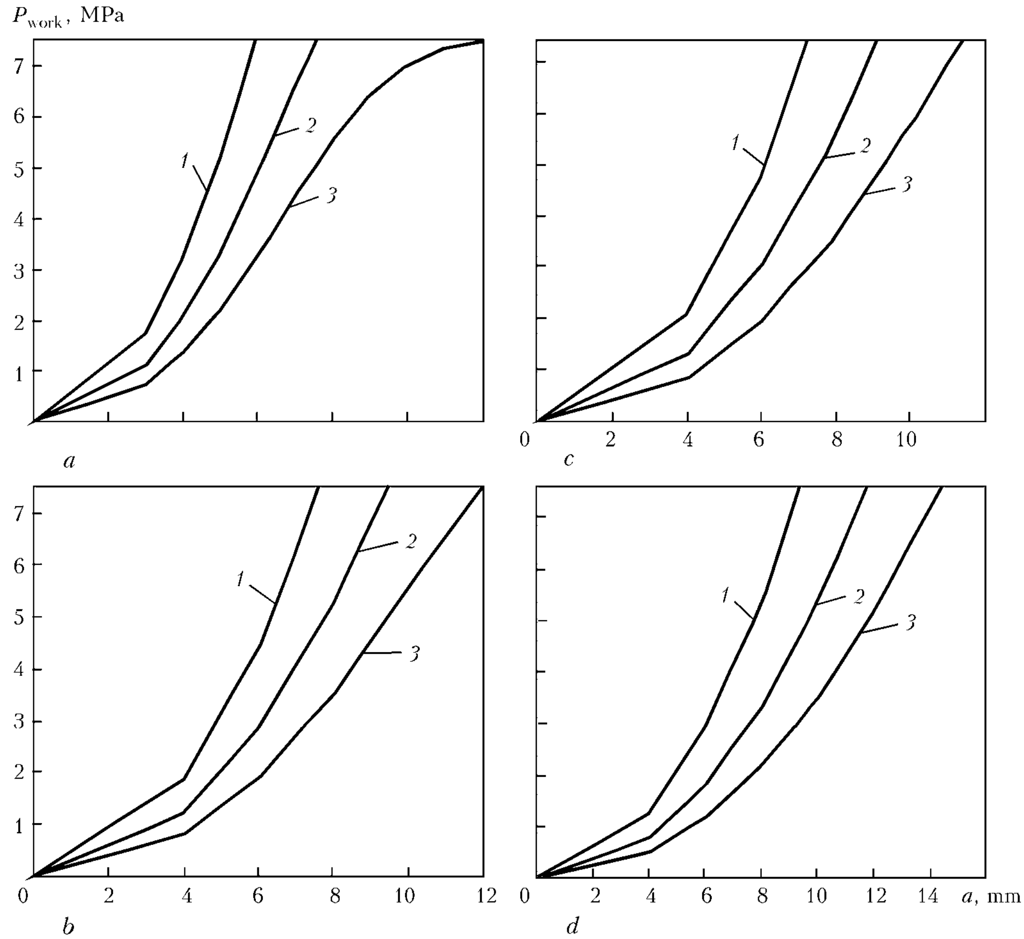

Figure 4. Dependence of calculated width a of circumferential weld fusion zone on internal pressure P_{work} at the moment of tee-joint installation: *a, c* ---- t_2/t_1 = 1; *b, d* ---- 2; *a, b* ---- t_1 = 10; *c, d* ---- 16 mm; *1* ---- Dn 700; *2* ---- Dn 1000 at L_1 = 1000 mm; *3* ---- Dn 1400 mm

axysymmetric case was considered, the influence of plastic deformations near the apex of a sharp cavity was disregarded, and stresses induced by the welding thermal cycle were ignored either.

The following input data were used for the calculations: pipeline material ---- 17G1S type pipe steel; elasticity modulus $E = 2\cdot10^5$ MPa; Poisson's ratio μ = = 0.3; σ_y = 360 MPa; σ_t = 510 MPa.

Material of the welded joints is similar in properties to the base metal, except for the K_{Ic} value. K_{Ic} = = 1500--1000 MPa·mm$^{1/2}$ was taken for the weld metal in order to receive conservative estimates of the permissible weld sizes, taking into account a very wide scatter of the experimental data.

Results of the calculations of size a for specific geometric parameters of pipelines and split tee-joints are given in Figures 4 and 5. The ratio of their wall thicknesses and internal pressure in the pipeline in installation of the split tee-joints were taken into account.

It can be seen from the Figures that the a value increases with increase in the pipeline diameter, and that the most intensive increase occurs at a pressure close to the operational one. Increase in wall thickness of a tee-joint wall requires high ultimate values of a. For example, a = 6.0 for the Dn 700 × 10 mm pipe at the t_2/t_1 = 1.0 ratio (t_2, t_1 ---- wall thickness of tee-joint and pipe, respectively), and a = 7.5 mm for the Dn 1000 × 10 mm pipe. The critical sizes change at the t_2/t_1 = 2.0 ratio: a = 7.5 for the Dn 700 × 10 mm pipe, and a = 9.5 mm for the Du 1000 × 10 mm pipe.

The calculated values of a significantly increase with increase in wall thickness of the elements joined (Figure 4, *c, d*). It can be seen from the above-said that width a of the circumferential welds (the zone of fusion with the pipeline wall) takes a significant value in all the cases with increase in rigidity of the tee-joint, particularly in its installation under a working pressure in the pipeline. This results in a large scope of welding operations in assembly of the above structure. Therefore, it is necessary to reduce (as far as possible) the internal pressure in the pipeline before installation of the split tee-joints in order to optimise the technological process and provide reliable performance of the welded assemblies.

Graphic dependences for a range of variants of installations the tee-joints with different ratios of walls thicknesses on the Dn 700 and Dn 1000 mm pipelines under a pressure of 5.5 MPa, with allowance for strength characteristics of metal of the structural elements joined, were plotted for receiving a quality picture of the influence of rigidity of the elements joined on geometric parameters of the circumferential welds. Figure 6 shows that dependence of width a of the circumferential weld on the tee-joint rigidity persists, in general, for both pipeline diameters, i.e. in-

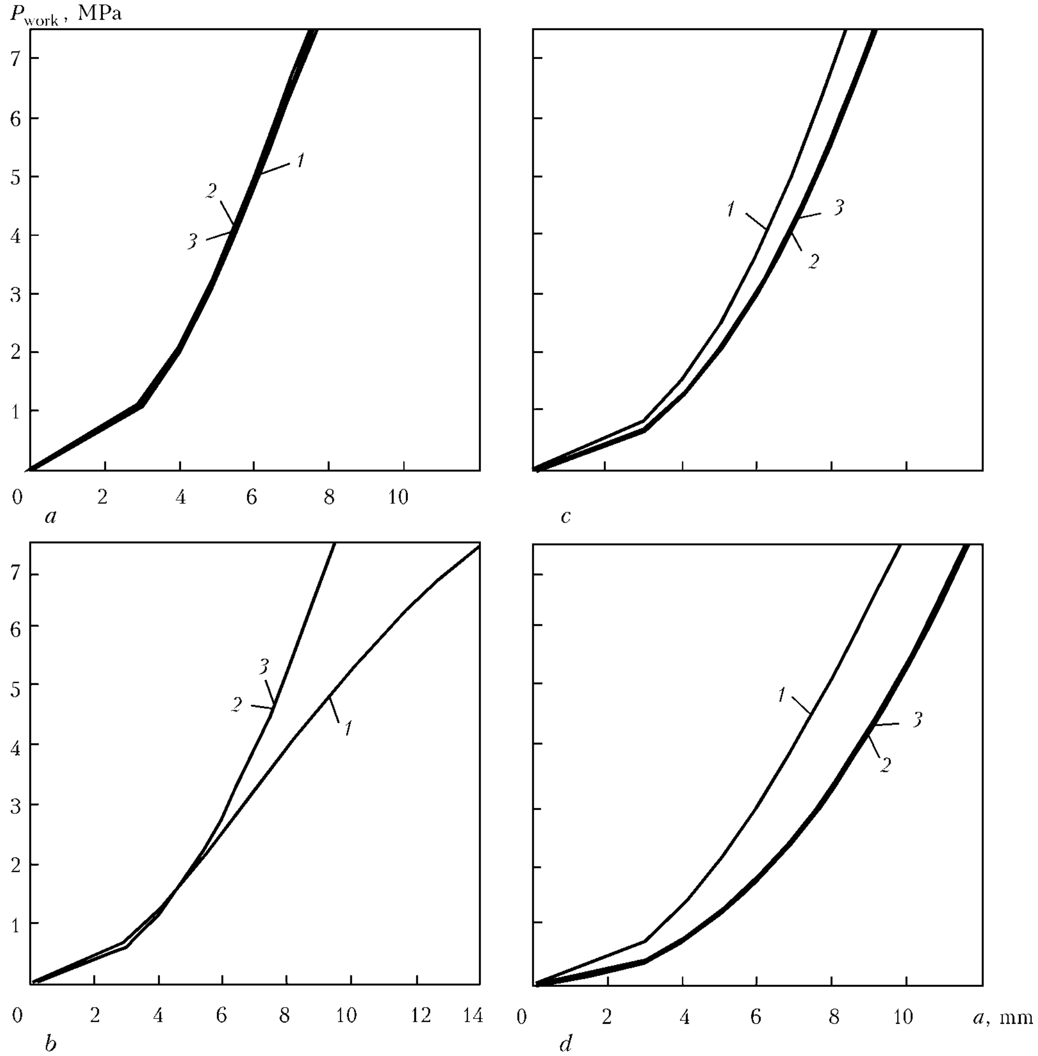

Figure 5. Dependence of calculated width a of circumferential weld fusion zone on internal pressure P_{work} at the moment of tee-joint installation for Dn 1000 mm pipe: *a, c* ---- $t_2/t_1 = 1$; *b, d* ---- 2; *a, b* ---- $t_1 = 10$ mm; *c, d* ---- 16; *1* ---- $L_1 = 200$; *2* ---- 500; *3* ---- 1000 mm

crease of wall thickness of the split tee-joints, which are installed on a running pipeline, results in increase in calculated component a. In this case, the larger the wall thickness of the pipeline, the higher is the a value. As to the influence of the pipeline diameter, it should be noted that the a value for the Dn 1000 mm pipe is higher then for the Dn 700 by 20--30 %. Moreover, increase in strength characteristics of the pipeline metal leads to increase in the above calculated value of width of the circumferential weld to pipe fusion zone.

Therefore, in development of the technology for welding of split joints on running pipelines, where geometric parameters of the circumferential welds calculated for a specific case are set, it is necessary to orient, first of all, to the fact that wall thicknesses of the pipeline and tee-joint are the input data, and that only the internal pressure in the pipeline can be changed towards its reduction for a time of assembly of a structural element.

Determination of permissible parameters of leak and strength hydraulic tests of the welded assembly. In addition to physical inspection methods, the operations on connecting branch pipes to pressurised main pipelines also provide for strength and leak tests of the welded joints between of a tee-joint and pipeline, which are performed before cutting out of a hole. In this case, the level of a test pressure, which is created by water or inert gas between the pipe and tee-joint walls, is varied in ranges of $(1.0\text{--}1.5)P_{work}$, where P_{work} is the working pressure. In some cases it is specified that the test pressure be equal to pressure in the pipeline.

According to the regulations, before starting up a pipeline should be subjected to hydraulic tests under a pressure which induces a load of about $0.95\sigma_y$ in its wall. As is well known, the effectiveness of the tests aimed at evaluation of strength and detection of defects in the pipeline assemblies increases with a rise in load. However, in this case the limiting values of pressure and deformation should be kept to.

The probability of a loss in stability of the wall of the main pipeline should be taken into account for setting the level of the test pressure for the welded joints between the tee-joint and pipeline, as the calculated thickness of wall of the tee-joint exceeds that of the main pipe.

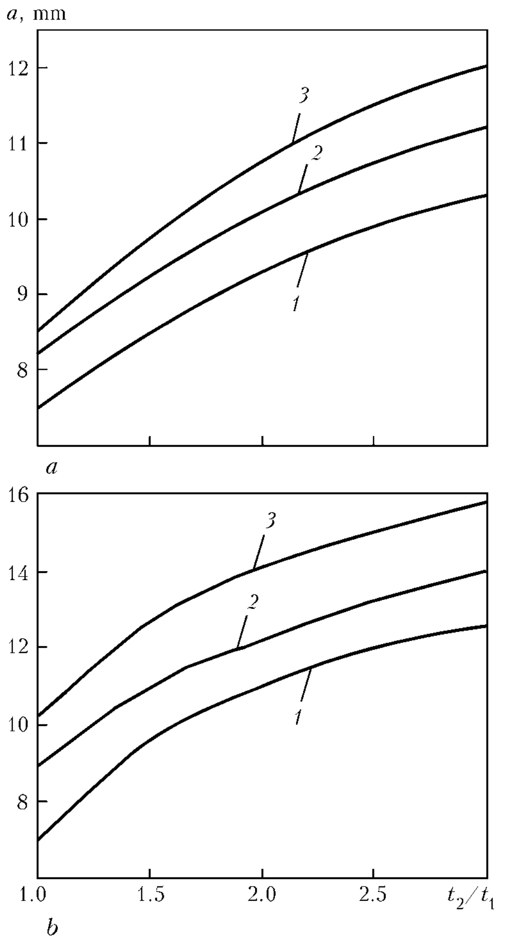

Figure 6. Influence of wall thickness t_2 of tee-joint at fixed wall thickness t_1 of pipe for Dn 700 mm pipeline on the *a* value at P_{work} = = 5.5 MPa, K_{Ic} = 1000 MPa·mm$^{1/2}$: *a* — σ_y = 360; *b* — 440 MPa; *1* — t_1 = 10; *2* — 12; *3* — 14 mm

The upper critical external pressure, at which the pipe wall bulges inside, is determined by the following formula from study [6]:

$$P_{cr} = \frac{D^* R^*}{n^2 - 1}\left\{\left(\frac{\pi^2}{l^2} + \frac{n^2}{R^2}\right)^2 + \frac{1}{R^4}\left[1 - 2\left(\mu\,\frac{\pi^2 R^2}{l^2} + n^2\right)\right]\right\} + \frac{E t_1}{R}\,\frac{\pi^4}{l^4}\,\frac{1}{\left(\frac{\pi^2}{l^2} + \frac{n^2}{R^2}\right)^2 (n^2 - 1)}, \qquad (1)$$

where $D^* = D - t_1$ is the median pipe diameter; R^* = $= 0.5D^*$; l is the pipe length, in this case it is the distance between the circumferential overlap butt welds, L_1. Coefficient n is calculated from formula

$$n = \sqrt[4]{6\pi^2\sqrt{1 - \mu^2}}\ \sqrt{\frac{R^*}{l}}\ \sqrt[4]{\frac{R^*}{t_1}}. \qquad (2)$$

Dependence of the critical pressure, at which the loss in stability of the pipe wall occurs, calculated from formula (1), allowing for the reduced coefficient of the ratio of geometric parameters of the pipe length limited by the two circumferential welds between the tee-joint and pipeline, is shown in Figure 7.

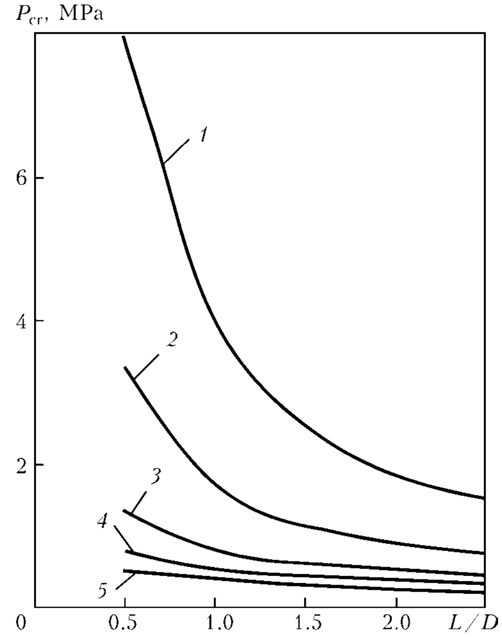

Figure 7. Dependence of critical pressure P_{cr} on pipe geometric parameters ratio L_1/D: *1* — D/t_1 = 40; *2* — 60; *3* — 80; *4* — 100; *5* — 120

It is notable that the value of the external pressure, which causes the loss in stability of the pipe wall, decreases with increase in the pipeline diameter, the wall remaining unchanged. The similar situation takes place with increase in the tee-joint length.

Experimental investigations carried out at test benches, which simulate the real design of a joint between the tee-joint and pipeline, confirm the loss of stability of the internal shell under a much lower pressure than that required for pressure tests of the external shell. Thus, the loss in stability for a shell with the 320 mm diameter, 3 mm wall thickness and 300 mm length takes place at an external pressure of 1.8 MPa, which is in good agreement with the calculation data. Inside bulging of a pipe along the generating line takes place suddenly upon reaching pressure P_{cr}. Then the plastic deformation of metal occurs in the bulging zone without further increase of load. In this case, a bend to the curvature centre increases, formation of other nicks is probable (Figure 8).

Seal failure of the circumferential welded joints was observed only at a value of width of the weld to pipe wall fusion zone equal to $a < 2$ mm and considerable angular deformations.

Thus, it is practically impossible to detect defects in the welded joints between the tee-joint and pipeline by the hydraulic method, as test pressure P_{test} in the pipe spacing should not exceed the internal one P_{in} in the pipeline by a value of critical pressure P_{cr}, which causes the loss in stability of the internal shell ($P_{test} - P_{in} < P_{cr}$). As shown by analysis of the calculations, in welding-assembly operations on a pipeline, involving decrease of the internal pressure down to 30 % P_{work}, the leak test of the welded joints can be carried out at a working pressure ($P_{test} = P_{work}$).

Implementation of developments. Instruction for connection of branch pipes to main gas pipelines and

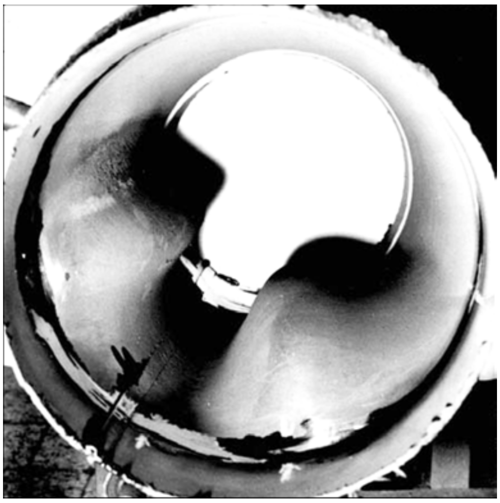

Figure 8. Loss in stability of internal shell (bulging) in internal pressure test

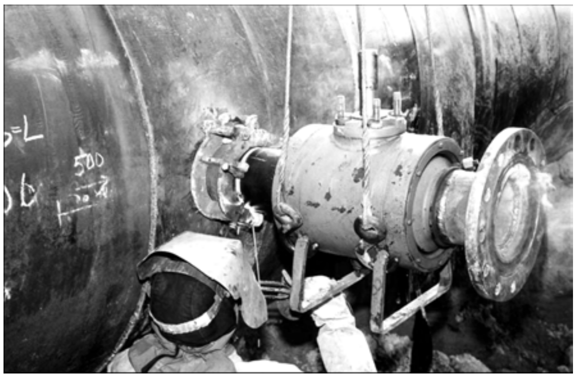

Figure 9. Connection of branch pipe Dn 150 mm to «Soyuz» main gas pipeline Dn 1400 mm under internal pressure of 4.9 MPa

specification VBN V.3.1-0001.3741-07--2007 «Main Oil Pipelines. Methods for Repair of Defective Regions» were developed on the basis of results of the R&D activities of the E.O. Paton Electric Welding Institute in collaboration with Sub-Company «Ukrtransgaz» and Open Joint Stock Company «Ukrtransnafta». These regulatory documents include the following: technological and design diagram of the branch pipe connection assembly; preparation and inspection of a pipe length; sequence of mounting of structural elements on a pipeline; technology for making of welded joints and their inspection by the ultrasonic method; and safety measures to be taken in repair operations.

The technology for connection of branch pipes to main gas pipelines by using the nipple--coupling welded assembly was applied in the «Ukrtransgaz» facilities. Thus, the Company «Lvovtransgaz» carried out works on connection of four distribution gas pipelines Dn 200 mm to main pipeline Dn 1400 mm, and the Company «Prikarpattransgaz» ---- one low-pressure distribution gas pipeline Dn 150 mm to main pipeline Dn 1400 mm for gasification of the near-by settlements (Figure 9).

Analysis of technical condition of the Ukrainian main pipelines confirms the need for development of new methods for their repair and reconstruction without removal from operation. Considerable scope of repair technologies was developed for recovery of the load-bearing capacity of a linear portion of pipelines with corrosion-mechanical damages and intolerable defects in circumferential joints of the pressurised pipelines. These technologies found wide application at the «Ukrtransgaz» and «Ukrtransnafta» facilities.

Still topical is the problem of replacement of extensive defective areas of main pipelines or connection of branch pipes under service conditions, for realization of which split tee-joints are used.

The minimum permissible geometric sizes of the circumferential welds in overlap butt welded joints between the tee-joints and pipeline, depending upon the internal pressure in installation, with allowance for the probable emergency interruption of transferring a product and reset of the pressure to zero, were determined by the calculation method in order to provide performance of a structure.

It was established that width of the circumferential welds should be increased at a pressure close to the working one with increase in the pipeline diameter. Increase of thickness of the tee-joint wall exerts the similar influence. The ratio of thicknesses of the elements welded has a significant influence on sizes of the circumferential welds, whereas influence of the strength characteristics of metal, from which the pipes are manufactured, is lower. Considering that wall thickness of the split tee-joints significantly exceeds that of the pipeline, the calculated width of the circumferential welds should be larger when they are installed on the pipeline with a working internal pressure. This increases the scope of welding operations in assembly of the above structure. Therefore, the internal pressure in the pipeline should be decreased before installation of the split tee-joints to optimise the technological process and provide reliable performance of the welded assemblies.

Hydraulic leak tests of the welded joints between the tee-joints and pipeline showed that the test pressure should not exceed the internal one by a value of the critical pressure at which the probability exists of a loss in stability of the wall of a pipe between the two circumferential welds.

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EFFECT OF DOUBLE-JET GAS SHIELDING ON PERFORMANCE OF WELDED JOINTS ON GL-E36 SHIPBUILDING STEEL

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The effect of double-jet gas shielding on the quality of welded joints on low-alloy shipbuilding steel in multilayer arc welding in gas mixture shielding atmosphere is considered. The possibility of reducing chemical and structural heterogeneities in the joints and improving their mechanical properties is noted.

Keywords: *arc welding, low-alloy steel, multilayer weld, double-jet shielding, chemical composition, hardness distribution, mechanical properties*

One of the main problems of the modern industry is improving technical and economic indices of welded structures by reducing their specific metal content, increasing service reliability, full strength and durability [1]. Improvement of manufacturing technology allowed increasing the level of operating properties of low-alloy and alloyed rolled metal and, first of all, its resistance to cold crack formation. The above steels provide an operating safety of large-size structures, bridge structures, ship hulls and main pipelines [2]. At the same time, it is desirable that the welded joints be characterized by the required technological and operating properties without additional heat treatment [3].

Susceptibility of alloyed steels to embitterment as result of saturation of weld metal with hydrogen [4] and formation of high-temperature chemical micro heterogeneity (HCMH) in the near-weld zone [5] that can be the reason of crack initiation and lead to failure of welded structure at high internal stresses or cyclic external loading is another factor complicating production of the sound full-strength welded joints.

Saturation of the weld metal with hydrogen occurs as a result of long-time dwelling of the weld pool in the liquid phase. This promotes improvement of mixing of the electrode metal with the base one and leads to reduction of HCMH level, structural and strength heterogeneity in the fusion zone [6]. The pulse-dynamic effects, for example, control of transfer of the electrode metal to the weld pool [7] or double-jet gas shielding atmosphere [8--10], etc., can help to reduce the time of dwelling of the weld pool metal in the liquid phase and simultaneously increase the rate of its mixing.

The aim of the present work is to determine the effect of double-jet gas shielding of the welding zone on chemical composition and operating properties of the joints on shipbuilding steel GL-E36.

Investigations were carried out on GL-E36 shipbuilding steel samples 150 × 300 mm in size and 18 mm thick with slot-like grooving (Figure 1), made by using two consumable-electrode stationary-arc welding methods in Ar + 18 % CO_2 gas mixture --- conventional with one-jet gas shielding (first method) and new with double-jet gas shielding (second method) [11].

Welding was performed with low-carbon welding wire Union K52, 1.2 mm in diameter, in accordance with earlier investigations [12]. The following mode was maintained in stationary arc welding: I_w = 185--190 A, arc voltage U_a = 26--27 V, welding speed v_w = = 25--26 cm/min, electrode wire feed speed $v_{f.w}$ = = 6.8--7.0 m/min, and shielding gas flow rate Q = = 11--12 l/min. ESAB Aristo 500 power source and VEB Schwesstechnik Finsterwalde BEM 5 201.05 automatic welding head were used.

Investigation of chemical composition of the weld metal and steel GL-E36 (Table 1), its structure, impact toughness, hardness distribution in the weld cross-section, and mechanical properties was carried out on produced welded samples (at Otto-von-Guericke-Universitaet Magdeburg, Institut fuer Werkstoff- und Fuegetechnik, Magdeburg, Germany).

As determined as a result of the investigation, decrease of silicon content in the weld metal by 20 % and manganese content by 12 % is observed during welding with the double-jet gas shielding in comparison with welding with the conventional one-jet gas shielding. Decrease in the silicon and manganese content is indicative of the intensity of metallurgical processes occurring in the weld pool, which increases ductility of the welded joints and decreases chemical heterogeneity.

Application of the double-jet gas shielding in combination with the efficient welding mode allows leveling of the values of impact toughness and hardness

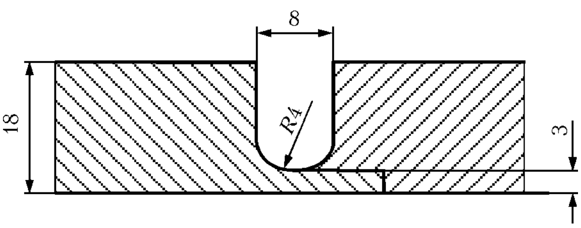

Figure 1. Schematic of slot U-groove

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Table 1. Results of chemical analysis of samples metal, wt.%

Investigated sample	C	Si	Mn	P	S	Cr	Al	Cu	N	Nb	V	Mo	Ni
Steel GL-E36	0.161	0.437	1.25	0.011	0.013	0.030	0.031	0.016	0.006	0.037	0.005	0.025	0.041
Wire Union K 52	0.080	0.850	1.50	0.025	0.025	0.200	--	--	--	--	--	--	0.250
Weld metal with the first welding process	0.098	0.665	1.20	0.013	0.025	0.051	0.004	0.092	0.004	0.002	0.009	0.011	0.037
Same with the second one	0.107	0.531	1.05	0.013	0.023	0.055	0.005	0.081	0.005	0.005	0.005	0.013	0.037

Table 2. Results of investigation of impact toughness and hardness of welded joints

Welding method	*KCV*, kJ/m^2, at --20 °C		*HV*		
	With notch in fusion line	With notch at weld center	Base metal (point *7*)	HAZ (points *4--6*)	Weld (points *1--3*)
First	32--71	98--119	156	175/181/193	194/193/215
Second	49--74	75--81		176/170/175	182/185/178

Note. Points *1--7* see in Figure 2.

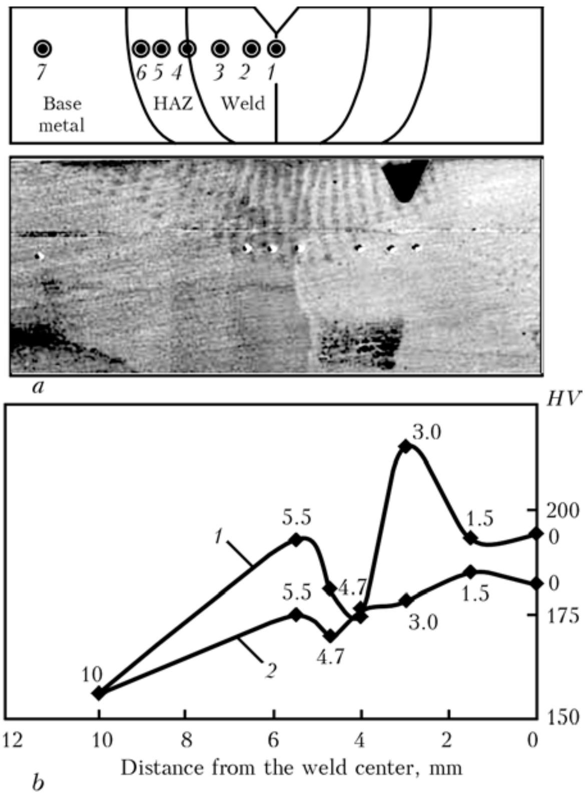

Figure 2. Measurement scheme (*a*) and distribution of hardness *HV* in welded joint cross-section (*b*): *1* ---- first welding process; *2* ---- second welding process

in the welded joint cross-section. The upper limit of the values of impact toughness along the fusion line practically coincides with the low limit at the weld center (Table 2), which also indicates to the intensive mixing of the electrode metal with the base one.

Therefore, the required level of mechanical properties of the weld metal is provided, thus allowing significantly reducing the danger of brittle fracture of the welded joints under the effect of external cyclic loading at low temperatures.

The diagram of hardness distribution (Figure 2) shows that a more uniform hardness distribution is observed in the welded joint cross-section at the double-jet gas shielding, which is another proof of the intensive mixing of the electrode metal with the base one.

It is important that, in comparison with the conventional welding method, the developed one allows avoiding a sharp change of hardness in the regions that are most susceptible to crack formation (fusion line and HAZ metal), which reduces residual stresses and probability of cold cracking.

The results of microstructure analysis (Figure 3) prove that welding with the double-jet gas shielding provides better mixing of the base metal with the electrode one, promotes refining of the weld metal structure, forms a smooth transition from the deposited metal to the base one, and increases full-strength of the welded joint (see Figure 2).

Tensile tests of the specimens were carried out by using equipment of the Zwick company (Table 3) (Otto-von-Guericke-Universitaet Magdeburg, Insti-

Table 3. Results of mechanical tensile tests of welded joints

Test object	$\sigma_{0.2}$, MPa		σ_t, MPa	
	First process	Second process	First process	Second process
Welded joints on steel GL-E36	$\frac{327\text{--}340}{334}$	$\frac{337\text{--}345}{341}$	$\frac{471\text{--}479}{475}$	$\frac{479\text{--}481}{480}$
Steel GL-E36	355		490--620	
Wire Union K 52	420--450		540--570	

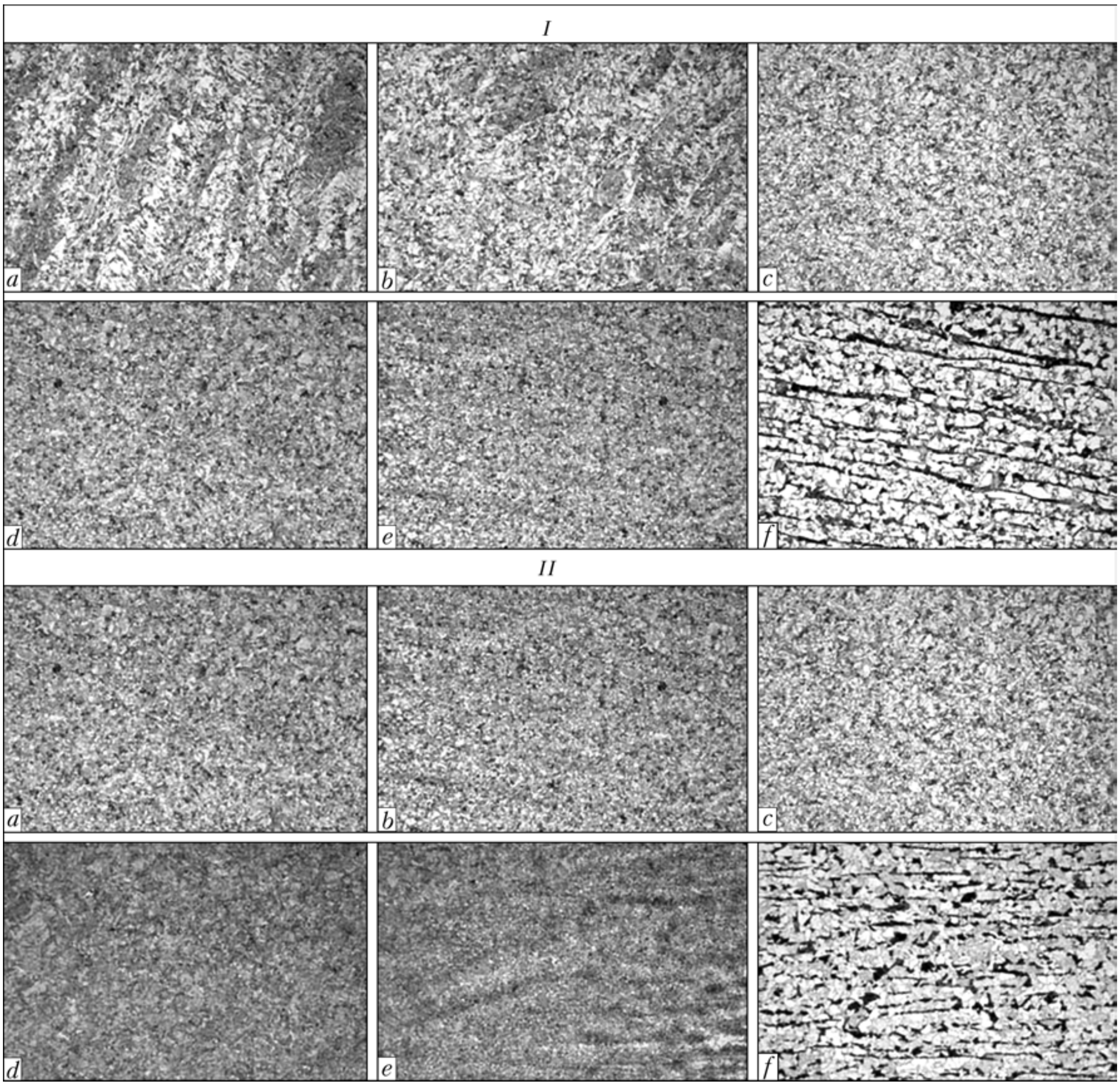

Figure 3. Microstructure (×140) of welded joints on shipbuilding steel GL-E36 produced by the first (*I*) and second (*II*) welding process: *a* ---- weld metal; *b* ---- fusion line; *c* ---- overheating region; *d* ---- normalization (recrystallization) region; *e* ---- partial recrystallization region; *f* ---- base metal

tut fuer Werkstoff- und Fuegetechnik, Magdeburg, Germany).

Comparative analysis of mechanical properties of the welded joints on steel GL-E36 with different types of the gas shielding front (Table 3) showed the stability and quality of performance of the welding process by the first and second methods. The tensile strength values of the specimens obtained by the two welding processes are close because of their close hardness values in the weakening zone, the hardness distributions in the cross-section being substantially different, as fracture always occurs in the place of weakening (see Figure 2). The weakening zone is most susceptible to heat input, and as comparable methods are almost similar in heat input, the values of hardness and tensile strength are commensurable.

It was established that the developed process of stationary-arc welding of multilayer joints on alloyed steels with slot-like grooving in the double-jet gas shielding environment provides reduction of chemical, mechanical and structural heterogeneity in the joints, reliable quality and required mechanical properties of the welded joints, promotes refining of the weld metal structure and forms a smooth transition from the deposited metal to the base one, which improves service reliability and full-strength of the welded joints. The developed process of slot-groove welding of alloyed steels can be widely applied in machine- and shipbuilding, defense industry, for repair and construction of pipelines.

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SOME ASPECTS OF THE TECHNOLOGY OF HIGH-TEMPERATURE FLUXLESS BRAZING OF ALUMINIUM ALLOYS

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Currently available methods of high-temperature fluxless brazing of aluminuim alloys, their typical application areas and characteristic disadvantages have been analyzed. A new highly-efficient method of brazing in argon, using porous titanium (getter), is proposed.

Keywords: *fluxless brazing, vacuum brazing, brazing in argon atmosphere, aluminium alloys, oxide film, braze alloy, getter, magnesium vapours, porous titanium, surface preparation, cleaner, brazed joint strength*

Presence of oxide films on aluminium surface is known to prevent its brazing, none of the processes of their removal (dissociation, sublimation, dissolution of oxides in the base metal and molten braze alloy) being spontaneously realized at heating in vacuum or neutral gas media.

Indeed, the condition of oxide film dissociation at heating up to aluminium brazing temperature is not fulfilled, as the pressure of dissociation of aluminium oxide $P_{Al_2O_3}$ is incommensurably smaller than the residual pressure of oxygen P_{O_2} in a practically achievable vacuum or inert gas atmosphere. In this connection, reaction equilibrium shifts to the left:

$$Al_2O_3 \leftrightarrow 2Al + 3/2O_2. \qquad (1)$$

Considering that Al_2O_3 oxide film is characterized by *n*-type conductivity, aluminium oxidation rate is practically independent on P_{O_2}, as

$$V = A\left(\sqrt[\nu]{\frac{1}{P_{Al_2O_3}}} - \sqrt[\nu]{\frac{1}{P_{O_2}}}\right), \qquad (2)$$

where V is the constant of reaction rate; A is const; ν is the coefficient, dependent on conductivity type and degree of oxide film disordering ($\nu \geq 2$).

Al_2O_3 oxide film does not dissolve either in solid, or in liquid metal; temperature of oxide sublimation in the vacuum of $1 \cdot 10^{-3}$ Pa is close to that of Al_2O_3 melting; aluminium evaporation temperature is above its melting temperature.

At present several methods of fluxless brazing of aluminium, which are of practical importance, have been developed, which include such kinds of brazing as high-vacuum brazing in the presence of magnesium vapours, low-vacuum brazing in the presence of magnesium vapours and titanium sponge, vacuum brazing in the presence of porous titanium, brazing in argon in the presence of porous titanium.

The method of high-vacuum brazing of aluminium in the presence of magnesium vapours [1–3] is based on their ability to enter into metal-thermal reaction with the oxide film, reducing it:

$$1/3Al_2O_3 + Mg \rightarrow 2/3Al + MgO. \qquad (3)$$

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Magnesium vapours and molten braze alloy, penetrating to aluminium surface through cracks in the oxide film formed at heating, lead to contact solid-gas and solid-liquid melting of brazed metal under the film, thus promoting its dispersion. For aluminium wetting by the braze alloy and its subsequent spreading, it is sufficient for local disturbances of oxide continuity to develop, as the oxide film is not restored, because magnesium vapours interacting with oxygen and water vapours:

$$Mg + 1/2O_2 \rightarrow MgO, \qquad (4)$$

$$Mg + H_2O \rightarrow MgO + H_2, \qquad (5)$$

lower the partial pressure directly in the reaction zone and in vacuum chamber.

The effect of oxide film breaking up is stronger, if magnesium is added to the base metal. By our data, during heating magnesium diffuses to metal--oxide phase boundary, interacting with the oxide film. After heating of AMg0.5 and AMg2 alloys in vacuum of $(2–5)\cdot10^{-3}$ Pa at temperature of 600 °C and soaking for 3 h, magnesium is practically absent on sample surface. Its content increases farther from the surface, becoming closer to magnesium content in the alloy in the initial condition. The depth of magnesium diffusion zone is about 300 μm.

Magnesium evaporation from the metal and braze alloy raises the oxide film defect level, while leading to binding of oxygen and water vapours directly in the brazing zone, thus promoting an improvement of brazed joint quality.

At present vacuum brazing (about $1\cdot10^{-3}$ Pa) in the presence of magnesium vapours is widely applied in fabrication of large-sized structures from aluminium alloys, for instance lamellar-ribbed heat exchangers.

This brazing process has the disadvantage of the need for periodical cleaning of the walls of furnace chamber, screens, heating elements and vacuum system from condensed magnesium vapours, as well as application of multicomponent braze alloys in brazing.

Application of brazing in the presence of vapours of magnesium and titanium sponge [4] allows conducting the process at heating in vacuum with less than 10 Pa residual pressure, and using silumins without magnesium as the braze alloy. Transition to low vacuum is possible owing to application of an auxiliary container with a gate, sealed by titanium sponge, and introduction of magnesium vapours from a sample located in the gate above the sponge, which acts as a non-evaporable getter, which is indicated by the data of mass-spectrometric analysis of the composition of air atmosphere after titanium heating in a sealed volume.

In order to regenerate the titanium sponge with the purpose of its further use in brazing, in work [5] it is proposed to anneal it in vacuum $5\cdot10^{-2}$ Pa at the temperature of 850 °C for 1 h. The lost getter properties of the sponge were restored, while the number of thermal cycles of brazing, at which aluminium wetting by the braze alloy was ensured, was reduced about 2 times.

Brazing in the presence of magnesium vapours and titanium sponge allows implementing the process in simpler equipment, which is, probably, promising in manufacture of small-sized products.

Vacuum brazing of aluminium alloys using porous titanium as non-evaporable getter [6] allows eliminating the application of magnesium vapours. Heating of the product together with the getter from room temperature up to brazing temperature is performed in vacuum with intermediate soaking for equalizing of the product temperature field, whereas cooling is conducted with soaking at the temperature of 500 °C for getter regeneration [7], thus allowing its multiple use.

The process runs in vacuum ($1\cdot10^{-3}$ Pa). It is established that in brazing, for instance, of AMts aluminium alloy by eutectic silumin, brazed joints have well-formed fillets, their shear strength is equal to 100 MPa.

Vacuum brazing allows only one heating method, that of radiation heating, without any alternatives. Broader capabilities in selection of the heating method (from purely radiation to purely convective) are found in brazing in a neutral gas atmosphere, for instance, in argon, thus allowing an essential reduction of the time of structure heating to brazing temperature.

Proceeding from the results of comparative analysis [8], a convective-radiation method of heating with inner circulation of heated gas and heat transfer from it to the product surface through forced convection and partial radiation from chamber metal structures was proposed for implementation of the process of brazing in argon atmosphere.

The brazing process, however, is possible in principle, if structure heating occurs in «non-oxidation atmosphere». On the other hand, the currently available commercial methods of inert gas purification from oxygen and water vapours causing aluminium oxidation, allow producing, for instance, argon with partial pressure of oxygen and water vapours of 0.15 and 0.18 Pa, respectively, which is much higher than in vacuum of $1\cdot10^{-3}$ ($P_{O_2} = 4.5\cdot10^{-5}$ Pa, $P_{H_2O} = 6.65\cdot10^{-5}$ Pa). Moreover, atmosphere composition in the brazing chamber changes continuously during heating. Gases evolving from the metals at thermal degassing form at chemical interaction of surface oxides and other compounds with the impurities, present in the metal being brazed, chamber materials and devices, which diffuse from the metal volume to its surface. The constant of chemical reaction rate and diffusion coefficient exponentially depend on temperature:

$$V = Ke^{-E/RT}; \quad D = K^{*}e^{-E^{*}/RT}, \qquad (6)$$

where K, K^* are the coefficients of proportionality; D is the coefficient of diffusion; E, E^* is the activation energy; R is the gas constant; T is the temperature.

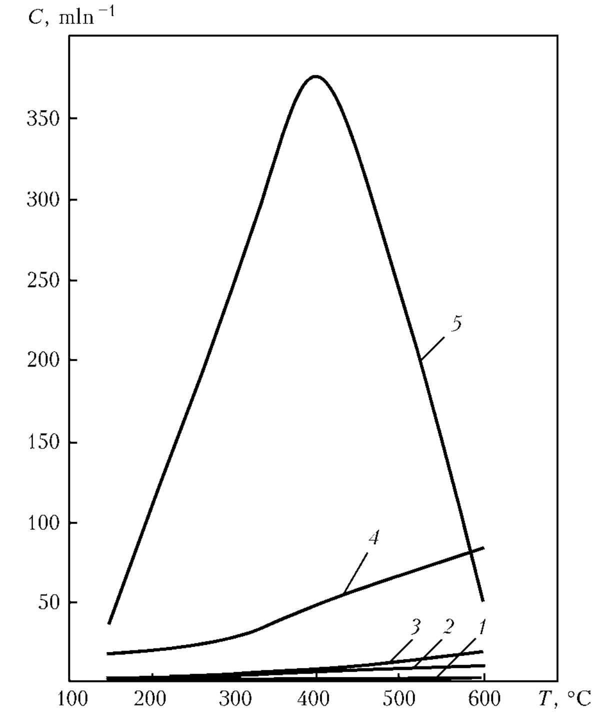

Figure 1. Change of the atmosphere composition at heating in pre-purified argon of AMts alloy (chamber material is 12Kh18N10T steel): *1* ---- O_2; *2* ---- CH_4; *3* ---- N_2; *4* ---- H_2; *5* ---- H_2O

Considering that the main amount of gas evolves from the metal volume, and diffusion is the limiting stage of the degassing process, increase of heating temperature from T_1 to T_2 shortens the degassing time by $\exp\left[\frac{-E}{R}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)\right]$ times.

Activation energy at gas diffusion from the metals is equal to tens of Joules per mole. Calculation showed that at increase of heating temperature, for instance, from 150 to 300 °C the intensity of gas diffusion rises hundreds of times.

As is seen from Figure 1, at heating up to the brazing temperature, oxygen content in the chamber changes only slightly, while concentration of water vapours increases considerably. The curve of the change of moisture concentration becomes maximum at 400 °C, then the water vapour concentration in the chamber decreases. This is mainly due to desorption from the surface of aluminium structure, chamber materials and devices of physically adsorbed moisture with subsequent oxidation of aluminium. Desorption of water vapours significantly decreases after chamber preheating [9]. Therefore, chamber preheating in combination with pumping down and subsequent filling with pure argon allows heating the product under more favorable conditions. However, sound brazed joints cannot be produced, as at the brazing temperature the concentration of water vapours in argon remains high ($1.6\cdot10^{-2}$ vol.%) and aluminium oxidizes. Therefore, an additional purification of the chamber atmosphere during heating and brazing is required, which is what getters are used for.

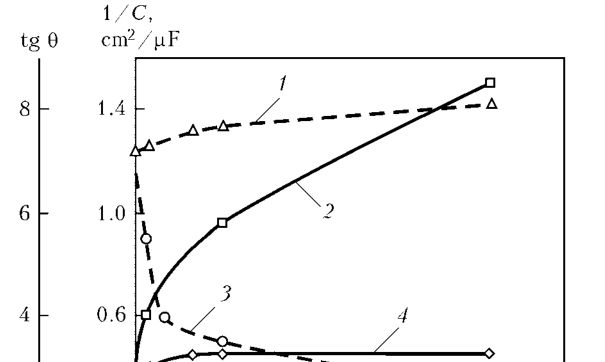

Figure 2. Dependence of tangent (*1, 3*) of the angle of dielectric losses tg θ and capacitive thickness of oxide film $1/C$ (*2, 4*) on AMts alloy on soaking time in argon atmosphere at 600 °C without (*2, 3*) and with (*1, 4*) getter

Application of porous titanium [10] as non-evaporable getter allows brazing to be performed in a practically nonoxidation atmosphere. This is indicated by the results of electrochemical measurements [11, 12] of oxide film capacitive thickness $1/C$ and tangent of the angle of dielectric losses tg θ after heating AMts alloy in argon (Figure 2). When getter is used tg θ and $1/C$ values practically do not change with increase of soaking time at the temperature of 600 °C; they point to the presence of a thin and porous oxide film on the alloy surface under these conditions.

The developed surface of phase contact and high sorption capacity of porous titanium allow its multiple use as a getter. However, after 120–150 h of heating at the brazing temperature its replacement or regeneration in vacuum are required (Tables 1 and 2). Mechanical testing of AMts alloy samples brazed in the presence of titanium in as-delivered condition and regenerated in the vacuum of $(1–5)\cdot10^{-3}$ Pa at 800 °C for 3 h demonstrated that their shear strength is similar. Brazed joints practically do not differ in quality, they have well-formed fillets and the same structure of the seam metal.

Proceeding from the derived results a fundamentally new process of fluxless brazing of aluminium and its alloy in the atmosphere of argon was developed [8, 9, 12, 13], which is more efficient compared to vacuum brazing, this being particularly important in fabrication of large-sized aluminium structures.

Thermal cycle of brazing includes several stages of heating and degassing, providing the minimum temperature gradient in the product and maintaining the required composition of the atmosphere in the brazing chamber. After braze alloy solidification the product

Table 1. Change of weight ΔG of samples of oxidized porous titanium after heating in vacuum of $5\cdot10^{-3}$ Pa for 3 h

Experiment #	Regeneration temperature, °C	ΔG, g/kg
1	500	–0.15
2	600	+0.12
3	800	–0.50

Table 2. Change of weight of porous titanium samples at heating in argon to 610 °C with soaking for 3 h and shear strength τ_{sh} of AMts alloy joints brazed in argon

Experiment #	Titanium surface condition	ΔG, g/kg	τ_{sh}, MPa
1	As-delivered	0.952	100
2	Oxidized during brazing in argon	0.517	70
3	Reduced in vacuum at 800 °C for 3 h	0.954	95

is cooled in air outside the chamber. In terms of formation and strength the produced brazed joints do not differ from those brazed in vacuum (Figure 3).

The disadvantages of the above process include the need for preliminary purification of argon to remove the impurities of oxygen and water vapours. Thus, application of porous titanium as a non-evaporable getter allows performance of fluxless brazing of aluminium alloy structures both in argon and in vacuum without application of magnesium vapours.

A rational selection of structural materials and braze alloys is important for producing sound brazed products. Non heat-hardenable commercial alloys of Al–Mn (AMts) and Al–Mg (AMg0.5 and AMg2) systems, as well as heat-hardenable alloys of Al–Mg–Si (AD31 and AV) and Al–Mg–Si–Cu (AD33) systems are most often used in fluxless brazing. In their brazing in vacuum in the presence of magnesium vapours braze alloys of Al–Si system and silumins alloyed with magnesium, are used. In brazing in vacuum or in argon in the presence of porous titanium there is no need for application of braze alloys containing magnesium.

Mechanical properties of alloys of Al–Mg–Si and Al–Mg–Si–Cu systems are essentially improved at hardening with subsequent natural or artificial ageing. In addition to the main strengthening phases of α + + Mg_2Si or α + Mg_2Si + Si, the alloys may also contain intermetallic compounds of AlSiFe, AlCrFeSi, AlFeMnSi, AlMnSi type [14]. Their brazed joints are characterized by formation of low-melting eutectics along the grain boundaries, thus reducing the positive effect of magnesium on joint strength. Intergranular penetration of the braze alloy is particularly characteristic for copper-containing alloys. In addition, copper diffusion into the braze alloy results in lowering of its melting temperature and greater dissolution of the brazed metal in the braze alloy.

Brazing temperature of AV, AD31, AD33 alloys should not exceed 580 °C, as their solidus temperature is equal to 592, 595 and 585 °C, respectively, and heating above this temperature leads to burning and deterioration of base metal mechanical properties. In addition, the process of producing sound brazed joints is aggravated by the closeness of the liquidus temperature of eutectic silumin (577 °C), traditionally applied for brazing, and the solidus temperature of Al–Mg–Si system alloys.

Lowering of brazing temperature can be achieved by application of braze alloys with a lower melting temperature than that of eutectic silumin SIL1. Promising in this respect, are braze alloys of Al–Ge–Si system [15–17]. Results of our investigations showed that application of braze alloys of this system at fluxless brazing of aluminium alloy AV allows lowering the brazing temperature to 560 °C, thus eliminating the possibility of base metal burning. Values of shear strength of joints brazed in vacuum with amorphous-crystalline braze alloy STEMET 1502, are higher (τ_{sh} = 120 MPa) than those of joints brazed with eutectic silumin (τ_{sh} = 90–100 MPa).

One of the causes for a higher strength of joints, brazed with STEMET 1502 braze alloy, is the small brazing gap, which is determined by braze alloy thickness (about 0.07 mm).

After brazing of AV alloy with eutectic silumin, the brazed seam metal structure consists of Al-based solid solution and Al–Si eutectic, which is uniformly distributed in the seam and along the grain boundaries.

Fractographic investigations of brazed joints failing at testing revealed differences in the fracture mode in brazing with braze alloys containing germanium in their composition and with Al–Si braze alloy of the eutectic composition. After brazing with STEMET 1502 braze alloy at 560 °C the seam fails in the tough mode along the grains without revealing their boundaries, and when SIL1 braze alloy is used at 580 °C brittle fracture of the joint prevails.

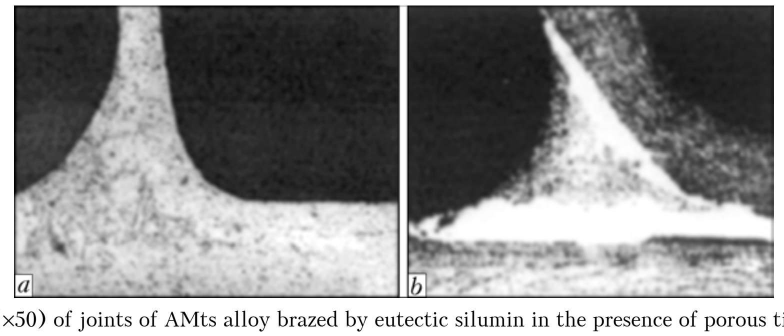

Figure 3. Microstructure (×50) of joints of AMts alloy brazed by eutectic silumin in the presence of porous titanium in vacuum (*a*) and in argon atmosphere (*b*)

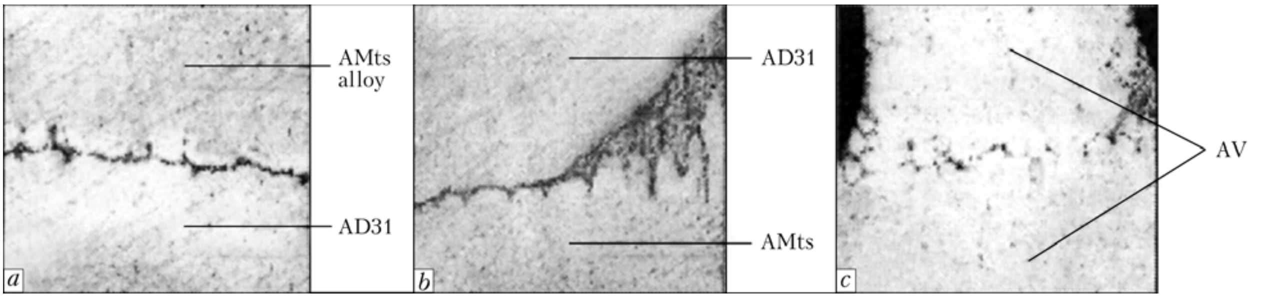

Figure 4. Microstructure (×50) of joints brazed in argon (*a, c*) and in vacuum (*b*) after treatment of aluminium alloys in the solution of Descaler FF cleaner

Aluminium alloys of other systems strengthened by heat treatment, namely, Al--Zn--Mg (V93, V94, V95, V96), Al--Cu--Mg and Al--Cu--Mn (D1, D16, D19, AKD4, AK4-1, AK6, AK8) have a higher content of copper, zinc and magnesium, which essentially influences the brazeability of these alloys. So, for instance, zinc and magnesium feature a high vapour pressure and evaporate during the process of vacuum heating, thus leading to deterioration of the alloy wettability by the braze alloy, and sometimes to base metal buckling and bubble formation [18]. Copper and magnesium form low-melting eutectics in the alloys at the brazing temperature, which are mainly located along the grain boundaries, thus lowering the alloy strength. In addition, alloys of these systems have a low solidus temperature, preventing application of the known braze alloys for their brazing.

Among the new wrought non-heat-hardenable aluminium alloys of a higher strength, the dispersion-hardening alloys alloyed with scandium can be of interest [15, 19]. Investigation results showed [15] that scandium additives to 3003, 3004, 3005 alloys allow increasing their strength 1.5 to 2 times. However, high-temperature heating significantly lowers the strength of these alloys as a result of coagulation of Al_3Sc phase, although after heating for 1 h at the temperature of 600 °C strength of alloy of 3004 type additionally alloyed with scandium, is equal to about 200 MPa. Similar data were derived when studying low-alloyed aluminium alloys of 01515 type with scandium additives. Despite the fact that scandium is a deficit and expensive element, application of alloys of Al--Mg--Sc system as the material for structure brazing can be justified in a number of cases.

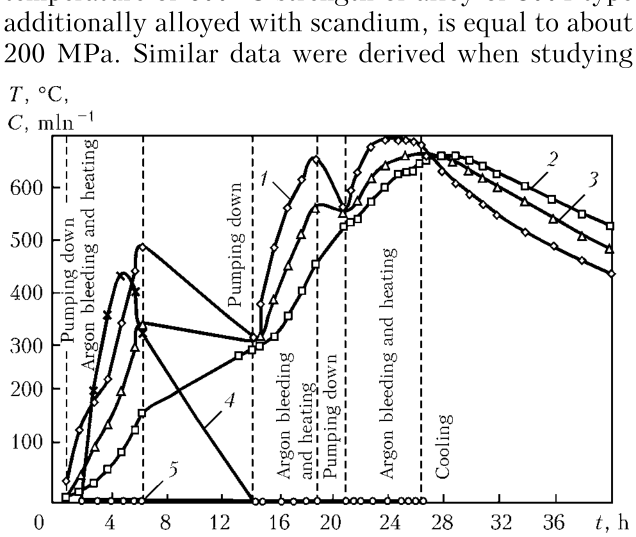

Figure 5. Thermal cycle of brazing in argon of lamellar-ribbed heat exchangers of 1050 × 850 × 3000 mm size and change of oxygen and water vapour content in the chamber during heating: *1* ---- gas temperature; *2, 3* ---- T_{min}, T_{max} of lamellar-ribbed heat exchanger, respectively; *4, 5* ---- content *C* of water vapours and oxygen, respectively

The quality of aluminium alloy brazed joints significantly depends on the method of preliminary preparation of the part surface for brazing. Traditional alkali and acid etching, even though they ensure removal of grease contaminations and old oxide films, are ecologically unsafe preparation processes and do not meet the modern requirements of environmental protection.

At present cleaners of a broad spectrum of application have been developed, which are non-toxic, explosion- and fireproof, completely biodegradable fluids, containing surfactants and components capable of removing grease contaminations and oxide films from the aluminium alloy surface.

Cleaners are water solutions of alkali and acid nature, which are manufactured in the form of concentrates to respective specifications. Proceeding from analysis of the results of investigations [20] of electrochemical characteristics of aluminium alloys, their dissolution rate, degreasing quality, change of thickness and defect rate of oxide films in the solutions of several tens of cleaners of various manufacturers, acid cleaner Descaler FF of OJSC ESTOS TEKHNO was selected from the wide range of cleaning agents. At the given concentrations and treatment modes, this cleaner is the most effective for preparation of the

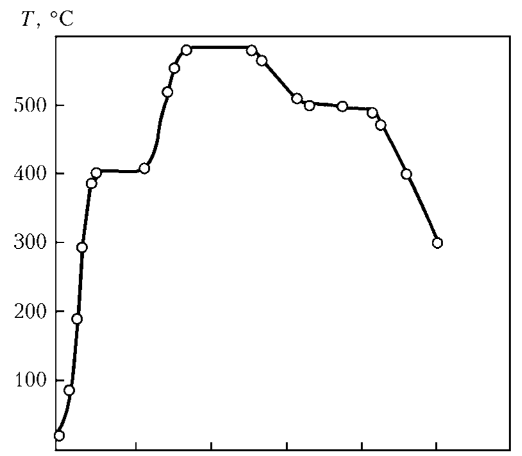

Figure 6. Thermal cycle of brazing in vacuum in the presence of porous titanium of turbo-expander wheel of 300 mm diameter

Figure 7. Appearance of turbo-expander wheel of 300 mm diameter

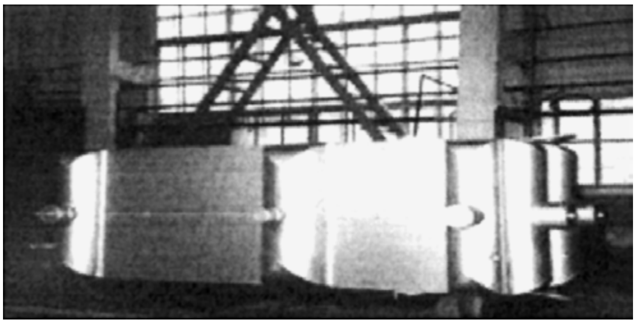

Figure 8. Appearance of brazed lamellar-ribbed heat exchanger of $1050 \times 850 \times 3000$ mm size

aluminium alloy surface for brazing by all the parameters in their totality (Figure 4).

In preparation of the surface of aluminium alloy parts for brazing in the solution of Descaler FF cleaner at complete removal of grease contaminations and oxide films, the rate of metal dissolution is by 2 orders of magnitude lower than with the traditional alkali etching.

In addition, due to formation of dense films of $AlPO_2$ and $AlPO_4 \cdot H_2O$ phosphate compounds on the alloy surface, the admissible time of interoperational storage of parts prepared for brazing increases essentially (up to 30 days).

As an example Figures 5 and 6 present the thermal cycles of brazing lamellar-ribbed heat exchangers and turbo-expander wheel, manufactured by fluxless brazing in the presence of porous titanium, as well as their appearance (Figures 7 and 8). Brazing of lamellar-ribbed heat exchanger was performed in a special brazing unit with aerodynamic heaters of the atmosphere of pre-purified argon [21], and wheel brazing — in a standard vacuum furnace.

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FROM HISTORY OF WELDING

WELDABILITY AND PERFORMANCE OF WELDED JOINTS

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The stages of development of conception of weldability, such as criteria, principles and methods of its evaluation, are considered. The appearance of complex-alloyed materials requires new scientific approach to evaluation of weldability. The relation and effect of weldability on performance of welded joints is shown. Different principles of qualitative and quantitative evaluation of weldability are analyzed including the allowance for an aggregate state of material in the zone of welding, methods of process realizing, energy input and consumption. The complex of factors is given to be considered at evaluation of weldability.

Keywords: *history of welding, fusion welding, quality of welding, weldability, joinability, degradation of properties, criteria of weldability, performance*

Up to nowadays the main problem of welding was the adaptability of metals to formation of a joint using different technological methods. It is known that bronze parts are joined by casting of overheated metal, however their joining by forge welding is impossible, the workpiece elements of metals on the base of iron were welded applying pressure because the heat energy on the base of coal and wood was insufficient for melting. To provide operational strength of constructions, machines and other workpieces remained one of the main problems of designers and manufacturers. Already at the beginning of the XIX century it was revealed that in all-welded structures the welds or areas surrounding them were of the lowest strength. The reason of brittleness of weld metal welded by carbon arc using N.N. Benardos method lied in carbonization and at appropriate flame structure using oxy-acetylene welding of the same metal the welds of better quality were performed. Thus, the dependence of weld quality (the term «weldability» was not in use by that time) on the environment composition in the welding zone was established. N.G. Slavyanov after application of metallurgical fluxes in arc welding succeeded to make «weldable» almost all technical alloys known by that time [1]. N.N. Benardos suggested several variants of weld metal improvement, including application of external magnetic field, hammering, sand, combustible gas [2].

The wide possibilities for improvement of quality were opened by the invention of a consumable electrode covered with substances protecting and ionizing the welding zone, by Swedish engineer O. Kjellberg [3]. Within next ten years the alloying elements were started to be introduced through coating in Great Britain (A. Stromenger, E.P. Johnes), USA (D. Stresau, O. Andrus) [4]. In such a way two methods of weld metal improvement were defined: physical-mechanical influence on the weld and chemical-metallurgical influence on the pool [5].

Till nowadays the metallurgical methods of weld metal quality improvement continue their development. In particular, high quality coatings of rod electrodes, fluxes, fillers and new designs of flux-cored wires, different mixtures of shielding gases and other are produced for arc methods of welding. «The high efficiency, low cost and versatility of arc welding methods promoted their wide development and application for joining firstly of ordinary steels based on iron, then complex-alloyed and finally alloys of different metals. Using electric arc, which is dominated today among sources of local heat, the majority of welding works is performed (probably over 80 %). Under the conditions of fusion welding the joining of materials is carried out by their melting, i.e. through a liquid phase.» [6].

Simultaneously with the appearance of new technologies the joints, units and structures were developed, where advantages of new materials were considered. In the first patent N.N. Benardos suggested new types of joint, including cellular and lattice structures [7].

O. Kjellberg and specialists of Great Britain realized the advantages of welding in design and building of small ships. In the 1930s the welding became to be used for structures of DneproGES, «Azovstal», bridges, buildings, ships and other critical constructions that facilitated acceleration of industrialization of the USSR. At that time the reliable welded structures were created by V.P. Vologdin, G.A. Nikolaev, N.O. Okerblom, E.O. Paton, G.P. Peredery. The large all-welded structures, transport vehicles, power equipment were manufactured abroad by the projects of Kerensky, Moon, Derden, O'Neil, Goodwin and others. Here a good operational

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quality was achieved by improvement of welding technology.

In 1937 in the USSR the official definition of weldability was given as «property of metals to produce good quality joints in welding, which are featured by degree of continuity and homogeneity of weld metal and adjacent zones of base metal» [8].

The quality of metal including that of structural steel was checked according to the criteria developed already for riveted and bolted joints. Here the strength values could be satisfactory at any components composition (often not controlled). The number of accidents of welded structures, including bridges across the Albert channel in Belgium in 1938, made to deal urgently with weldability problems. It gave the impetus to study peculiarities of metal behavior in HAZ, its structural transformations, lamination, deformations, stresses and other. The data bank on «spontaneous» fracture of welded structures kept on accumulating at the beginning of the World War II, including the information about accidents of American dry cargos of «Liberty» type in 1940--1943 [9].

At the end of the 1940s the specialists of many countries verified the ability of metal to weldability in welding of different specimens for study the tendency to crack formation [10].

In 1940 Derden and O'Neil suggested the carbon equivalent as the basis of quantitative characteristics of weldability of steel [4]. The formula, accounting for a relative influence of basic admixtures was introduced into manuals and is still remaining the basis of quantitative estimate, corrected and supplemented in the process of development of new alloys. Meantime the searches for new criteria were continued. However, plenty of ideas were based on metallographic investigations of different zones of welded joint, concerning not only alloys of iron with carbon and other elements but also the number of other structural materials [11].

As the characteristic example of weldability dependence on welding conditions (method, condition parameters, joint geometry) the history of armored steels welding at the beginning of the 1940s can be considered. The armored plates of thickness of some tens of millimeters of tank bodies in the USSR, the USA and other countries, and also ship armor in Germany were joined by multilayer welds using manual arc welding as a rule with steel electrodes of an increased nickel content, i.e. those steels were weldable. The transition to automatic welding was successful as a result of application of wire with a low sulphur content [12] (it should be noted that the wire was manufactured of steel with practically zero sulphur content, as a part of the Urals furnaces operated using charcoal).

In the 1940s--beginning of the 1950s in many countries the problems of weldability and reliability of welded structures were discussed. In 1946 the criteria of weldability were considered in the journal «Avtogennoe Delo» by U.M. Kuzmak [10]. On the pages of journal a discussion stirred up on the causes of crack and brittle fracture formation, peculiarities of melting of pool metal and structural transformations and also other problems connected with weldability, quality improvement of welded joints and reliability of welded structures. In the same period the scientists of many countries studied the influence of base metal quality on the quality of welded joints.

In particular, at the E.O. Paton Electric Welding Institute the attention was drawn on the sulfide inclusions in rolled metal, located layer-by-layer and revealed in HAZ metal. It is noted that tendency to near-weld crack formation is increased with the increase in thickness of metal being welded at the presence of coarse-grain initial structure and clearly expressed stringer-type structure [13] (it did not occur at riveting).

In the 1950s the final conception on welding was formed as the complex of metallurgical and physical-chemical processes occurring under the conditions of considerable energy concentration, intensive heating and subsequent relatively rapid cooling. In that period the opinion prevailed that «weldability» even of the certain metal can not be considered beyond the conditions of fabrication of the material, design solutions in manufacture of structures, conditions of product service, technology of welding and postweld treatment. The task of welders remained to be the development of technologies, expanding the nomenclature of alloys to be welded, and also decrease in power intensity of the process and material consumption of the structures.

From the second half of the XX century new structural materials appeared with high strength, cool resistance, heat resistance, radiation resistance and other. In the process of welding quick change of thermal cycles occurs often connected with residual stresses. Here in thermomechanical-affected zone (TMAZ) the microstructure of the base metal can be radically changed, usually deteriorating the operational characteristics of the workpiece in spite of local character of changes.

For many alloys (not only non-ferrous metals, but also high-alloyed) the conventional formula of weldability evaluation by a carbon equivalent turned to be incorrect. Many researchers began to use structural transformations as the criterion of weldability. However this indicator was complex and required specifications for each group of new alloys.

One more aspect of weldability was considered by N.N. Prokhorov in 1952 in monograph devoted to investigations of hot cracks [14]. He determined the temperature range of loss of ductility properties of weld metal and formulated the hypothesis of technological strength of crystallized metal. As the strength criterion of crystallizing metal (called as technological range of brittleness) such a temperature range was accepted where strength and ductility had minimal values.

However welding using high-concentrated power sources (beam, contracted arc) is not always preferable to improve weldability. Thus, at the high welding speed of some titanium alloys (and, respectively, the intense cooling) the considerable strengthening and loss of toughness occur in HAZ metal [15].

During TIG welding and change of condition parameters, but preserving the constant value of q/v, the tendency of corrosion-resistant austenite alloys to crack formation varies which is connected with the shape of weld pool and stresses distribution. In electron beam and laser welding the resistance of metal to hot crack formation increases [16].

Quite different are the characteristics of weldability of heat-resistant alloys. In the opinion of many investigators the methods and conditions of welding do not affect much on the mechanical properties of welded joints [17].

In the 1960s, the high-alloyed two-phase steels with increased resistance in aggressive environment were developed. In the 1970s, at the E.O. Paton Electric Welding Institute, Institute for Low Temperature Physics and Engineering, SPA «Kriogenmash» and I.P. Bardin Central Research Institute a large volume of investigations was carried out, the compositions and technologies of producing steels for structures, operating at low temperatures, including in aerospace industry, were developed [18].

The tendencies of high-strength steels application in critical structures keep on growing. In the 1970s the carbon and low-alloy steels began to replace martensite-bainite steels with yield strength of up to 950 MPa. In these steels the tendency to delayed fracture was revealed, different heating conditions were used to improve quality of joints. The index of weldability of these steels (according to the carbon equivalent) was high due to the carbon level content and such alloying elements as chromium, molybdenum, boron and others [19].

The volume of application of new generation of high-strength steels, weldability of which was improved by decrease of carbon content (down to 0.12 %) and conventional alloying elements (not more than 3–4 % in total), was increased. The cast heat-resistant nickel alloys in spite of high operational properties (heat resistance) are applied limited due to the high tendency of welded joints to hot crack formation [20]. The austenite chromium-manganese steels 03Kh13AG18 (ChS-36) and 07Kh13AG20 (ChS-46), being the substitutes of the steel 12Kh18N10T, showed advantage at the service of different welded structures of cryogenic engineering, in chemical machine building and their application in power equipment [21].

The tendency of steels and alloys to formation of near-weld cracks was suggested to be estimated using different technological samples by calculation of total length of cracks per unit of length of fusion line and in cross section of a weld [22].

Y. Ito and K. Bessyo derived the parametric equation to estimate the sensitivity of welded joints of steels to cold crack formation [23]. Basing on the results of tests on tendency to crack formation using methods of implants and samples «Tekken», F.R. Coe [24] derived one more equation by considering that one of the criterion, indicating the possible embrittlement of HAZ metal due to the structural transformation is hardness. The steel, the value of carbon equivalent of which is higher than 0.40--0.45, is still considered to be sensible to cold crack formation in welding.

However the methods of determination of material weldability, based on the application of technological samples, are often incorrect since they do not correspond to welding conditions of real assemblies. The geometry of the majority of technological specimens predetermines the hot crack initiation, namely in weld metal, which promotes the reduction of deformations and decrease of probability of cracks formation in the near-weld zone [25].

One of the basic indicators of weldability of chromium-nickel steels is resistance of weld metal to hot crack formation. The estimate of their tendency to hot crack formation is evaluated according to results of welding of circular bead weld on the square specimen composed of four plane bars ($50 \times 50 \times 15$ mm). The weld metal on the investigated chromium-nickel steels welded using electron beam is less prone to hot crack formation than that in welding using consumable electrode in inert gas [26].

Finally, in evaluation of steels weldability it is necessary come from the fact that the welded joint should be first of all sound, i.e. without macro- and microcracks, lack of penetration, pores, slag inclusions, etc. The weldability of steel is defined not only by inner, but also external factors. The latter refer to welding technology, fixture of welded assembly, etc. Finally, the weldability is predetermined also by a complex of requirements set forth to welded joint during service, i.e. it should be characterized by a necessary sum of useful properties. Poor designs of joints and assemblies, presence of stress concentrators, residual inner stresses, being a serious cause of fracture of welded structures, are considered as factors affecting the strength of workpieces. Therefore, the search for constructive solutions and technologies is also connected with weldability [27].

Reduction in residual stresses and elimination of concentrators improve the level of resistance against initiation and development of fatigue and brittle fractures [28].

The research works, carried out at the E.O. Paton Electric Welding Institute under the supervision of I.K. Pokhodnya, are devoted to the search for optimal technologies of submerged-arc welding of low-alloy steels. It was established that refining of grain in the TMAZ overheated region, decrease in its width, reduction of metal duration within the temperature region of austenite decay and reduction of homogeneity level of residual austenite can be achieved in welding at direct current using a pulsed arc. After the analysis of works, devoted to metallurgical methods for increase of weld metal resistance in shielded gas welding, and after performance of own research works, V.N. Lipodaev, V.P. Elagin and other colleagues of the E.O. Paton Electric Welding Institute have shown that addition of small mass fraction of nitrogen and oxygen (3 %) exerts both austenizing and also modifying effect on austenite metal [29].

To increase the ductility of welded joints of high-strength steels, it was suggested in the USA to deposit «soft» beads along the fusion line at the depth of 1--2 mm by remelting the weld metal for the width of 2--3 mm (Patent 3484930 USA, cl. 29497). To increase ductility preserving sufficient strength, the technologies of fusion of weld boundaries using TIG process were developed at the E.O. Paton Electric Welding Institute [27].

In NTUU «Kiev Polytechnic Institute» (V.P. Chernysh, V.D. Kuznetsov, et al.) the equipment and technologies of effect of magnetic fields on the processes during arc welding were developed that contributed to the increase in weld metal resistance against cracks and pores formation. In particular, the external electromagnetic effect, coordinated with a pulsed feeding of filler wire, improved the characteristics of weldability of nickel alloys [30].

Since the end of the 1950s, with widening the volumes of application of aluminum alloys in manufacture of critical structures, one of the major factors of weldability became the lamination of semi-products in TMAZ ---- the «heritage» of technologies of casting and pressure treatment. To produce high quality welded joints simultaneously with the development of compositions of new high-strength steels (aluminum-lithium, aluminum-yttrium, etc.) the search for technologies of processing the ingots and semi-products was carried out. It is known that weldability of such alloys is affected by the conditions of annealing and homogenization, and the methods, parameters and technique of welding should be preset according to the conditions of preserving the properties of base metal and satisfying the specific requirements to each certain product [31].

Having applied the sources with high energy concentration (electron beam, arc plasma) for welding of structures of carrier rockets of large-size forgings of aluminum alloy 1201, V.A. Kazakov, V.N. Mironenko and other scientists (Central R&D Institute of Machine Building) succeeded in enhancing the level of mechanical properties of welded joint independently of the fiber direction [32].

During recent years the attempts were made to find the criteria of evaluation of weldability of complex-alloyed aluminum and titanium alloys. Thus, V.A. Frolov (MATI) developed the method of criterial multi-factor approach to the evaluation of weldability of materials, level of production technology, its certification and adaptability of products to manufacture. According to these complex criteria it is suggested to conduct quantitative evaluation of materials weldability, the criteria can be supplemented, and their structure specified on the basis of physical-mathematical and computer modeling of welding processes [33].

The behavior of other non-ferrous alloys during the change of fusion welding conditions is theoretically unpredictable and determined only in experimental way. For example, during welding of Zr--2.5 % Nb alloy the cooling at the speed of 1.3--5.0 K/s facilitates the formation of equilibrium and hardening phases. The increase of cooling speed up to 45--1000 K/s results in formation of the most homogeneous structural state of a hardening type [34].

The success of application of composite materials depends greatly on the solution of problem of the joint conformity to all criteria of weldability. Here the most difficult task is the development of fusion welding technologies. The tests, performed by T.A. Chernysheva and other scientists at the A.A. Bajkov Metallurgy and Materials Science Institute of RAS (Moscow) on MIG welding of composite material with matrix of aluminum alloy AL2 armored with particles of silicon carbide, showed satisfactory formation of weld and absence of coarse macrodefects (undercuts, lacks of fusions, cracks), and the possibility to preserve the armored filler in weld. During crystallization of a weld pool, containing SiC particles, three main zones are formed with different filling of particles. The width of zones and size of structural elements in these zones depend on welding conditions. The decrease of energy input of welding results in better distribution of armored filler in matrix metal of a weld, larger dispersion of cellular-dendrite structure of matrix and hardness of weld metal [35].

Besides the metallurgical problems the more attention was paid to the accuracy of sizes and internal stresses. The tasks of decrease of shrinkage and distortion of welded joints are caused by increasing the range of loads, temperatures and other conditions of service of welded structures of the new generation. One of the ways of solution of such complex of problems as TMAZ decrease and reduction of deformations became the development of welding processes using concentrated heat sources: arc plasma, electron beam, laser, light beam. During recent years the hybrid processes based on interaction of two different heat sources in welding zone are being developed. As far as most technologies, based on these processes, are performed in inert environment or vacuum, one can consider that metallurgical effect decreases. Nevertheless, the temperature-power features of certain technology influence should be taken into consideration in the development of new materials which will be subjected to welding using combined heat sources.

It is noted in the work [36] that during certification of technology it is necessary to be based not on the presence or absence of undesirable phases or components of microstructure, but on the properties of a joint, corresponding to operational requirements to the workpiece, first of all strength characteristics under the service conditions.

The development of technologies, providing the weldability of alloys of new generations (complex-alloyed, heat-hardened steels, special-property alloys, aluminium-lithium alloys, titanium and other materials) is the important stage on the way of creation of critical engineering structures, increase of service reliability and life. Moreover, at the beginning of the XXI century the choice of welding methods remains relatively not large. If to exclude pressure welding methods, not adaptable for full final fabrication of many structures (especially large-sized volumetric structures of intricate geometry), the fusion welding is limited by arc, beam and hybrid technologies. This conventional classification, accepted already at the beginning of the 1930s, could not in principal serve as the basic one or at least the optional one for the quantitative characteristic of weldability, because it does not account for the diversity of physical processes and substance condition at the interaction of energy source and material. In the recent years the classification of welding processes was offered with account for the aggregate condition of substance. According to this classification, the welding technologies stand in one line with the technologies of structures manufacture (melting out, casting, rolling, heat treatment, etc.), physical formation of which is also realized through the change of aggregate conditions. The account for the aggregate condition of substance in welding zone (liquid, solid, vaporous) is necessary for quality evaluation and can serve as the basis for quantitative evaluation of joinability (weldability). Such approach can be applied to estimate new probable technologies, methods of joining of metallic and nonmetallic materials [6].

The main quality criteria of welded workpiece and welded joint becomes the definition of «weldability». The IX Commission of IIW «Materials Behavior in Welding» the definition of weldability, suggested by H. Granjon, was considered. In May 1967 it was approved by recommendation to ISO R 581, on the basis of which the ISO 581–1980 standard was adopted. However in 1984 in the USSR in new terminological GOST 2601–84 the same meaning preserved, not admitting in principal the possibility of a poor weldability: «The property of metal or combination of metals to form the joint at established welding technology, meeting the requirements specified by design and service of workpiece». In 1998 for the term «weldability» the standard of Ukraine DSTU 3761.1–98 was adopted (based on ISO 581--1980) for the term «weldability.» In work [37] the analysis of available approaches to the evaluation of «weldability» according to the standards of different countries and organizations such as ISO 581--1980, DIN 8528 (Germany), The Welding Institute (Great Britain), Bratislava Welding Institute, GOST 2601–84 (USSR), DSTU 3761.1–98 (Ukraine), American Welding Society and others was carried out. The following conclusions have been made:

• almost in most cases the «weldability» is evaluated qualitatively and subjectively on the principle «present–absent» (i.e. material is weldable or not);

• in some cases it is stated that «weldability» is a property (ability) of metal to form the joint. Here, the property and its evaluation are not mentioned. Such an approach is also a subjective evaluation;

• almost in all definitions, regulating the term «weldabilty», it is mentioned that «appropriate technological process» or «certain process and certain technology» are required or «subjected to welding using any method» and without special measures (however, this is in case of perfect weldability), or «at established technology» or «at proper welding procedure», i.e. it is only mentioned about influence of technology itself on weldability. The recommendations on the account for the influence of the technology on weldability are conditional;

• in all cases in any kind the «weldability» is connected with «own quality of parts being welded and structures which they form» or «welds should satisfy specified requirements to properties and influence on the structure», or «produce the joint, the properties of which allow complete application of material», or «welded joint should meet the requirements specified by structure and service of the workpiece». In all cases the methods and criteria of weldability evaluation are not given, and even if they are given they are not versatile, i.e. they are true only for some narrow classes of materials, i.e. even in these definitions the subjective evaluation system is observed.

The reasonability of development of versatile physical approach and evaluation criterion of weldability of materials, different in their nature, such as metals, alloys, ceramics, composites, polymers, live tissues, etc. was expressed. It is possible to state that such characteristic of material as «weldability» should have relation with the changes of its functional properties. These changes are characteristic for the processes of degradation of materials under the influence of technology of formation of permanent joint. The term «joinability» becomes more usable in engineering. They have the same physical sense from the point of view of formation of permanent joint. The conclusion is also made that weldability can be estimated by the level of degradation of material [38].

CONCLUSIONS

1. In 1937 for the first time the definition of weldability as property of metals to produce sound joints in welding, characterized by the level of discontinuity and homogeneity of weld metal and adjacent zones of base metal, was given. The quality of metal, including the structural steel, was verified according to the criteria developed already for riveted or bolted joints at different (often uncontrolled) composition of components.

2. As the basis of quantitative characteristics of weldability of steel, Derden and O'Neil suggested in 1940 the calculated index, so-called carbon equivalent, which is determined by the formula, accounting for the content of elements. In the following years

with the development of new alloys the formula continued to be corrected and supplemented.

3. In the 1940s on the pages of magazines of many countries a discussion stirred up on the causes of formation of cracks and brittle fractures, peculiarities of melting of pool metal and structural transformations and also on the other problems, connected with weldability, quality improvement of welded joints and reliability of welded structures. E.O. Paton paid attention to the fact that weldability of alloys is deteriorated at the presence of coarse grain structure in semiproducts and strongly expressed stringer inclusions, in particular, sulfide inclusions located layer-by-layer in the rolled metal.

4. In 1967 the IX Commission of IIW worked out recommendation to ISO R 581 for formulation of weldability, on the basis of which the acting standards ISO 581--1980 and DSTU 3761.1--98 were adopted.

5. At the present moment there is no generally accepted definition of material weldability, even in available nowadays national and international standards, the criteria and methods of weldability evaluation are not indicated.

6. At the E.O. Paton Electric Welding Institute the classification of processes of welding by aggregate condition of substance in the area of weld formation was suggested. The account for the aggregate condition of substance in welding zone (liquid, solid, vaporous) is necessary for quantitative evaluation of joinability (weldability).

7. The most objective and promising criteria of evaluation of weldability as a property of material is degradation level which allows evaluation of any kind of materials and technologies of their joining.

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NEW EQUIPMENT FOR HARD-FACING OF CHARGING DEVICE BELLS AND CUPS

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New hard-facing apparatus A-1812 and a microprocessor-based control system were developed for machines of the U-50, U-75 and U-125 types. The equipment is meant mainly for hard-facing of blast furnace charging devices. Specifications of the new equipment are given, and its peculiarities are described.

Keywords: *arc hard-facing, flux-cored strip, charging device, machine, hard-facing apparatus, control system, information-recording system*

At present, many metallurgical plants use a classical design of the blast furnace loading equipment. It is a double-bell charging device consisting of a big bell and cup, hopper and a small bell. These main components, which are designed for distribution of charge inside the blast furnace, also serve as valves for maintaining the specified pressure under the throat. The strength of charging devices dramatically decreases with intensification of the blast-furnace process caused by growth of the excessive pressure and temperature. Replacement of a charging device is an expensive operation. Moreover, not less than three-day shutdown of the blast furnace for third-class overhaul leads to great losses in melting of cast iron. Service life of the charging devices can be extended by hard-facing.

Operation conditions of different regions of charging device bells and cups are different. They can be subdivided into two main types: protective surface (charging materials move over it, thus causing its abrasive wear) and contact surface (it serves as a gas locking device and, hence, is subjected to gas-abrasive wear). It should be noted that several tons of the electrode material are consumed for hard-facing of one charging device. Therefore, important factors are automation of the hard-facing process and its productivity.

Hard-facing of blast furnace bells and cups was started with deposition of contact surfaces using stick electrodes, which provided metal of the deposited layer of the type of «Sormite-1». Low productivity of the deposition process and small thickness of the deposited layer did not lead to increase of strength of the above components to the required level. Utilisation of flux-cored wires also failed to give the expected result.

The situation was radically changed with emergence of a new electrode material, i.e. flux-cored strip, developed by the E.O. Paton Electric Welding Institute [1]. Application of this strip made it possible to substantially raise the deposition efficiency (up to 25 kg of the deposited metal per hour). It provides layers of the deposited metal with a high degree of alloying. New hard-facing equipment and technology for treatment of the blast furnace components were developed to utilise the new capabilities to the maximum possible degree [2].

Unique machines U-50, U-75 and U-125 were developed for one- and two-strip wide-layer hard-facing of bells and cups of blast furnace charging devices. The machines consist of manipulators with a carrying capacity of 50 or 75 t, and a movable column with a specialised welding deposition device mounted on it. The latter provides weaving of an electrode, while a manipulator moves a workpiece to a deposition step. Design of the machines provides for circumferential deposition, as well as open- and submerged-arc welding of large-size parts by using flux-cored or all-drawn wires.

The hard-facing machines (Figure 1) and apparatus A-1640 designed and manufactured in 1960–1970 are now physically and morally depreciated. New hard-facing apparatus A-1812M (see its specification below, and Figure 2) and control system of the SU-320 type for hard-facing of bells and cups of blast furnace charging devices by the electric arc method were developed to upgrade them.

Specifications of apparatus A-1812M

Cross section of flux-cored strip, mm	10×3; 16.5×4; 18×4
Diameter of electrode wire, mm	3–5
Arc voltage, V	25–50
Electrode feed speed, m/h	20–100
Speed of reciprocal movement of electrodes, m/h	20–70
Length of reciprocal movement of electrodes, mm	not more than 550
Horizontal movement of hard-facing apparatus on slides, mm	not more than 750
Duty cycle, %	100

Apparatus A-1812M has the following design peculiarities:

- feed mechanisms include the asynchronous motor drive, which provides a more uniform feeding of the electrode material;
- length of the rod is increased by 150 mm; when using the apparatus it is possible to increase it by another 750 mm owing to the slides, which is especially important for hard-facing of large internal surfaces;

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Figure 1. Appearance of machine U-125

• brackets of the feed mechanisms allow hard-facing to be performed simultaneously by two arcs, both in sequence (the second arc deposits the second layer) and in parallel (the strip to be hard-faced is split into two regions);

• the apparatus is fitted with a stepping device, which makes it possible to improve the accuracy of movement of a workpiece by a deposition step and adjust the latter directly from the control panel;

• control system SU-320 is made as a set with the apparatus. It is microprocessor-based and controls actuating devices of the entire hard-facing machine through logical processing of the information coming from different sensors.

Distinctive feature of the new electric circuit is a complete refusal from DC motors. They are replaced by the asynchronous motors, which make it possible to gradually adjust the rotation speed. The circuit provides indication of the process parameters being checked on the display screen by recording deposition conditions in real time, thus allowing documentation of manufacture of workpieces being hard-faced. With this system, for the first time for the given type of the machines, input of all the process parameters is done from the display located on the control panel. An important advantage of the new apparatus is the possibility to set and monitor a real welding speed in welding and hard-facing of cone-shaped parts.

Control system SU-320 (further on — CS) is meant to control the process of hard-facing and welding of bells of blast furnace charging devices and other parts of metallurgical equipment under production conditions at Open Joint Stock Company «West-Siberian Metallurgical Plant» (Novokuznetsk, Russian

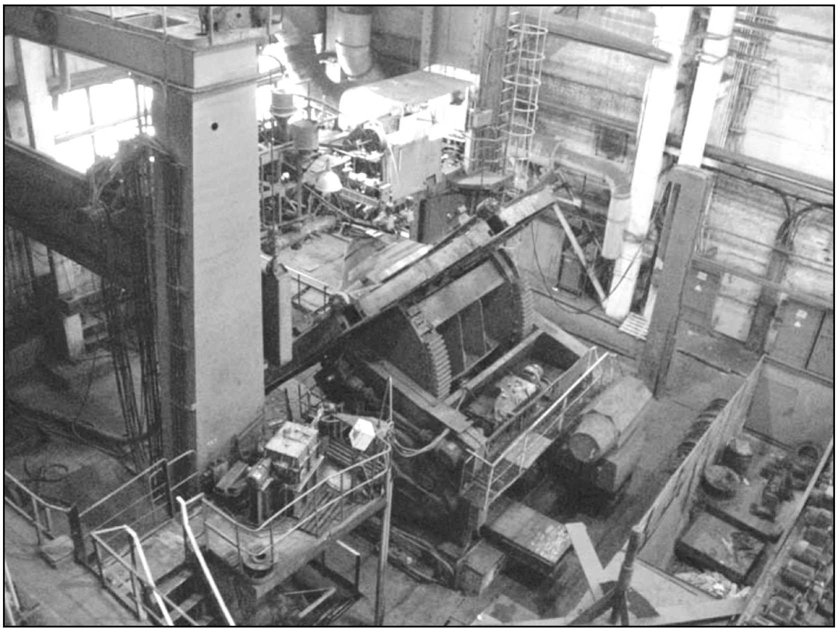

Figure 2. Appearance of apparatus A-1812M

Federation). SU is based on the OMRON (Japan) components and consists of the following main parts:

• programmable controller of the CQM1H type with software to control the hard-facing process;

• inverter frequency electric drives of the «Varispeed F7» and «Varispeed V7» types for motors of machines U-125 and apparatus A-1812M;

• operator's panel (terminal) of the NT-11S type for input of the process parameters;

• starting-protective equipment, measuring instruments and controls;

• information-recording system (IPS) –– personal computer with special software to visualise the process and record the process parameters.

Equipment of the machine is controlled from the main control panel (MCP) located on a welder's work platform, and auxiliary control panel located on the auxiliary platform for assembly of a workpiece on a faceplate.

Control cabinets with the controller, electric drives and starting-control equipment, cabinet with power contactors and bypasses are located in an electric control room (control room) of the workshop.

CS provides functioning of the equipment in three modes –– «Setup», «Welding» and «Hard-facing». Selection of a mode is performed with the help of a switch on MPC. Operation of all mechanisms of the machine and setting movements before hard-facing are checked in the «Setup» mode. The «Welding» and «Hard-facing» modes are intended to automatically control the welding and hard-facing processes following a preset program. Indication of parameters on digital devices and operator's panel are provided, and an operator has the possibility to adjust parameters during the hard-facing or welding process in all the operation modes.

To check operation of the equipment, technological or emergency messages of the type of «No current, stop process», «Failure of feed drive», «Parameter is out of limit» are indicated on the operator's panel.

IRS for visualisation of the process and recording of the process parameters is a computer with special software, which is located in a non-production room with normal atmospheric conditions. Length of the communication cable (control cabinet–computer) is up to 150 m. Software functions in the Windows-XP environment and provides the following options: real-time visualisation of the process parameters, entry of the number of a workpiece, operator's name and other additional information about the process by the operator, saving of the process protocol to the data base, access to the information on the saved process parameters from the protocol data base, and printing out of the protocol.

IRS displays the information on the monitor screen and provides operation with protocols in the «Excel» program.

Associates of Department for Hard-Facing Technologies and Consumables, Design Bureau and Pilot Plant for Welding Equipment of the E.O. Paton Electric Welding Institute, as well as Limited Liability Company PLAN-T participated in development of the new equipment.

Hard-facing apparatuses A-1812M and control systems of the SU-320 type were manufactured and applied at the Metallurgical Plant «Krivorozhstal» in 2003, Open Joint Stock Company «Azovmash» in 2005, and repair enterprise of Open Joint Stock Company «West-Siberian Metallurgical Plant» in 2008.

The new equipment demonstrated in operation its reliability and proved to be easy to use and maintain.

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TO THE TWENTY FIFTH ANNIVERSARY OF APPLICATION OF WELDING IN OUTER SPACE

On the 25th of July 2009 there were 25 years since accomplishment of the world-first experiments on welding, cutting, brazing and coating in the outer space, which was conducted by the USSR space pilots S.E. Savitskaya and V.A. Dzhanibekov. This really unique event forever went down to history of development of the space science and technology.

Arrangements in celebration of this historic date were held in Kiev from 14 till 16 July 2009. The grand meeting took place in the Big Conference Hall of the NAS of Ukraine. Taking part in the meeting were S.E. Savitskaya and V.A. Dzhanibekov — Twice Heroes of the Soviet Union and USSR space pilots, as well as V.P. Nikitsky — former department chief at Rocket-Space Complex «Energiya» and now Director General of Inter-Industry Scientific-and-Technical Centre «Payloads of Space Objects», who made a big contribution to implementation of this experiment. The grand meeting was attended by associates of R&D institutions of the NAS of Ukraine, rocket-space industry and institutes of higher education training specialists for the rocket-space industry, as well as L.D. Kuchma — ex-President of Ukraine, L.K. Kadenyuk — first cosmonaut of the independent Ukraine, B.M. Danilishin — Minister of Economy of Ukraine, S.N. Konyukhov — Director General of Design Bureau «Yuzhnoe», and others.

The grand meeting was opened by Professor B.E. Paton, President of the NAS of Ukraine. He greeted participants of that unique experiment present in the hall, as well as all other attendees of the meeting.

In his presentation dedicated to the 25th anniversary of conducting welding in the outer space, B.E. Paton noted that the successful experiments on welding, cutting, brazing and coating carried out under conditions of the outer space had proved the possibility of performing complicated operations by cosmonauts on board the manned orbital complex in the outer space. The space exploration programs implemented at present and planned for the future provide for construction of large-size space objects in the space and on the Moon. Naturally, a long-time operation of such objects will require systematic preventive maintenance, as well as repair-and-renewal and erection operations to be conducted both inside the pressurised compartments and in EVA. Welding is one of the most promising processes for these purposes. Cosmonauts will have to work in different sections of a spacecraft, and deal with different structural materials. For these purposes the E.O. Paton Electric Welding Institute built the versatile electron beam hand tool. The experiment conducted proved a high level of perfection of the welding equipment made owing to the many years' intensive efforts of a big team of scientists and engineers of the Institute in close collaboration with the Yu.A. Gagarin Space Pilot Training Centre. Cosmonauts S.E. Savitskaya and V.A. Dzhanibekov displayed a true heroism by being the pioneers in these basic space experiments. In fact, they broke the ice of distrust of sceptics who doubted the possibility of employing welding technologies in space. Their deed forever went down to history of development of the space science and technology. The experiments showed that compact versatile tools of the VHT type allow the cosmonauts to perform the work related to repair or erection on the external surface of a space object

Presidium of the Grand Meeting

WELCOME ADDRESS
CABINET OF MINISTERS OF UKRAINE

To Participants of the Grand Meeting
dedicated to 25 years since application
of the welding technology in outer space

Dear friends,

I am sincerely greeting participants of the meeting with the 25th anniversary since application of the welding technology in the outer space.

Today nobody has any doubt that the experiment conducted in the outer space in 1984 by using the electron beam tool made by scientists of the E.O. Paton Electric Welding Institute headed by Professor Boris Paton is of the world-wide importance.

The space welding technology has been continuously improved by specialists of the Institute. New possibilities are being opened, a new plasmatron tool has been built, and technology for laser-microplasma welding has been applied.

We relate the future of our country particularly to such innovation technologies, which improve competitiveness of the national scientific-and-technical potential and adequately represent the Ukrainian science in international space exploration programs.

Let me express the most sincere gratitude to you for your devoted work and substantial achievements, which increase the scientific authority of Ukraine in the world.

Wishing you strong health, prosperity, fruitful work and high ideas.

Prime Minister of Ukraine
Yulia Tymoshenko

14 July 2009
Kiev

After discussions with associates of National Technical University of Ukraine «Kiev Polytechnic Institute»

by assuring the required quality of the welded joints. Space ships and stations, as well as infrastructure of the expedition colonies on the Moon surface meant for a long-time service under space conditions should be fitted with sets of the welding equipment to perform erection and repair operations in construction and exploitation of the objects, while the spacecraft and expedition crews should have the basic knowledge about the welding technologies and practical skills in performing the above operations.

B.E. Paton noted that welding and related technologies will have to play an important role in exploration of space. The electron beam technologies tested in the outer space can find application both in various physical experiments and in production of unique semiconducting materials. This will make it possible to come from experiments with the electron beam on board the orbital stations to construction of real space facilities, e.g. building of lunar settlements and various plants on the Moon, as early as in the first half of the 21st century.

The USSR space pilots S.E. Savitskaya and V.A. Dzhanibekov, as well as V.P. Nikitsky shared their memories about the unique event — preparation for and carrying out of the experiment in the outer space.

Then the floor was taken by B.M. Danilishin, the Minister of Economy of Ukraine, who read the welcome address to the meeting attendees from Yu.V. Tymoshenko, the Prime Minister of Ukraine.

From the Council for Space Research under the NAS of Ukraine, the meeting was addressed by Prof. Ya.S. Yatskiv, Deputy Chairman of the Council, Director of the Main Astronomical Observatory of the NAS of Ukraine and academician of the NAS of Ukraine, who emphasised a high importance of this outstanding event.

In connection with celebration of the 25th anniversary of application of welding in the outer space, Presidium of the NAS of Ukraine awarded S.E. Savitskaya, V.A. Dzhanibekov and V.P. Nikitsky with medals of the NAS of Ukraine «For Scientific Achievements», which were presented to them by Prof. B.E. Paton.

Cosmonauts S.E. Savitskaya and V.A. Dzhanibekov, as well as V.P. Nikitsky visited the Electric Welding Institute, where they were received by Prof. B.E. Paton, Director of the Institute. The points of the discussions were new developments of the Institute in the field of welding and related technologies, as well as achievements of welding in medicine. The issues of repair-and-renewal and erection operations in the outer space were discussed with specialists of the Institute.

The guests visited National Technical University of Ukraine «Kiev Polytechnic Institute», where they had a discussion with Prof. Yu.I. Yakimenko — the first Pro-Rector of the Institute and Academician of the NAS of Ukraine, Prof. S.I. Sidorenko — Pro-Rector and Corresponding Member of the NAS of Ukraine, and others. Professors L.M. Lobanov and Ya.S. Yatskiv, Academicians of the NAS of Ukraine, took part in the discussions. The guests were told about the history of this Institute and its current activity.

The guests visited the lecture room where S.P. Korolyov, the founder of practical cosmonautics and prominent designer of Soviet space systems, studied, and were acquainted with the exhibits presented there. S.E. Savitskaya, V.A. Dzhanibekov and V.P. Nikitsky placed flowers on the monuments to S.P. Korolyov, E.O. Paton and I.I. Sikorsky, and visited the aerospace museum of NTUU «Kiev Polytechnic Institute».

E.A. Asnis, V.F. Shulym,
N.V. Piskun, I.I. Statkevich, PWI

OPENING OF RUSSIAN-GERMAN CENTER OF LASER TECHNOLOGIES

On August 3, the opening of Russian-German Center of Laser Technologies, founded on the base of Institute of Laser and Welding Technologies (ILWT) of Faculty of Technology and Research of Materials took place at St.-Petersburg State Polytechnic University (SPSPU). The purpose of founding the Center is the search for ways of effective application of laser technologies in industry and research works. The furnishing of the Centre with the most advanced equipment allows its direct participation in realization of definite projects in aerospace branches, shipbuilding, metallurgy, in chemical, oil-gas-production industries and other sectors of industry.

At the opening ceremony of the Center Prof. M.P. Fyodorov, Corr. Member of RAS, rector of SPSPU; Prof. Karl-Dieter Grueske, rector of Erlangen-Nurnberg University; Prof. V.A. Lopota, Corr. Member of RAS, President of RSC «Energiya»; Prof. Michael Schmidt, director of Bavarian Laser Center; Prof. G.A. Turichin, director of Russian-German Center of Laser Technologies of SPSPU, took part.

In the presentations the honorary guests and official persons outlined mainly the role of the Center in scientific-educational and industrial cooperation between Russia and Germany.

Prof. Fyodorov, after receiving the symbolic key for the newly opened Center from the hands of Prof. Schmidt, said: «This key is going to open the new pages of our cooperation and never to close them».

Prof. Grueske said: «It was a pleasure for us to work on founding this Center together with Russian colleagues. This project united the efforts of Ministry of Science and Education of Germany and a number of German companies-producers of laser equipment. I foresee a great potential of cooperation between our universities to be developed».

Speech of Prof. V.A. Lopota, Corr. Member of RAS, President of RSC «Energiya»

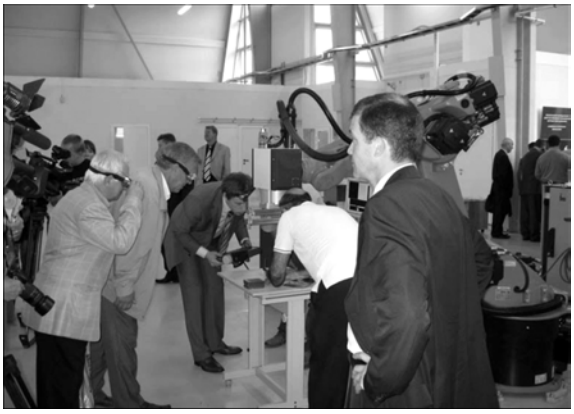
Prof. Lopota said: «The equipment, presented today, is a result of almost 30-year work of Russian and German scientists. The technological processes which could be realized on its basis can provide success of one of the main problems of machine building, i.e. making the structures lighter. Before us now there are real technologies capable to make revolution in machine building, create systems providing the vital activity of a man».

Holger Junge from the Ministry of Science and Education of Germany, expressed the following: «We have been cooperated already over 20 years. Russia has strong science, Germany has strong machine building, and we can achieve a lot by common efforts. The main purpose of this Center is teaching of students. The future technologists, designers can use the equipment for teaching and practicing. This Center will be the demonstration site for medium and small enterprises as well. Besides, the Center will be able to earn».

Prof. Turichin, Director of the Center, said: «This Center is visible embodiment of dream of a big group of people working on the performance of the project on founding the Center. It is equipped with the most updated laser technological complexes covering as to its possibilities almost all spheres of application of laser technologies in machine building. Together with ILWT, the SPSPU forms the largest structure in Europe in the field of machine building laser technologies. The Center will not only provide teaching of students, performance of research works and developments, and orders of industrial enterprises, but also will serve as «the crystallization center» for innovation of companies working in the field of laser and related technologies».

After the opening ceremony Prof. Turichin made technical excursion for honorary guests, representatives of science and industry and journalists. The

Prof. G.A. Turichin, Director of Russian-German Center of Laser Technologies of SPSPU, making a tour around the Center



Demonstration of robotic system of remote-control laser welding ROFIN SWS

equipment of the Center allows realization of the following technologies:

• ERLASER® HARD+CLAD — the robotic laser powder cladding and thermal strengthening;

• JENOPTIK VOTAN C-BIM — the laser 3D cutting of non-metallic materials and thin metals;

• ROFIN SWS — the robotic remote-control laser welding of metallic materials;

• ROFIN StarWeld 500 — the laser pulsed microwelding and deep engraving;

• ROFIN StarShape 300C — the laser perforation, holes drilling, marking of non-metallic materials;

• ARNOLD — the laser welding and cutting of 3D metallic billets including thick-walled and large-size ones;

• LIMO-LASER WORKSTATION — the laser welding of plastics.

The flexibility of the presented equipment and high level of its automation allows quick resetting of technological complexes and change of technologies being used, thus processing the wide range of materials and workpieces.

In the same day the Agreement was signed on the cooperation between SPSPU and High School of Advanced Optic Technologies of Erlangen-Nurnberg University. In accordance with the Agreement the universities will conduct research works on the trends of mutual interest. The Agreement implies the students and post graduate students exchange; realization of common research projects; participation of professors, engineers and students in conferences, seminars and trainings which will be held in both universities; organization of different mutual events.

On August 4, the excursion to ILWT of SPSPU took place headed by G.A. Turichin who outlined the following trends in ILWT activity:

• investigation of processes of interaction of laser radiation with substance;

• technological investigations and developments in the field of laser and electron beam technologies;

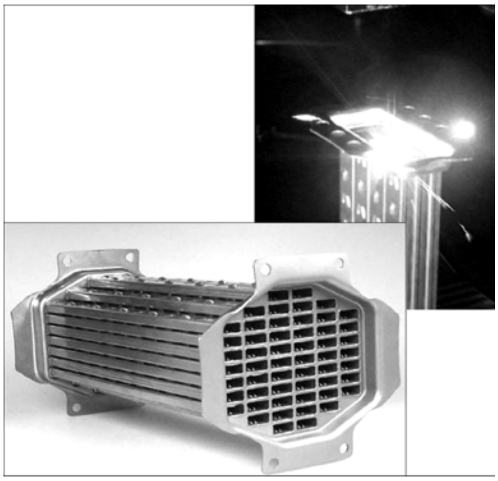
• development of hybrid technologies and laser-arc welding and cladding;

• construction of mathematical models of laser, electron beam, laser-arc and light-laser welding.

Laser thermal strengthening of press-form (Erlaser Hard+Clad)

ILWT is equipped with two unique continuous ytterbium fiber lasers of the capacity of 5 and 15 kW of the company IPG (IRE-Polus Group). The output beams divergence of these lasers is much lower than that of other lasers having the same range of capacity allowing the use of long-focal focusing optics with a large working range. I.A. Tsybulsky, Deputy Director on Production, noted that considering simplicity of supply of laser radiation to the object the main fields of application of fiber lasers can be 3D cutting, remote-control welding, pipe welding, body welding, cladding and other related technologies of material treatment.

We hope that at the Sixth International Conference «Beam Technologies and Lasers Application»



Remote-control laser welding of heat exchanger (ROFIN Scan Welding System)

(September 23–25, 2009, St.-Petersburg) the colleagues of Russian-German Center of Laser Technologies of ILWT of SPSPU will present new results in the field of application of lasers in welding, cladding, brazing and cutting.

Dr. A.T. Zelnichenko